FLOW ANALYSIS OF A COMPOUND MEANDERING CHANNEL

A Thesis Submitted in Partial Fulfilment of the Requirement for the Degree of

Master of Technology
In
Civil Engineering

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DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
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Submitted by

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In partial fulfilment of the requirements
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Master of Technology
In
Civil Engineering
(Water Resources Engineering)
Under The Guidance of
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DECLARATION

I hereby state that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by any other person nor substance which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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CERTIFICATE

This is to certify that the thesis entitled **“FLOW ANALYSIS OF A COMPOUND MEANDERING CHANNEL”** is a bonafide record of authentic work carried out by **MAMATA RANI MOHAPATRA** under my supervision and guidance for the partial fulfilment of the requirement for the award of **Master of Technology** degree in **Civil Engineering** with specialization in **Water Resources Engineering** at the National Institute of Technology, Rourkela.

The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Date:

Place: Rourkela

PROF.K.C.PATRA

PROFESSOR

Department of Civil Engineering

National Institute of Technology, Rourkela

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ABSTRACT

Despite substantial research on various aspects of velocity distribution in meandering rivers no systematic effort has been made to investigate the experimental and numerical simulation on a meandering channel at the bend apex section for overbank flow conditions. In this research work, detailed investigations of longitudinal velocity distribution, Depth averaged velocity distribution, velocity contours, boundary shear distribution has been carried out. The analysis is performed at bend apex that is at the point of maximum curvature and the fluid flow behaviour has been studied. The results iterate that the higher longitudinal velocity always remains towards the inner bank that is at the convex side of the meandering curve and lower velocity lies at the inner side or at the concave side of the curve. The experimental results are then validated through numerical modelling by using 3 dimensional numerical software ANSYS (FLUENT) by taking large Eddy Simulation (LES) turbulence model .The numerical results are found to be well complimenting with the experimental results.

Keywords: bend apex, meander path, longitudinal velocity distributions, boundary shear stress, numerical modeling, turbulence, Ansys-Fluent

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SYMBOL	DESCRIPTION
A	Cross-sectional Area of Channel
C	Chezy's channel coefficient
C_d	Coefficient of Discharge
d	Diameter of Preston tube
f	Darcy-Weisbach Friction factor
g	Acceleration due to Gravity
h	Pressure Difference
H	Average flow Depth of water at a Section
h_w	Height of Water
H_n	Height of water above the Notch
L	Length of Channel for one Wavelength
L_n	Length of Rectangular Notch
n	Manning's Roughness Coefficient
ΔP	Differential Pressure
Q_a	Actual Discharge
Q_{th}	Theoretical Discharge
r_c	Radius of Curvature of a Sinuous Channel
ρ	Density of the Flow
S	Bed Slope of the Channel
S_r	Sinuosity
SF_{Bed}	Shear Force at the Bed of the Channel
SF_{Inner}	Shear Force at the Inner Wall of the Channel Section
SF_{Outer}	Shear Force at the Outer Wall of the Channel Section
SF_T	Total Shear Force
τ_c'	Average Shear Stress

τ	Boundary Shear Stress
υ	Kinematic Viscosity
V_w	Volume of Water
v	Point Velocity
W	Width of Channel
x^*,y^*	Non-Dimensional Parameters
λ	Wavelength of a Sinuous Channel

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF RIVER

Beauty and historic livelihood of a settlement are always related with Rivers. For the sake of food, water, and transport people have been living near the banks of rivers for decades. Flooding brings a huge damage to the properties and lives of people so it has always been a threat for mankind. Due to climate change, growing population on the banks of rivers and industrialization the frequency of occurrence of floods has increased recently. So it is essential to understand the flooding problem by analyzing the physics behind it. Normally river flow patterns are categorized in to three types such as (i) Straight river ii) Meandering river and (iii) Braided river. When moving water in a stream erodes the outer banks and widens its valley a meander formed .The river near the inner side has less energy so it deposits the material it carries along with it during flowing. Thus results a snaking pattern formation as the stream meanders back and forth across its down-valley axis. Almost all natural rivers possess meander geometry. Straight rivers of length more than 10 times the widths are not exists in nature. Discharges through meandering type are totally different from that of the straight type. According to the geometrical shape and other hydraulically independent parameters Such as velocity, depth, channel width and slope flow through meandering channel are more complicated than straight channel. A meander, in general, is a bend in a sinuous watercourse. Secondary circulation in the cross sectional plane is the second reason of formation of meander as suggested by **Leopold (1996). Leliavsky (1955)** named the centrifugal force as the basic fundamental principles of the meandering theory due to helicoidal cross currents formation. Sinuosity and least centreline radius (r_c) to channel width (b) ratio are the two critical parameters that govern the flow in compound meandering channel. How much a river course deviates from shortest possible path (how much it meanders) is defined by Sinuosity. Sinuosity is defined as the ratio of Channel length to valley length.

The degree of meandering was described by **Chow (1959)** as follows:

TABLE 1.1: DEGREE OF MEANDERING

SINUOSITY RATIO	DEGREE OF MEANDERING
1.0-1.2	Minor
1.2-1.5	Appreciable
1.5 AND GREATER	Severe

Meandering channels are categorized as deep or shallow depending on the ratio of the average channel width (b) to its depth (h). **Rozovskii (1961)** mentioned a channel as a shallow channel if its width (b) to depth (h) ratio is greater than 5.In shallow meandering channel the central portion is called the "core zone" and it is free from the wall effects. In this type of channel the wall effects are limited to a small zone near the wall which may be called as "wall zone". In deep meandering channel the width (b) to depth (h) ratio is less than 5.In deep channels the influences of walls are felt throughout the channel width. However meandering channels are still subjects of research which involves numerous flow parameters that are intricately related giving rise to complex three dimensional motions in the flow. Because of this 1D and 2D of open channel flows fail to estimate the discharge precisely. So a hypothesis shift is towards the study of 3D modelling of open channel flows that can capture and take into account the complicated unseen phenomena called "*turbulence*". To analyse practical problems occurring in rivers such as flood protection, flood plain management, bank protection, navigation, water intakes and sediment transport-depositional patterns experimental facilities, instrumentation and computer models have been gradually improved in the world.

1.2 TYPES OF FLOW CHANNELS

The channels can be classified on the basis of geometry of their flow path as follows,

1) STRAIGHT CHANNEL

2) MEANDERING CHANNEL

3) BRAIDED CHANNEL

1.2.1 STRAIGHT CHANNEL:

If a channel does not deviate from its path then a straight channel is formed. Straight channels of longer lengths are not exists due to its unstable nature. Experiment show that pool and riffle orders are rapidly developed in straight channels.

The straight rivers in Owatonna The straight river township Minnesota

Figure 1.1 Different types of straight channels

1.2.2 MEANDERING CHANNEL

If a straight channel deviates from its axial path and a curvature of reverse order is developed then it is called a meandering channel. The degree of adjustment of water and sediment load in the river is called Meander. Mainly meander is formed by sediment erosion from the outer wall of bend (concave side) and depositing them on the inner wall of the bend (convex side).

A meander is formed when the fluid flow erodes the outer bank or concave side and deposits the sand grains at the inner side that is convex side. Due to this outside bank becomes deeper than the inside bank. A helical or corkscrew shaped flow is occurs in meandering channels which means the water surface being raised on the outer bank and return existing at a depth directing the flow towards the opposite bank as shown in the Figure 1.3.

Typically Meandering Channel

(River Amazon)

Typically Meandering Channel

(Northern Owens Valley)

Figure 1.2: Different types of meandering channels

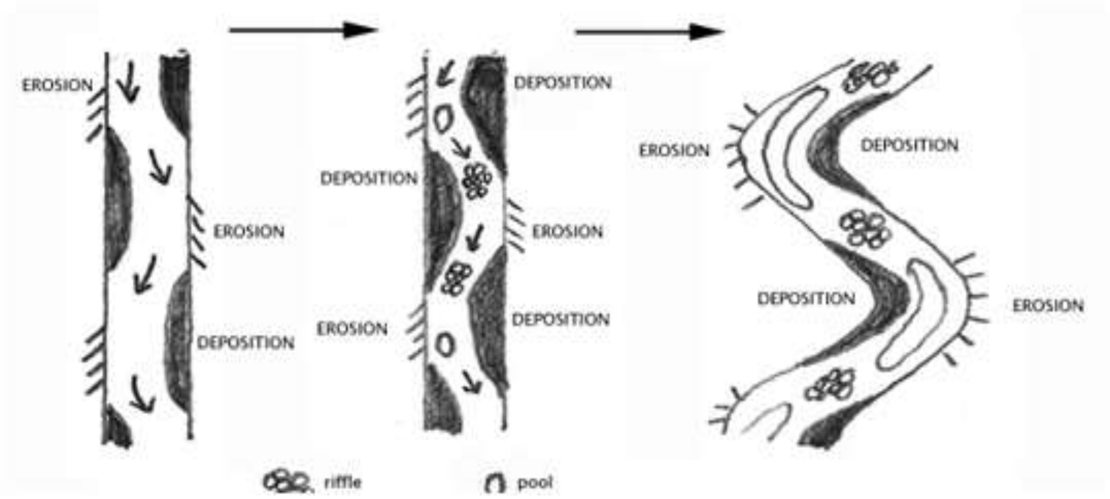


Figure1.3: A simple illustration of meandering channel formation.

An overview of geometry of meandering channel **Watson et al. (2005)** is shown below in Figure 1.5. In the figure given below wavelength describes the distance between successive crests of a wave and the wavelength as the maximum extent of a oscillation, measured from the position of equilibrium.

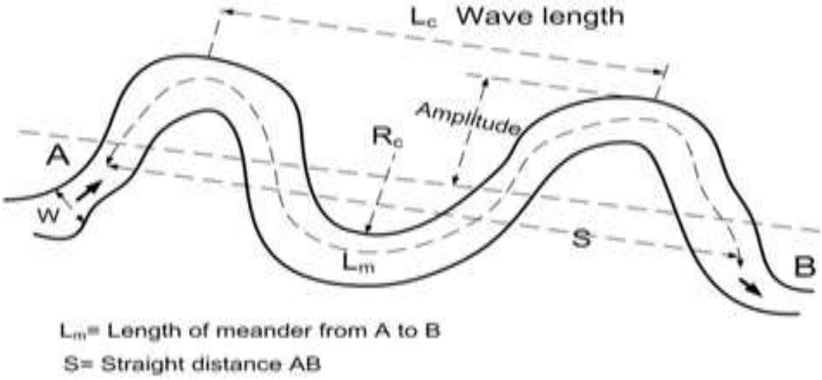


Figure1.4: Geometry of the meandering channel

1.2.3 BRAIDED CHANNEL

A river consisting of a network of small channels is called braided channel. In this type of channel water courses are divided by small Islands into multiple channels. It diverts from the main channel and rejoins it at the downstream.

Waimakariri River in New Zealand

The white river in U.S

Figure1.5: Different types of braided channel

1.3 MEANDER PATH

The flow path undertaken by a river is called meander. The meandering study is taken from one bend apex to the next bend apex. The section where the river has the maximum

Curvature is called Bend apex or the axis of bend. A channel passes through the crossover when it moves from one bend apex to the other. The inner side of the channel along the flow direction is called convex bank and the outer side is called concave bank. In a meandering channel always erosion takes place at the outer region and sedimentation takes place at the inner region. The meander path changes its course at the cross-over, which is a section at the point of inflection.

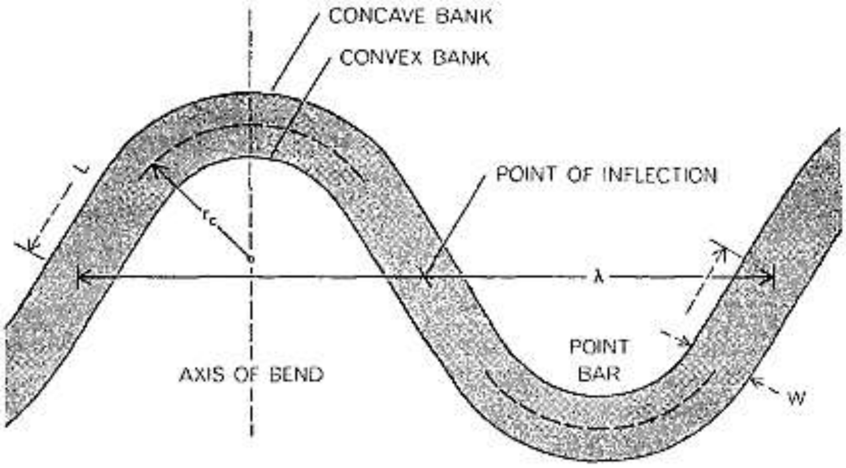


Figure1.6: Properties of River Meander **(Leopold and Langbein, 1966)**

In this Fig.1.6 W=Width of the channel

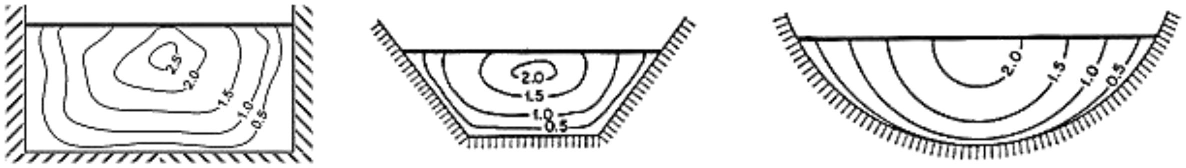
L=Length of the channel for one wavelength

rc =Radius of the channel

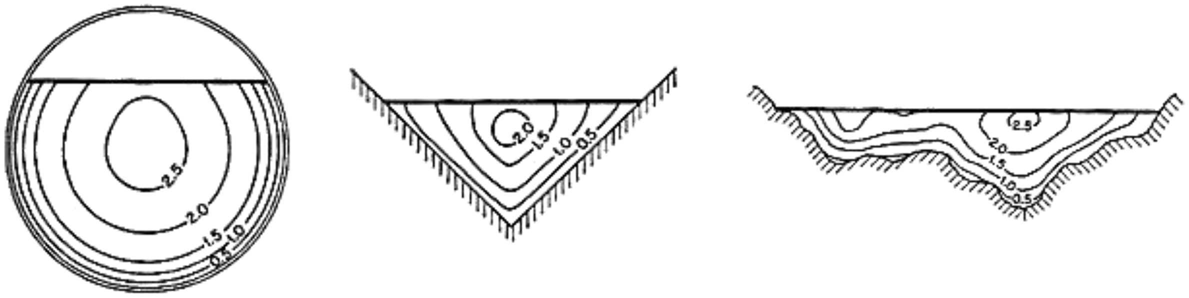
λ=Wave Length

1.4 LONGITUDINAL VELOCITY DISTRIBUTION

Velocity magnitude at each point across a flow section can be identified by velocity distribution curves. Velocity distribution in curved meanders has been done by many researchers but no systematic effort has been made to study the variation of velocity along a meander path. Velocity distribution varies with different width-depth ratio for straight channel but in a meandering channel the velocity distribution depends on various other parameters such as aspect ratio, sinuosity, etc. making the flow more complex to investigate. Maximum stream wise velocity occurs at water level for laminar flow but for turbulent flows the maximum stream wise velocity occurs at about 5-25% of water depth below the water surface **(Chow, 1959).** Fig.1.2 shows the typical stream wise velocity contour lines (isovels) for flow in various cross sections.



a) Rectangular b) Trapezoidal c) Shallow ditch



d) Circular e) Triangular f) Natural river

Figure 1.7: Contours of constant velocity in various open channel sections (Chow, 1959).

From the above velocity contours we can draw a conclusion that maximum velocity is considered to be present somewhere in the middle of the cross-section below the free water surface for straight channels. But this condition is not valid in the case of meandering river. In meandering river the local maximum velocity is seen to occur at convex side or inner wall of the channel.

1.4.1 Logarithmic law

The logarithmic law formulation for the velocity profile for turbulent open channel flow is based on **Prandtl's (1926)** theory of the "law of the wall" and the "boundary layer" concept.

The boundary layer is a thin region of fluid near a solid surface (bed or wall) where the viscous effect affects the fluid motion and subsequently, the velocity distribution. In the turbulent boundary layer zone a viscous sub layer or laminar layer exists where viscous force predominates but at a distance farther away from the wall or boundary the turbulent shear stress plays a major role in the defect layer or turbulent layer. According to the "Law of the wall" in the stream wise direction, the average fluid velocity in the boundary layer region varies logarithmically with the distance from the wall surface.

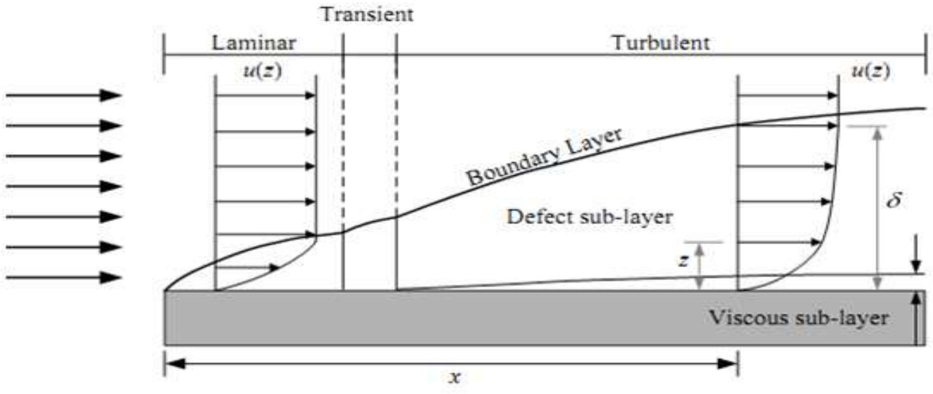


Fig.1.8: External fluid flow across a flat plate (after Messy, 1998)

1.4.2 Power law

"Power law" is an alternative function for the determination of velocity distribution. **Barenblatt and Prostokishin, 1993**; **Schlichting, 1979** approached this law. The standard form of this law is: $U+ = C4 (z^{+})^{m}$, where C4 and m are the coefficient and exponent of the power law.

1.5 DEPTH AVERAGED VELOCITY DISTRIBUTION

In meandering rectangular channel it is very difficult to model flows as the inner and outer banks exert unequal shear drag on the fluid flow which controls the depth-averaged velocity. Depth averaged velocity is defined as average velocity measured at a height of 0.4h from the bed level.

1.6 BOUNDARY SHEAR

When fluid flows in a channel the reactions from the channel bed and side wall offered resistance to the force acting along the flow direction. This resistive force is called boundary shear force. The tangential component of the hydrodynamic force acting along the channel bed can be stated as boundary shear force. Boundary shear force distribution takes place along the wetted perimeter of the channel. Boundary shear force directly affects the flow structure in an open channel. Boundary shear stress is an important factor to define velocity profile and fluid field. To determine the sediment transport, side wall correction, cavitations, channel migration, conveyance estimation the knowledge on boundary shear distribution is very important. For steady uniform flow shear force is related to hydraulic radius, bed slope and unit weight of fluid. From practical point of view the boundary shear forces are not uniform even for straight prismatic channels. The secondary current is the main reason of non uniformity of boundary shear stress. The non-uniformity is formed by anisotropy between vertical and transverse turbulent intensities which was given by **Gessner (1973)**. **Tominaga et al. (1989)** and **Demetriou (1983)** stated that boundary shear stress increases when the secondary currents flow towards the wall and shear stress decreases when it flows away from the wall. The distribution of shear stress along the channel’s wetted perimeter is affected by the presence of secondary flow cells in main channel. The presence of secondary flow is illustrated in the figure shown below in Fig.1.9.Shape of the channel cross section, depth of flow, lateral- longitudinal distribution of wall roughness and sediment concentration also affects the shear stress distribution. For meandering channel sinuosity is regarded to be a critical parameter in the shear stress distribution along the channel bed and walls.

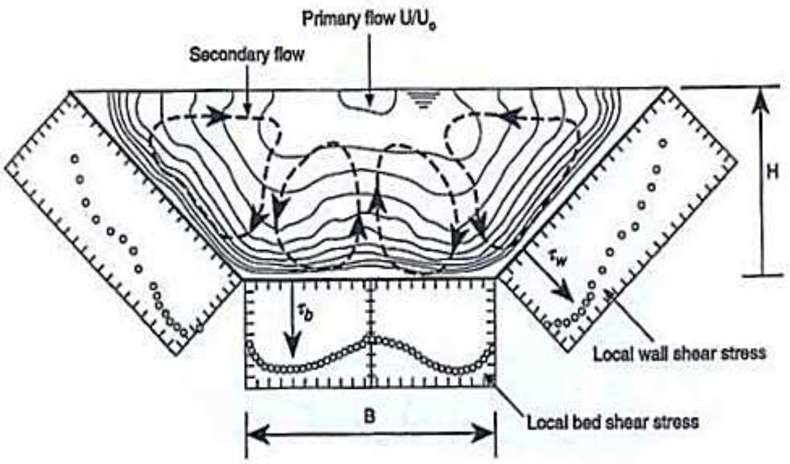


Figure1.9: Schematic influence of secondary flow cells on boundary shear distribution.

Compound channel consists of a deeper main channel and shallow flood plains on one or both sides of the main channel. When rivers are at high stage like during flood, the flow from the main channel spills and spreads to the adjacent floodplain. When water flows over the flood plain its wetted perimeter increases. The velocities in floodplain are less than that of the main channel due to higher roughness magnitude. Due to the interaction between faster moving fluid in main channel and slower moving fluid in floodplain vortices are formed. Knight and **Hamed (1984)** stated it as “turbulence phenomenon”. Consequently there is a lateral momentum transfer occurs. The mechanism of momentum transfer in straight two stage channel is demonstrated in fig.1.10.

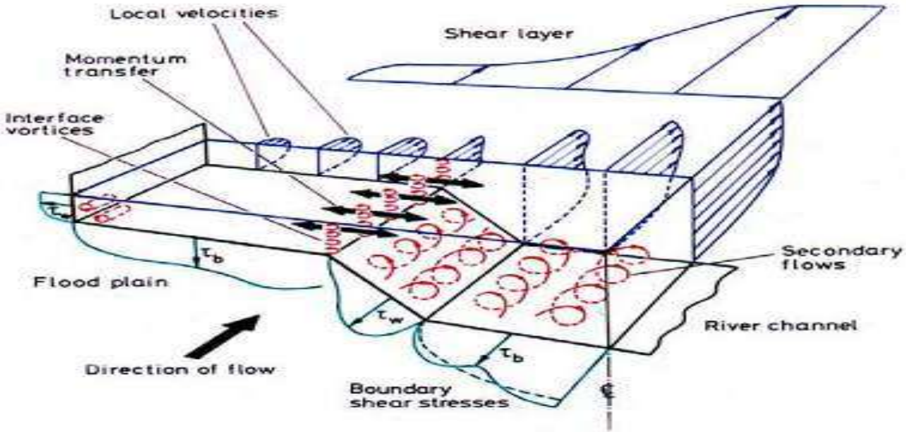


Figure1.10 3D Flow structures in open channel (Shiono and Knight, 1991)

1.7 OBJECTIVES OF THE RESEARCH

The present work is intended to analyse the various flow characteristics of a meandering path of a 60^0 cross-over angle meandering channel. Though various researches has been carried out on flow characteristics of free surface flows with curves with different angles, but not much research has been done along a path of meandering channel followed by the meandering channel of same aspect ratio and sinuosity.

The objectives of the present work summarized as:

- To study the distribution of depth- averaged velocity at channel bend apex for depths for overbank flow conditions.
- To simulate a 60^0 compound meandering channel using large eddy simulation model (LES) to derive the flow phenomena like longitudinal velocity distribution, depth averaged velocity distribution ,velocity contours using applications of computational fluid dynamics.
- To carry out an investigation concerning the distribution of local shear stress in the compound meandering channels.

1.8 THESIS STRUCTURE

- The thesis consists of five chapters. General overview is provided in chapter 1,Chapter 2 contains literature survey, experimental work and the methodology is described in Chapter 3,experimental results are illustrated and analysis of results are done in Chapter 4,Chapter 5 contains the conclusions drawn from the analysis and then references are presented.

- **Chapter 1** represents a general view about overview of river, types of channels and and meander path. Also the chapter introduces Concept of velocity distribution and boundary shear distribution in meandering channel. A brief description on numerical modelling is also included in this section.
- **Chapter 2** gives detailed literature study by other researcher on straight simple channel, straight compound channel, simple meandering channel, compound meandering channel. Literature on numerical analysis is also included in this section. The previous research works arranged according to the year of publication with the latest work at the later.
- **Chapter 3** gives details about the construction of the meandering channel and the apparatus and equipments used for the experimentation. The methodology adopted for obtaining velocity distribution, boundary shear stress and boundary shear force by experimental and numerical analysis is also discussed. Numerical modelling and numerical simulation are also added in this chapter.
- **Chapter 4** illustrates the experimental results which are then analysed. The results discussed are the velocity distribution in lateral direction, the depth averaged velocity distribution the boundary shear stress distribution at bend apex obtained from numerical analysis and experimental analysis and validation of the results obtained from the above research analysis.
- **Chapter 5** summarizes the conclusions reached by the numerical and experimental research and the recommendations for further work are listed**.**
- **Chapter 6** describes the conclusion reached by the present research and recommendation for further work is listed out**.**

References that have been made in subsequent chapters are provided at the end of the thesis.

CHAPTER 2
LITERATURE SURVEY

2.1 OVERVIEW

In this chapter a detailed literature survey is prerequisite to any expressive and successful research in any subject. In this present work there is no exception and hence a focused and intensive review of literature was carried out covering various aspects concerning the meandering channels. In the literature review the researchers‟ studied mainly on hydraulic engineering problem which was related to the behaviour of rivers and channels collected to obtain the various features and characteristics of meandering rivers. In a river the flow characteristics is overbearing for different conditions such as flood control, channel design, and renewal projects include the transport of pollutants and sediments. Flow in meandering channels is common for natural rivers, and research work was conducting in this type of channel for flood control, discharge estimation and stream restoration.

2.2 PREVIOUS EXPERIMENTAL RESEARCH ON STRAIGHT SIMPLE CHANNEL

Coles (1956) proposed a semi-empirical equation on velocity distribution, which can be connected to outer region and wall region of plate and open channel. He summed up the Logarithmic equation of the wall with attempted wake capacity, w(y/8).This formula is asymptotic to the logarithmic mathematical statement of the wall as the distance y approaches the wall. This is essential detailing towards outer layer region.

Coleman (1981) recommended that the mathematical equation for velocity distribution for silt loaded stream comprises *o*f two sections, as initially examined by Coles for clear-water flow. Likewise he has uncovered that the von Karman coefficient is free of sediment concentration. The rise of the greatest speed and the deviation of speed from the logarithmic equation at the water surface are functions of the aspect ratio of the channel. The log law is produced into a mathematical statement applicable to the entire flow including the region.

close to the water surface for different boundary conditions. The wake law depicts the velocity

M. Salih Kirkgoz et al. (1997) deliberate mean velocities utilizing a Laser Doppler Anemometer (LDA) in creating and completely developed turbulent subcritical smooth open Channel flows. From the trials it is observed that the boundary layer along the middle line of the channel grows up to the free surface for a low aspect ratio. In the turbulent internal regions of creating and completely developed boundary flows, the measured velocity profiles agree well with the logarithmic "law of the wall" distribution. The "wake" impact gets to be vital in the velocity profiles of the completely developed boundary layers.

Sarma et al. (2000) attempted to define the velocity distribution law in open channel Flows by taking generalised version of velocity distribution, which joins the logarithmic law of inner region and parabolic law of the external or outer region. The law grew by taking velocity-dip in to account.

Guo and Julien (2005) solved the momentum and continuum equations and proposed a system to determine average bed and side wall shear stresses in smooth rectangular open-channel flows. The investigation demonstrated that the shear stresses were functions of three components: (1) gravitational; (2) secondary flows; and (3) interfacial shear stress. An analytical solution in terms of series expansion was obtained for the case of constant eddy viscosity without secondary currents.

Wilkerson et al. (2005) utilizing the information from three past studies, built up two models For anticipating depth averaged velocities in straight trapezoidal channels that are not wide, where the banks apply form drag on the fluid and thereby control the depth averaged velocity distribution. The information they utilized for building up the model are free from the impact of secondary current.

Knight et al. (2007) utilized Shiono and Knight Method (SKM), which is another way to calculating the lateral distributions of depth averaged velocity and boundary shear stress for flows in straight prismatic channels, additionally accounted secondary flow impact. It represents bed shear, lateral shear, and secondary flow impacts via3 coefficients- f, λ, and Γ thus joining some key 3D flow feature into a lateral distribution model for stream wise motion. This strategy used to examine in straight trapezoidal open channel. The number of secondary current differs with aspect ratio. It is three for aspect ratio less than equal to 2.2 and four for aspect ratio greater than equal 4.

Afzal et al. (2007) analyzed power law velocity profile in completely developed turbulent Pipe and channel flows in terms of the envelope of the friction factor. This model gives great estimate for low Reynolds number in outlined procedure of actual system compared to log law.

Yang (2010) research depth–averaged shear stress and velocity in rough channels. Mathematical statements of the depth averaged shear stress value in open channels have been derived taking into account a theoretical connection between depth averaged shear stress and boundary shear stress.

Albayrak et al. (2011) joined the detailed acoustic Doppler speed profiler (ADVP), large scale particle image velocimetry (LSPIV) and hot film estimations to examine secondary current dynamics within the water column and free surface of an open channel flow over a rough movable (not moving) bed in a wider channel, with a higher bed roughness and at higher Reynolds number.

Kundu and Ghoshal (2012) re-explored the velocity distribution in open channel. Flow in view of flume experimental data. From the investigation, it is suggested that the wake layer in external region may be divided into two regions, the relatively weak outer region and the relatively strong outer region. Combining the log law for inner region and the parabolic law for relatively strong outer region, an explicit equation for mean velocity distribution of steady and uniform turbulent flow through straight open channels is proposed and verified with the test information. It is discovered that the sediment concentration has significant effect on velocity distribution in the relatively weak outer region.

2.3 STRAIGHT COMPOUND CHANNEL

Wormleaton and Hadjipanos (1985) deliberate the velocity in every subdivision of the channel, and found that even if the errors in the calculation of the overall discharge were small, the errors in the calculated discharges in the floodplain and main channel may be exceptionally very large when treated independently. They likewise watched that, regularly, underestimating the discharge the on the floodplain was compensated by overestimating it for the main channel. The disappointment of most subdivision systems is because of the complicated interaction between the main channel channel and floodplain flows.

Myers (1987) displayed theoretical considerations of ratios of main channel velocity and discharge to the floodplain values in compound channel. These proportions took after a straight- line association with flow depth and were free of bed slope yet dependent on channel geometry only. Equations depicting these relationships for smooth compound channel geometry were displayed. The discoveries demonstrated that at low depths, the conventional methods always overestimated the full cross sectional conveying limit and underestimated at larger depths, while floodplain flow limit was constantly underestimated at all depths. He underlined the requirement for systems for compound channel investigation that precisely show extents of flow in floodplain and fundamental channel and also full cross-sectional discharge capacity.

Tominaga & Nezu (1992) measured velocity with a fiber-optic laser-Doppler anemometer in steep open-channel streams over smooth and not completely rough beds. As velocity profile in steep open channel is vital for taking care of the issues of soil erosion and sediment transport, and he watched the integral constant A in the log law coincided with the standard estimation of 5.29 regardless of the Reynolds and Froude number in subcritical flows, whereas it diminished with an increment of the bed slope in supercritical flows.

Czernuszenko, Kozioł, Rowiński (2007) depicts some turbulence estimations done in a trial compound channel with flood fields. The surface of the main channel bed was smooth and made of concrete, while the flood plains and slanting banks were secured by cement mortar composed with terrazzo. Instantaneous velocities were measured by means of a three-segment acoustic Doppler velocity meter (ADV) produced by Sontek Inc. This article displays the results of estimations of primary velocity, the distributions of turbulent intensities, Reynolds stresses, auto correlation functions and the turbulent scales.

M. M. Ahmadi et al. (2009) proposed an unsteady 2D depth-averaged flow model taking into consideration the dispersion stress terms to simulate the bend flow field using an orthogonal curvilinear co-ordinate system. The dispersion terms which arose from the integration of the product of the discrepancy between the mean and the actual vertical velocity distribution were included in the momentum equations in order to take in account the effect of the secondary current.

M. M. Ahmadi et al. (2009) proposed an unsteady 2D depth averaged flow model taking into thought the dispersion stress terms to simulate the bend flow field utilizing an orthogonal curvilinear co-ordinate framework. The dispersion terms which arose from the integration of the product of the discrepancy between the mean and the actual vertical velocity distribution were included in the force momentum equations in order to take into account the impact of the secondary current.

2.4 MEANDER SIMPLE CHANNELS

Johannesson and Parker (1989) exhibited a analytical model for ascertaining the lateral distribution of the depth averaged primary flow velocity in meandering rivers. The moment method, commonly used to solve the concentration distribution, is then used to acquire an approximate solution. This makes it conceivable to consider the convective transport of primary flow momentum stream by the secondary flow.

Maria and Silva (1999) expressed the friction factor of rough turbulent meandering flows as the function of sinuosity and position (which is determined by, among other factors, the local channel curvature).They validated the expression by the lab information data for two meandering channels of different sinuosity. The expression was found to yield the computed vertically averaged flows that are in agreement with the flow pictures measured for both large and small values of sinuosity.

Zarrati, Tamai and Jin (2005) built up a depth averaged model for anticipating water surface profiles for meandering channels. They connected the model to three meandering channels (two simple and one compound). The model was found to anticipate well the water surface profile and velocity distribution for simple channels and also for the main channel of compound meandering channel.

Khatua (2008) gives the result of energy loss in a meandering channel. It is calculated in different depth of flow which gives the resistance factors Manning's *n*, Chezy's *C*, and Darcy-Weisbach *f* for meandering channel. Stage-discharge relationship from in-bank to the over-bank flow is given.

Pinaki (2010) analysed a series of laboratory tests for smooth and rigid meandering channels and developed mathematical equation using dimension analysis to evaluate roughness coefficients of smooth meandering channels of less width ratio and sinuosity.

Seo and Park (2010) carried out laboratory and numerical studies to find the effects of secondary flow on flow structures and dispersion of pollutants in curved channels. Primary flow is found to be skewed towards the inner bank at the bend while flow becomes symmetric at the cross-over.

Absi(2011) analytic solution of the Reynolds-Averaged Navier-Stokes equation was carried out to get ordinary differential equation for velocity distribution in open channel. The proposed equation was helpful in predicting the maximum velocity below the free surface. Two different degrees of approximation was done. A semi-analytical solution of the proposed ordinary differential equation for the full dip-modified-log-wake law and another simple dip-modified-log-wake law. Numerical solution of the ordinary differential equation and velocity profiles of the two laws are compared with the previously published experimental data.

Bonakdri*et. al*. (2011) studied numerical analysis of a flow field of a 90° bend. Prediction of data was carried out by using Artificial Neural Network and Genetic Algorithm. CFD model was used to investigate the flow patterns and the velocity profiles. ANN was used to predict data at locations were experimental data was not available.

Baghalian*et. al.* (2012) studied the velocity field in a 90° bend channel. Investigations were carried out by using artificial intelligence, analytic solutions and numerical methods. Experimental results were compared with the models with ANN and numerical methods which gave better performance than analytic solutions.

Khatua and Patra (2012) used dimensional analysis to develop a mathematical model by taking series of experiments data to evaluate roughness coefficients for smooth and rigid meandering channels. The vital variables are required for stage-discharge relationship such as velocity, hydraulic radius, viscosity, gravitational acceleration, bed slope, sinuosity, and aspect ratio.

Khatua*et.al.* (2013) proposed a discharge predictive method for meandering channels taking into account the variation of roughness with depth of flow. He compared his model with several other models to evaluate its performance.

Dash (2013) analysed the important parameters affecting the flow behaviour and flow resistance in term of Manning's *n* in a meandering channel. Factors affecting roughness coefficient are non- dimensionalized. To predict and find their dependency with different parameters a mathematical model was formulated to predict the roughness coefficient which was applied to predict the stage-discharge relationship.

Mohanty (2013) predicted depth-averaged velocity distribution in a trapezoidal meandering channel. A nonlinear form of equation involving overbank flow depth, main channel flow depth, incoming discharge of the main channel and floodplains etc. was formulated. The validation of the experimental result of depth averaged velocity was carried out by using a quasi1D model Conveyance Estimation System (CES).

2.5 MEANDER COMPOUND CHANNEL

D. Alan Ervine, et al. (2000) displayed a practical system to predict depth averaged velocity and shear stress for straight and meandering overbank streams. An analytical solution to depth –integrated turbulent form of the Navier-Stokes mathematical statement was exhibited that included shear and secondary flows in addition to bed erosion. The novelty of that approach was not just its incorporation of the secondary flows in the formulation additionally its appropriateness to straight and winding channels.

Patra and Kar (2000) reported the outcomes of the experimental results concerning the boundary shear stress, shear force, and discharge characteristics of compound meandering Channel. The cross section of the channel is rectangular and one or two floodplains disposed of to its sides. They used five dimensionless channel parameters to form equations representing the total shear force percentage carried by floodplains. A set of smooth and rough sections were studied with aspect ratio varying from 2 to 5. Apparent shear forces on the assumed vertical, diagonal, and horizontal interface plains were found to be different from zero at low depths of flow and changed sign with increase in depth over floodplain. They proposed a variable-inclined interface for which apparent shear force was calculated as zero. They presented empirical equations predicting proportion of discharge carried by the main channel and floodplain.

Patnaik (2013) analyzed the distribution of boundary shear stress at the point of maximum curvature or at the bend apex for both in bank and overbank flow conditions. Data from the experimentations were gathered under different discharge and relative depths maintaining the geometry, slope and sinuosity of the channel. Effect of aspect ratio and sinuosity on wall (inward and external) and bed shear forces were evaluated and equation was created to determine the percentage of wall and bed shear forces in smooth trapezoidal channel for in bank flows only. The proposed equations were compared with past studies and the model was extended to wide channels.

2.6 LITERATURE REVIEW ON MUNERICAL ANALYSIS

Cokljat &Younis and Basara & Cokljat (1995) approached the RSM (Reynolds Stress Model) for numerical simulations of open channel flows in a rectangular compound channel and satisfied with the predicted and measured data.

Thomas and Williams (1995) proposed the Large eddy simulation model for a compound trapezoidal channel with steady uniform flow at a Reynolds number of 43000.They have predicted the bed stress distribution, secondary circulation, velocity distribution across the flood plain area. The results were compared with the experimental data. They got the experimental data from FCF (Flood channel facility) at Hydraulics Research Ltd, Wallingford, England.

Salvetti et al. (1997) approached Large Eddy Simulation model for a relatively large Reynolds number for predicting results for bed shear distribution, secondary motion of fluids and vortices. He compares the experimental results with the numerical ones.

Ahmed Kassem, Jasim Imran and Jamil A.Khan (2003) defined the 3D modeling of negatively buoyant flow in a diverging channel with a sloping bottom. They modified various things in numerical models for diverging channels. They modified the k-€ turbulence model and Boussinesq approximation for the Reynolds-averaged equations in diverging channels.

Lu et al. (2004) applied a three dimensional numerical model to 180^0 bend. He adopted k-€ turbulence model to simulate boundary shear stress distribution, longitudinal and transversal changes of water depth and velocity distribution components.

Bodnar and Prihoda (2006) used the K-epsilon turbulence model to analyze the nature of non –linearity of water surface slope for a sharp bend.

Booij (2003) and Vanbalen et al. (2008) used the LES (Large Eddy Simulation) model to a mildly curved 180^0 bend to define the secondary flow structure.

Sugiyama H., Hitomi D., Saito T. (2006) used Reynolds stress transport equation which is included in algebraic stress model. They concluded that near the free surface the vertical velocity approaches to zero. In addition, the compound meandering open channel was clarified somewhat based on the calculated results. As a result of the analysis, the present algebraic Reynolds stress model is shown to be able to reasonably predict the turbulent flow in a compound meandering open channel.

Jing, Guo and Zhang (2009) approached Reynolds Stress model for compound meandering channel flows. The Reynolds stresses, wall shear stresses, velocity fields are calculated for a range of input conditions. They found good agreement between predicted and experimental data. It indicates that RSM can successfully predict the complicated flow phenomenon.

B.K. Gandhi, H.K. Verma and Body Abraham (2010) determined under real flow conditions the velocity profiles in both the directions. To numerically model the flow situations ‘Fluent’ a Commercial computational fluid dynamics (CFD) code has been used.

Esteve et.al., (2010) used the experimental configuration of Muto and Shiono (1998) to simulate the turbulent flow structures in a compound meandering channel. The model is performed within the in-house code LESOCC2.The predicted secondary vectors and stream wise velocities as well as turbulent intensity are in good agreement with the LDA measrements.

Ansari et. al., (2011) determined the boundary shear distribution in trapezoidal channels and analyzed the variation of aspect ratio and composite roughness on the shear stress distribution. The results indicate the significant contribution on secondary currents and overall shear stress at the boundaries.

RasoolGhobadian and Karman Mohammodi (2011) simulated the stream design for a Subcritical stream in 180^0 uniform and united open channel curves utilizing SSIIM three dimensional model with maximum bed shear stress. He presumed that toward the end of the united twist, bed shear stress show higher qualities than those in the same area in the Channel with a uniform curve.

Khazaee&M.Mohammadiun (2012) investigated three-dimensional and two phase CFD model for flow distribution in open channel. He considers seven cases of different aspect ratios, different inclination angles or slopes and convergence divergence condition by using finite volume method (FVM) with a dynamic sub grid-scale.

Omidseyedashraf, Ali Akbar Akhtari &MiladKhatibShaidi (2012) reasoned that the standard k-ϵ model has the ability of catching specific flow features in open channel bends all the more precisely.

Anthony G. Dixon (2012) approached Computational fluid dynamics (CFD) programming with fluid flow interactions between phases and he investigated and enhanced it. He included utilization of CFD to simulate an experiment on multiphase flow to compare results on flow regime and pressure drop.

Larocque, Imran, Chaudhry (2013) introduced 3D numerical simulation of a dam-break flow utilizing LES and k- ε turbulence model with following of free surface by volume-of-fluid model. Results are compared with the experimental results got by others utilizing a shallow water model. The outcomes demonstrate that both the numerical models satisfactorily reproduce the temporal variation of the measured bottom pressure. Nonetheless, the LES model catches better the free surface velocity variation with time.

Ramamurthy et al. (2013) simulated three-dimensional flow pattern in a sharp curve by utilizing two numerical codes alongside distinctive turbulent models, and by looking at the numerical results with experimental results accepted the models, and asserted that RSM turbulence model has a superior concurrence with test results.

From writing review, it was observed that very work on velocity and boundary shear stress distribution have been accounted for rectangular compound meandering channel. Although sufficient writing is accessible on numerical studies that make utilization of diverse turbulence models for demonstrating compound meandering channels.

CAPTER 3
METHDOLOGY

3.1 GENERAL

Experimental work on natural rivers is very complicated due to complex geometry hence the hydraulic characteristics of a fluid flowing in a river can be analysed by studying them on a model designed close to natural rivers. Natural rivers are having different sinuosity throughout their path. Flow patterns are studied on experimental models for different sinuosity and can then be used to model them on natural channels. Evaluation of discharge capacity is in a meandering channel is a difficult process due to complicated geometry, channel alignments and flow conditions. The prediction of discharge capacity is directly dependent on accurate evaluation of velocity distribution at various sections in channels for different flow conditions. To study the flow behaviour and characteristics of meandering rivers a meandering channel having a sinuosity 2.04 is constructed and the velocity and bed shear distributions are measured at the bend apex. Velocity distribution is never uniform across a channel section. The main channel is deeper than the flood plain and the flood plain offers more resistance to the fluid flow than main channel offers. So the velocity is more across the main channel than that of the flood plain. Because of these variations in velocity a lateral momentum transfer takes place between the main channel and adjoining flood plains. The present research work utilises the flume facility available in the Fluid Mechanics and Hydraulic Engineering Laboratory of the Civil Engineering Department at the National Institute of Technology, Rourkela, India.

3.2 DESIGN AND CONSTRUCTION OF CHANNEL

The experimental channel was built in a masonry concrete flume of 1.67 m wide **9.67**m long.

The channel has been built with the Perspex sheet to carry out the experiments. The thicknesses of the Perspex sheets are of 6 mm to 10mm thick. The meandering channel is constructed having a bank full depth of 0.12m with a width of 0.28m. Fig. 3.1 illustrates the schematic view of the channel setup. The main channel is a sinuous channel, similar to a sine curve of one and half wave length. The total wavelength (λ) 0f 2.230 and a amplitude of1.130m for the meandering channel. Water into the channel is circulated from an underground sump to an overhead tank with the help of centrifugal pumps (15HP). Overhead tank is helpful in maintaining a constant head of water, where the excess water is allowed to flow back into the sump. Through adjustable pipes water comes into the flume from the overhead tank. The water in the overhead tank can be used to maintain a desired quantity of discharge. Straighteners are provided at the upstream section of the channel to reduce the turbulence of the incoming water and to achieve a more steady flow in the channel. The flow attains a steady and Quasi-Uniform flow.

In free surface flows water flows in the channel due to gravity. This slope is accomplished by providing a slight slope to the channel. There is a tailgate at the downstream end of the channel through which flow of water after running through the main channel is directed into a volumetric tank. The tail gate is provided to control the flow depth and maintain a uniform flow. The volumetric tank is connected to the underground sump. The actual discharge of the flow can be measured by the volumetric tank. Otherwise the water is allowed to move into the underground sump. The sump feeds the back water to overhead tank through pumping. Hence a complete recirculation of water is achieved. All the measurements are observed at the second bend apex .Observations are recoded under steady and uniform conditions.

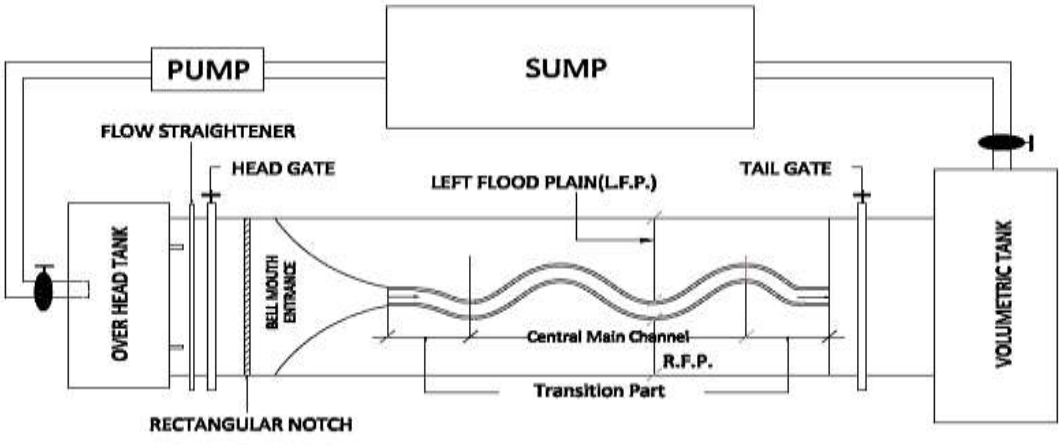


Fig.3.1: Schematic Diagram of Experimental Meandering Channels

Along the width of the channel a moving arrangement is provided. The width of the moving bridge is around 1.2m and the length is 2.2m.The measuring instruments such as point gauges and Pitot tubes are arranged on the bridge. The following photograph shows the channel details.

Fig.3.2: Photo of tail gate at downstream.

Fig.3.3: Photo of volumetric tank.

Fig 3.4: Front view of the RCC overhead tank

3.3 APPARATUS AND EQUIPMENTS USED

The moving bridge arrangement is fitted with one Pitot tube of an external diameter of 4.7mm along with a pointer gauge of least count 0.1mm. The moving bridge is set at the

the bend apex before the experiment was started. The pointer gauge is utilized to find out the water depth. The Pitot tube measure the pressure difference at every predefined location of the bend apex. Velocity at those points is calculated from the pressure difference. The following photograph shows equipments used during the experimentation.

Fig.3.5 Photo of the inclined manometer used

Fig.3.6 photo of the point gauge, pitot tube

3.4 EXPERIMENTAL PROCEDURE

3.4.1 EXPERIMENTAL CHANNEL

The meandering main channel with a sinuosity of 2.04 is constructed with a wavelength of 2.230.The main channel is a rectangular section having a width of 0 .28m and 0.12m as the bank full depth.

Fig.3.7: Meandering channel

The detailed geometric parameters of the meandering channel are illustrated in the following tabulation. In the following table the detailed geometric parameters of the meandering channel are described.

Table 3.1: Details of Geometrical parameters of the Channel

Sl NO	Parameter	Descriptions
1	Types of channel	Simple meandering
2	Flume Dimensions	9.67*1.67*0.25(m^3)
3	Meander Channel Geometry	Rectangular
4	Type of Bed surface	Rigid and Smooth Bed
5	Width of the channel	0.28m
6	Bank Full Depth	0.12m
7	Bed Slope of the Channel	0.0006
8	Sinuosity of the Channel	2.04
9	Amplitude of the Meandering Channel	1.130m
10	Wavelength of the meandering channel	2.230m

Fig.3.8: Moving Bridge Arrangement at the Bend Apex

3.4.2 POSITION OF THE MEASUREMENT

All the obsevations are recorded at third bend apex of the meandering channel and at the crossover.Point velocities were measured along verticals spread across the main channel as well as flood plain so as to cover the width of entire section of the 60^0meandering curve. Experimental measurements are taken at different points of the bend apex and cross over of a compound meandering channel to calculate the velocity distribution and bed shear disstribution.The grid points where measurements are taken are show in Fig:3.7. Also at a number of horizontal layers in each vertical for both main channel as well as flood plain, point velocities were measured. Measurements were thus taken from left edge point to the right edge of the main channel as well as for the flood plain bed and side vertical walls. The lateral spacing of grid points over which measurements were taken was kept 5cm inside the main channel and also Pitot tube is moved from the bottom of the channel to upwards by 0.2H, 0.4H, 0.6H, 0.8H (H=total depth of flow of water)(Fig.3.7shows the grid diagram used for experiments). Velocity measurements are taken by pitot static tube (outside diameter

4.77mm) and two piezometers fitted inside a transparent fibre block fixed to a wooden board by making an angle of 33^0 with the vertical. The ends of which were open to atmosphere at one end and the other end connected to total pressure hole and static hole of Pitot tube by long transparent PVC tubes. Velocity measurements are taken by pitot static tube (outside diameter 4.77mm) and two piezometers fitted inside a transparent fibre block fixed to a wooden board by making an angle of 330 with the vertical. The ends of which were open to atmosphere at one end and the other end connected to total pressure hole and static hole of Pitot tube by long transparent PVC tubes. Before taking the readings the Pitot tube along with the long tubes measuring about 5m were to be properly immersed in water and caution was exercised for complete expulsion of any air bubble present inside the Pitot tube or the PVC tube. Even the presence of a small air bubble inside the static limb or total pressure limb could give erroneous readings in piezometers used for recording the pressure. steady uniform discharge was maintained in each run of the experiment and the differences in pressure were measured at each allocated points.

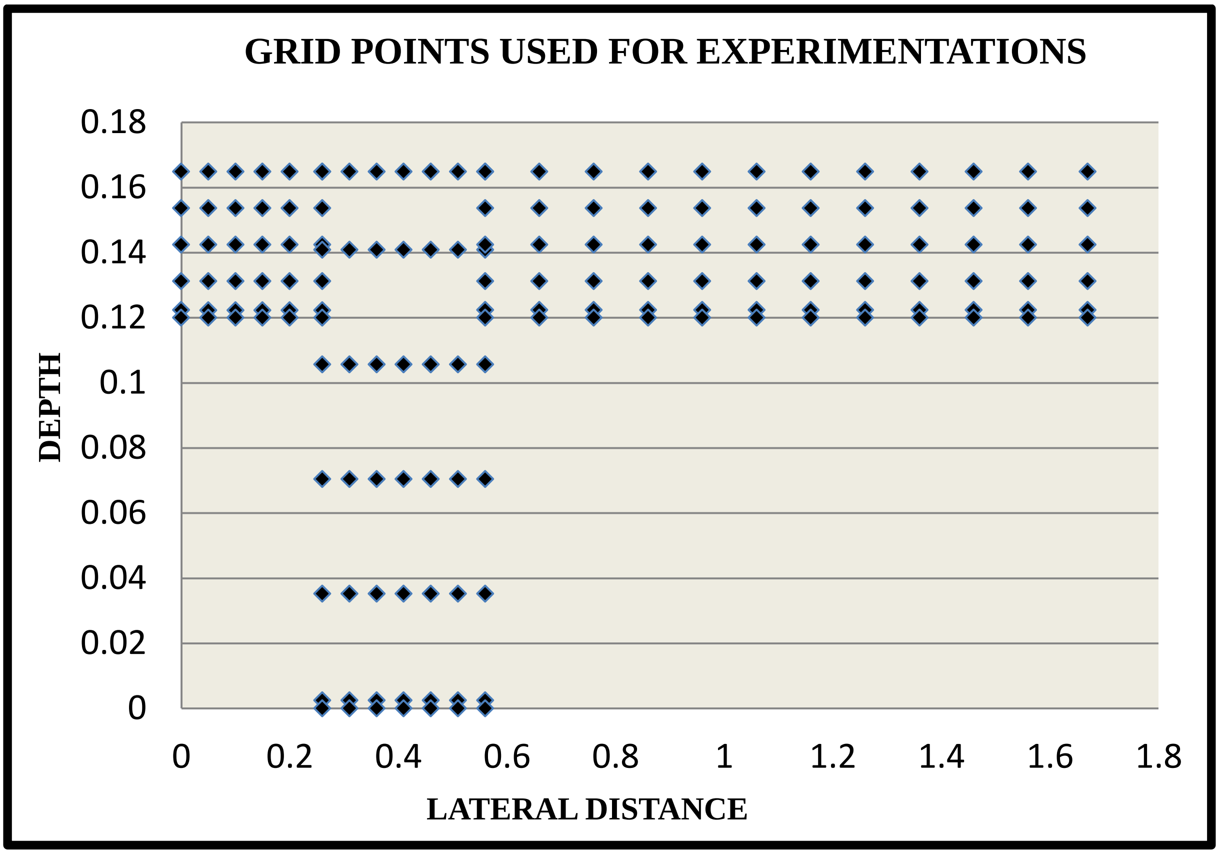


Fig.3.9: Typical grid showing the arrangement of velocity measurement points along horizontal and in vertical direction at the test section for the rectangular compound channel.

3.5 MEASUREMENT OF BED SLOPE

For measurement of bed slope of the channel point gauge is used. The distance of water level from the bed of the channel at the upstream and at the downstream of the flume is 2.250m. The water level is taken from the bed of the channel without considering the thickness of the Perspex sheet. Difference in the two corresponding point is measured. Slope is measured by dividing this vertical difference with the horizontal distance between the two observed points. Five such readings are taken and averaged for accuracy. The slope calculated is 0.0006.

3.6 MEASUREMENT OF LONGITUDINAL VELOCITY

Pitot tubes are utilized for the measurement of velocity at each point of the bend apex for ovebank flow conditions. Pitot tube and point gauge arrangements are used for measurement of the pressure difference at every predefined point on the channel bend apex. The pitot tubes are attached to manometers placed on a inclined wooden board. The angle between the manometer and the vertical axis is 33^o.The connections between the Pitot tubes and the manometer are made by long transparent PVC tubes of small diameters. Extra care is taken to drive out any air bubbles inside the tubes. Pitot tubes are placed against the direction of flow perpendicular to it. The pressure difference at every pre-defined grid of the channel bend apex is achieved. The velocity is measured by $v=\sqrt{(2gh \sin\theta)}$, where g is the acceleration due to gravity and h is the difference in pressure head and here the tube coefficient is taken as unit. First the velocity readings are taken at the bed (0.2385cm from bed) and then moved up by0.2H, 0.4H, 0.6and 0.8H from the bed for main channel and 0.2(H-h),0.4(H-h),0.6(H-h),0.8(H-h) for flood plain depending upon the depth of flow in the compound channel. The the velocity value at the bed of the channel is assumed to be zero considering the no slip condition. Experiments are carried out by considering the flow as steady and uniform.

3.7 MEASUREMENT OF BOUNDARY SHEAR STRESS

Many river related problems such as bed load transport, momentum transfer, channel migration; etc can be examined by measuring the shear stress in open channel flow. The shear force at the bed helps in finding out bed load transfer where as channel migration can be identified by shear force at the wall. The stress developed between two layers of water at flowing condition is called shear stress. The stress that is developed between the water flowing in the channel and its bed as well as wall of the channel is called Boundary shear stress. It is generally denoted by the symbol τ. The boundaries of the channel offer resistance to the fluid flow, due to this resistive force boundary shear develops along the channel. A reduction in velocity occurs due to bed shear stress. So boundary shear is a parameter which is required to find out. There are several formulae which are used to evaluate wall and bed shear.

3.8 NUMERICAL MODELLING

3.8.1 TURBULENCE MODELLING

GI Taylor and von Karman, 1937 stated “Turbulence is an irregular motion which in general makes its appearance in fluids, gaseous or liquid, when they flow past solid surfaces. They also stated turbulence also occurs when neighbouring streams of the same fluid flow past or over one another.

3.8.3 Common *Turbulence Models*

(1) Zero equation models

(2)1 equation models

(3)Two equation models

(4) Seven equation models

Zero equation models

Mixing length model comes under zero equation model.

Two equation models

The turbulent models comes under this category are:

- k-ϵ models
- RNG (Renormalization Group)k-ϵ models
- Realizable k-ϵ model
- k-ω models
- Algebraic stress models

Seven equation models

Reynolds stress model included in this type model.

3.8.7 CREATION OF GEOMETRY

The first step in CFD analysis is creation of computational geometry of the fluid flow region. For creation of geometry we adopted consistent frame of reference for coordinate axis. In the present study z axis represents the stream wise fluid flow direction. X axis represents the width of channel bed and Y axis represents the vertical component or depth of water.

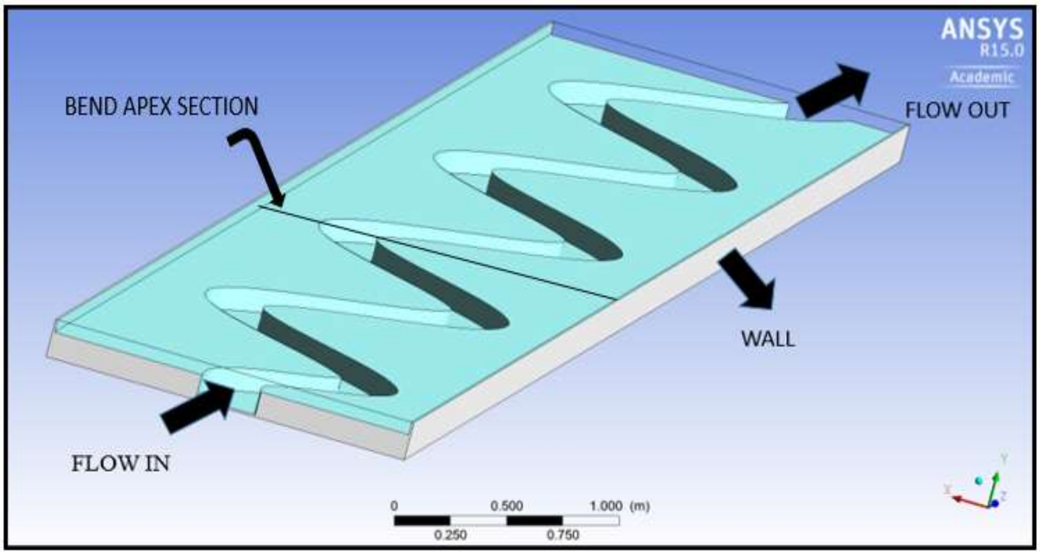


Figure3.11: Geometry details of the compound meandering channel.

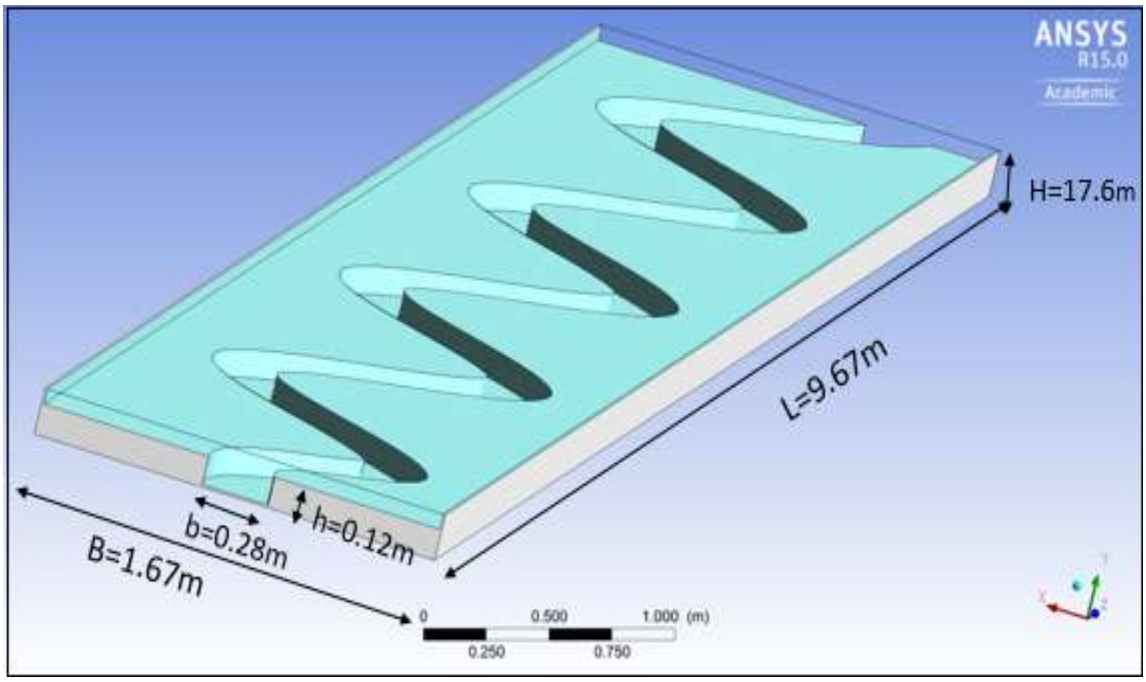


Figure3.12: Dimension details of the compound meandering channel.

As can be seen from the figure 3.12, the main channel geometries were 0.12 m height, 0.28 m width and 9.67m length. In the compound meandering channel, the width of the compound channel was 1.67m and flood plain height was 0.02m for one depth and 0.056 for another depth. During the model construction, an additional consideration is to identify any entity of the geometry which need to be identified for future reference as to identify a particular domain for conduct some analysis and for applying boundary condition upon a particular domain. Figure 3.13 shows the geometrical entities used in a compound meandering channel. For identifying the domain five geometries are created

(1)Inlet

(2) Outlet

(3) Free surface symmetry

(4) Channel Bottom

(5) Side Wall

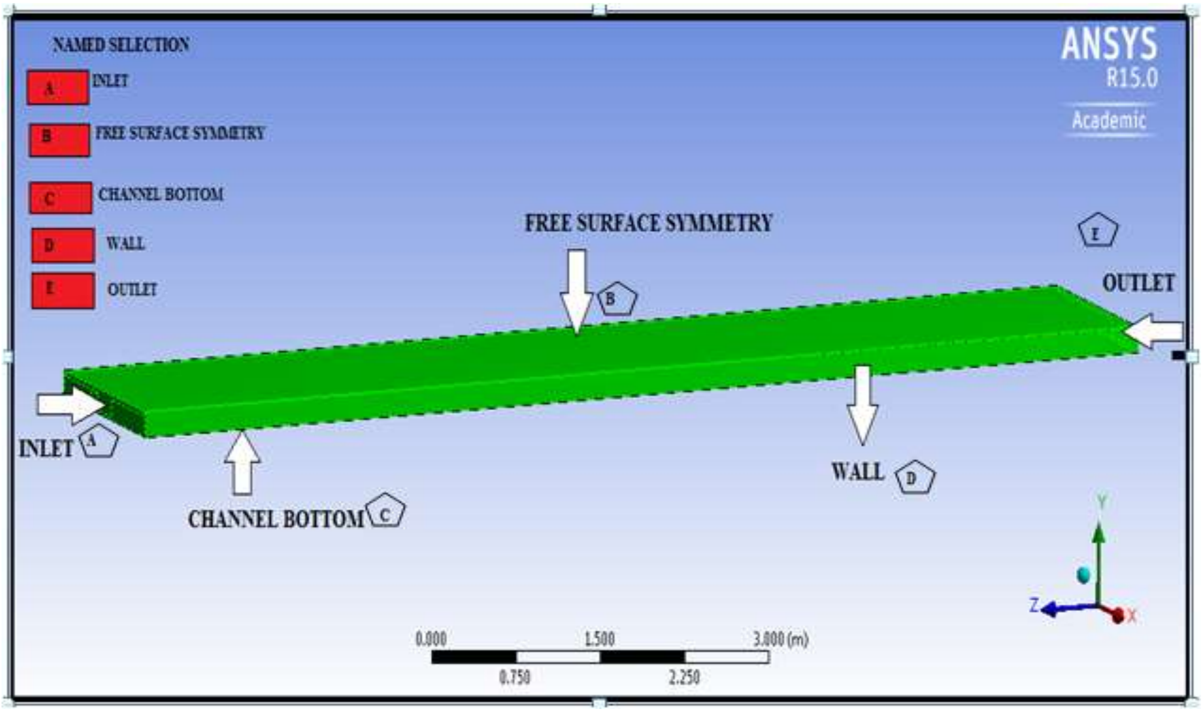


Fig.3.13: Different geometrical entities used in a compound meandering channel

3.8.8 MESH GENERATION

The detailed meshing of the flow domain with two views is shown in Figure 3.14.

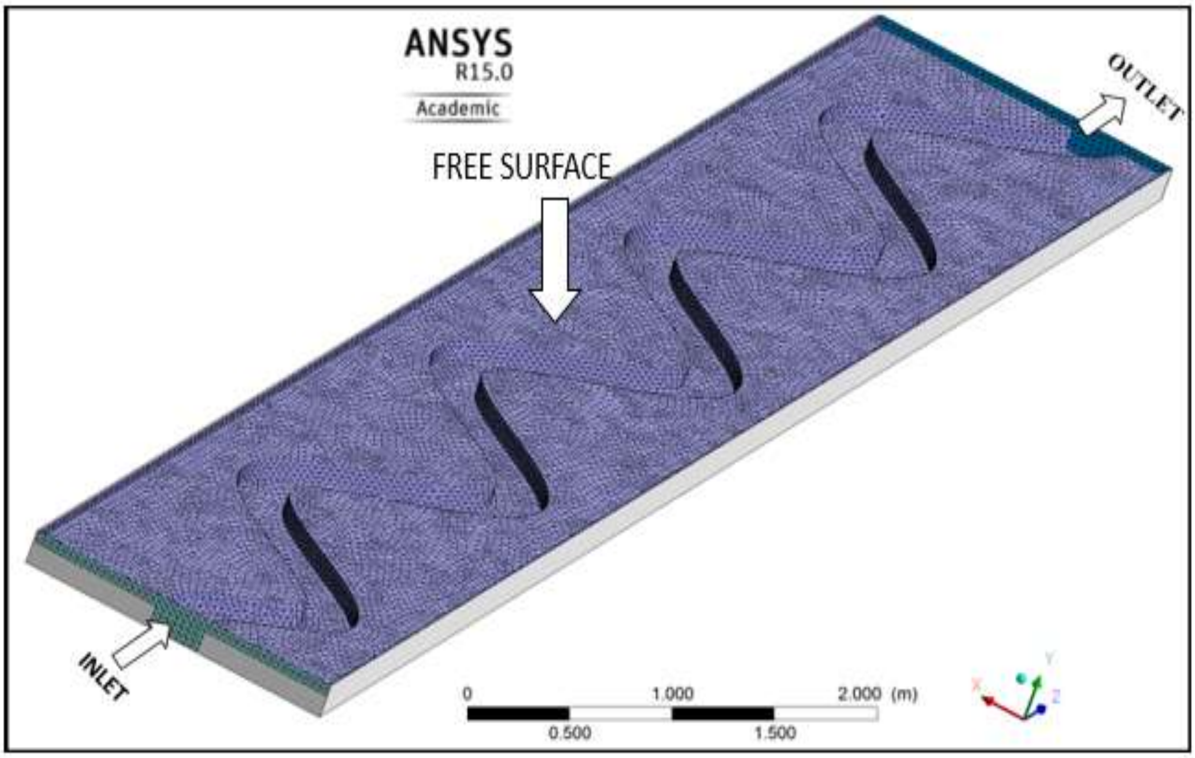


Figure3.14: Schematic view of the mesh grid used in the numerical model.

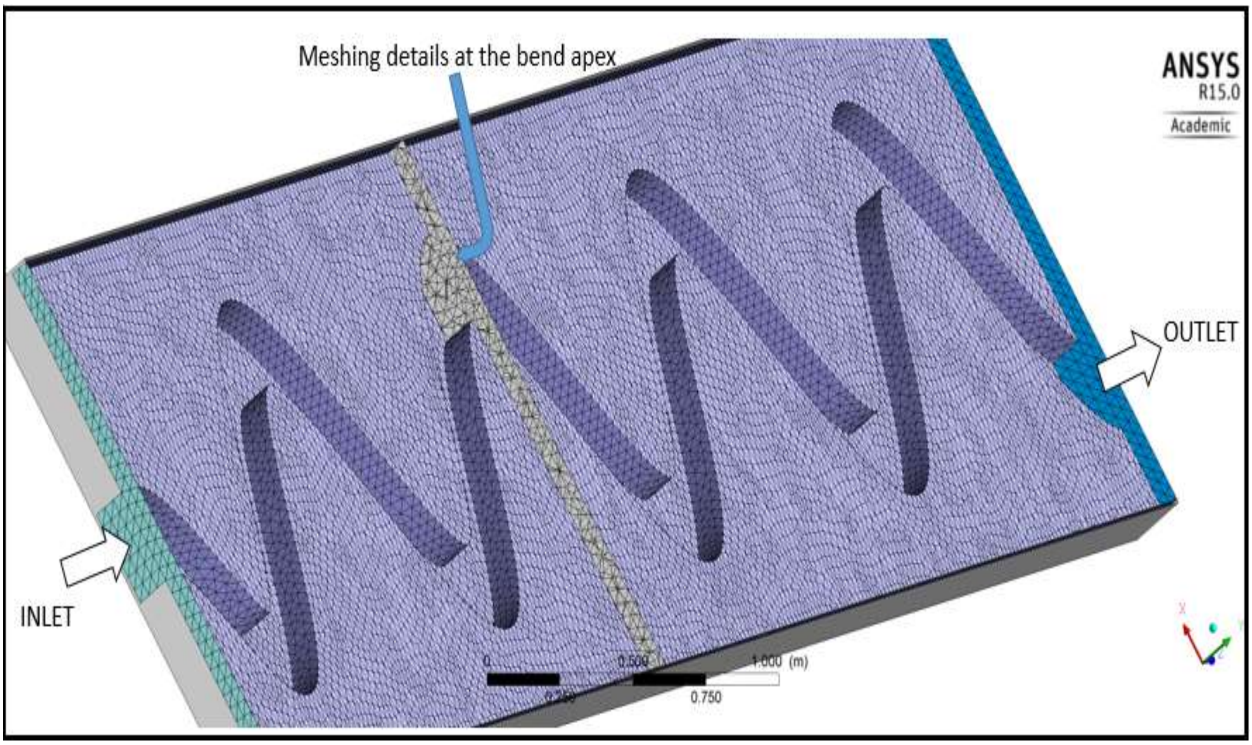


Figure3.15: Meshing of the cross section at bend apex.

3.12 SOLVING FOR TURBULENCE

3.12.1 USED LARGE EDDY SIMULATION TURBULENCE MODEL

Large eddy simulation model is an intermediate approach to DNS and RANS turbulence model. Turbulent flows have generally wide range of length and time scales. To distinguish eddies that are going to be calculated from those that are going to be modelled, a filtering function (eg. Gaussian, Box cutoff, Fourier) is used.

Here the velocity component is split into a resolved component $\overline{U}$ and an unresolved component u′. The governing equations employed for LES are obtained by filtering the time-dependent Navier-Stokes equations in either Fourier (wave-number) space or configuration (physical) space. The instantaneous velocity variable u can be written as:

$$u = \overline{U} + u' \qquad \text{Eq.3.19}$$

Where u' is the unresolved part and $\overline{U}$ is the large scale part defined through volume averaging as:

$$\overline{U}\left(x_j, t\right) = \int_{vol} G(x_i - x_i')u\left(x_j', t\right)dx_i' \qquad \text{Eq.3.20}$$

Where $G(x_i - x_i')$ is the Gaussian filter.

The non-filtered Navier-Stokes equation is:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \mu\frac{\partial^2 u_i}{\partial x_i x_j} \qquad \text{Eq.3.21}$$

After performing the volume averaging and neglecting density functions, the filtered Navier-Stokes Equations become

$$\frac{\partial(\rho\overline{U_i})}{\partial t} + \frac{\partial\left(\rho\overline{u_i u_j}\right)}{\partial x_j} = -\frac{\partial\bar{p}}{\partial x_j} + \mu\frac{\partial^2\overline{u_i}}{\partial x_i x_j} \qquad \text{Eq.3.22}$$

The Non-linear transport term in equation (15) can be explained as:

$$\overline{U_i U_j} = \overline{(\overline{U}_i + u_i')\left(\overline{U}_j + u_j'\right)}$$

$$= \overline{\overline{U}_i\overline{U}_j} + \overline{\overline{U}_i u_j'} + \overline{\overline{U}_j u_i'} + \overline{u_i' u_j'} \qquad \text{Eq.3.23}$$

(i) (ii) (iii) (iv)

In time averaging the term II &III vanish but not in volume averaging.

Introducing the residual stress or subgrid scale (SGS) stresses defined as τ_{ij} and expressed as

$$\tau_{ij} = \overline{u_i u_j} - \overline{U_i U_j}$$

Now equation (3.22) can be written as:

$$\frac{\partial(\rho\overline{U_i})}{\partial t} + \frac{\partial\left(\rho\overline{U_i U_j}\right)}{\partial x_j} = -\frac{\partial\bar{p}}{\partial x_j} + \mu\frac{\partial^2\overline{U_i}}{\partial x_i x_j} - \frac{\partial(\rho\tau_{ij})}{\partial x_j} \qquad \text{Eq.3.24}$$

Equation (3.24) is the basis of the LES turbulence model.

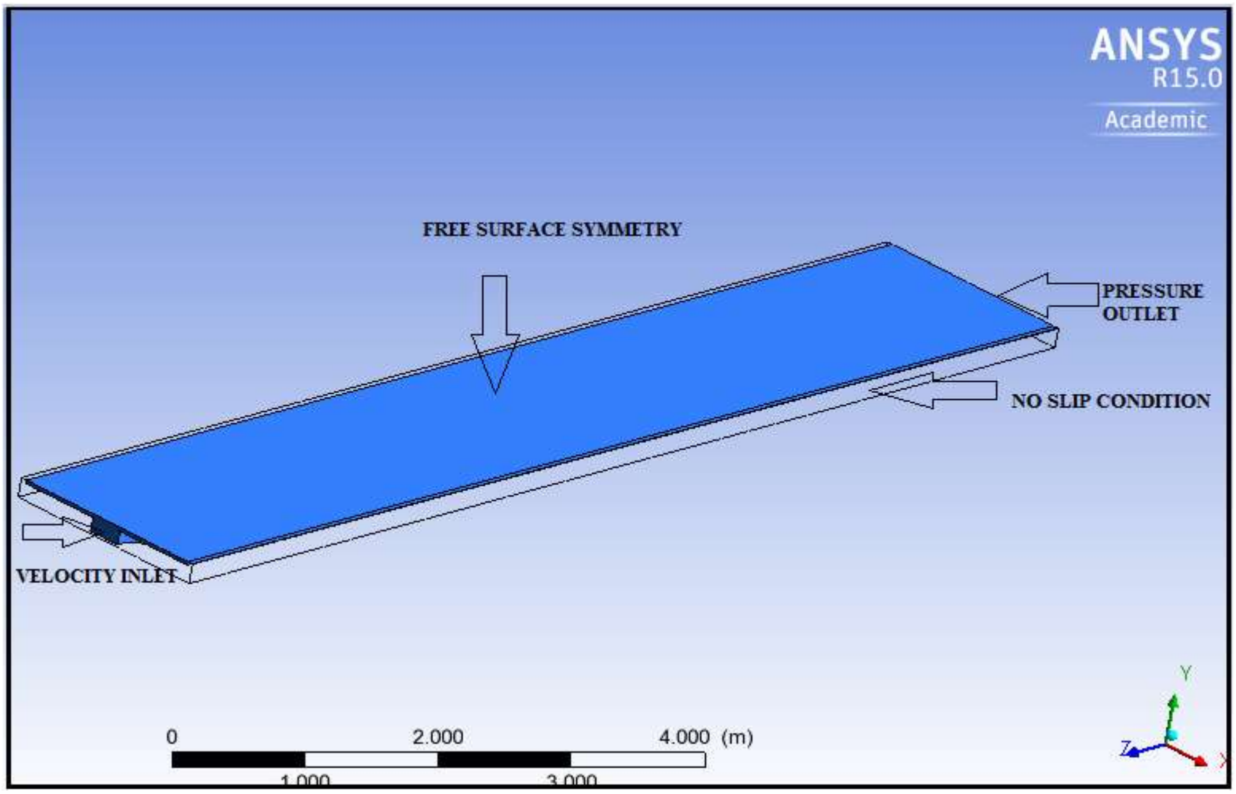


Figure3.16: Schematic diagram of the compound meandering channel with boundary conditions.

The boundary conditions implemented for this study are shown in Fig3.17. Subsequently these conditions are discussed in the follows.

3.13.1 Inlet and Outlet Boundary Conditions

The gravity vector is resolved in x, y and z directions and the component of the gravity in x,y, and z directions can be summarised as:

$$(0, -\rho g \cos\theta, \rho g \sin\theta) \qquad \text{Eq.3.28}$$

Where θ = angle between bed surface to horizontal axis and tan θ=slope of the channel. Here, in the z directions the fluid is flowing. The y component is responsible for creating the hydrostatic pressure upon the channel bed. The component of the gravity vector in the “z” directions $\rho g \sin\theta$ is found to be responsible for the convergence problem of the solver. Here the experimental bulk velocity of the flow is initially approximated as: U = 0, V = 0, W=

0.338.

3.13.2 Wall

The channel walls i.e. side walls and bottom are represented as non-slip walls. A no-slip boundary condition is the most common boundary condition implemented at the wall and prescribes that the fluid next to the wall assumes the velocity at the wall, which is zero i.e. U=V=W=0 Eq.3.29

3.13.3 Free Surface symmetry

For top free surface generally symmetry boundary condition is used.This condition follows that, no flow of scalar flux occurs across the boundary. Thus, there is neither convective flux nor diffusive flux across the top surface. In implementing this condition normal velocities are set to zero and values of all other properties outside the domain are equated to their values at the nearest node just inside the domain.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 OVERVIEW

The results of experiments concerning the distribution of velocity, flow in the meandering channels are presented in this chapter. Analysis is also done for depth averaged velocity in the meandering channel. The overall summary of experimental runs for the meandering channel is given in Table-2.

4.2 STAGE-DISCHARGE RELATIONSHIP IN MEANDERING CHANNELS

In the present work it was not easy to achieve steady and uniform flow condition in meandering channels due to the effect of curvature and the influence of a number of geometrical and hydraulic parameters. However, it is tried to achieve the water surface slope parallel to the valley slope so as to get an overall steady and uniform flow in the experimental channels. In all the experimental runs this simplified approach has been tried to achieve which is also in line with the experimental work of Shino, Al-Romaih and Knight (1999). This stage of flow is considered as normal depth, which can carry a particular flow only steady and uniform condition. The stage discharge curves plotted for meandering channel of sinuosity 2.04 is shown in Fig. 4.1. From the figure it is seen that the discharge increases with an increase in stage in the channel.

Table 2. Hydraulic parameters for the experimental runs

Runs	Discharge Q (in lit/s)	Flow depth H (in cm)	Relative depth β	Froude No. (F_r)	Reynolds No. (R)
INBANK FLOW			(H/h)		
1	3	1.7	0.1416	0.208	9554.140
2	4.81088	2	0.166	0.330	15034
3	5.432	2.86	0.238	0.363	16109.134
4	6.732	3	0.25	0.449	19800
5	7.32	3.8	0.3166	0.477	20561.797
6	9.389	4.86	0.405	0.594	24891.3043
7	11.298	7.8	0.65	0.665	25912.8440
8	13.042	8.6	0.7166	0.754	28853.9823
9	19.8965	9.86	0.82166	0.76	41694.2581
OVERBANK FLOW			(H'-h /H')		
1	26.751	12.5	0.04	0.197	15923.214
2	34.77	13.5	0.111	0.254	20452.941
3	40	14.5	0.1724	0.291	23255.813
4	46.5	16	0.25	0.335	26571.428
5	52.165	16.5	0.2727	0.375	29639.2045
6	60.68	17.6	0.318	0.434	34051.6273

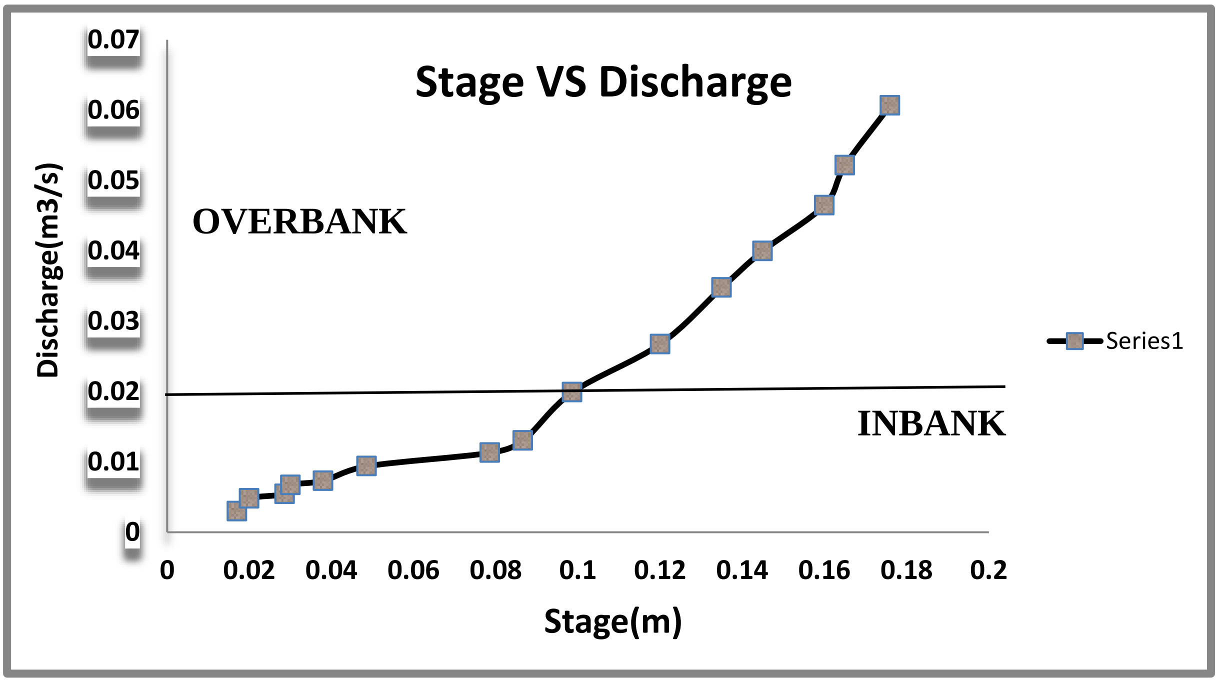
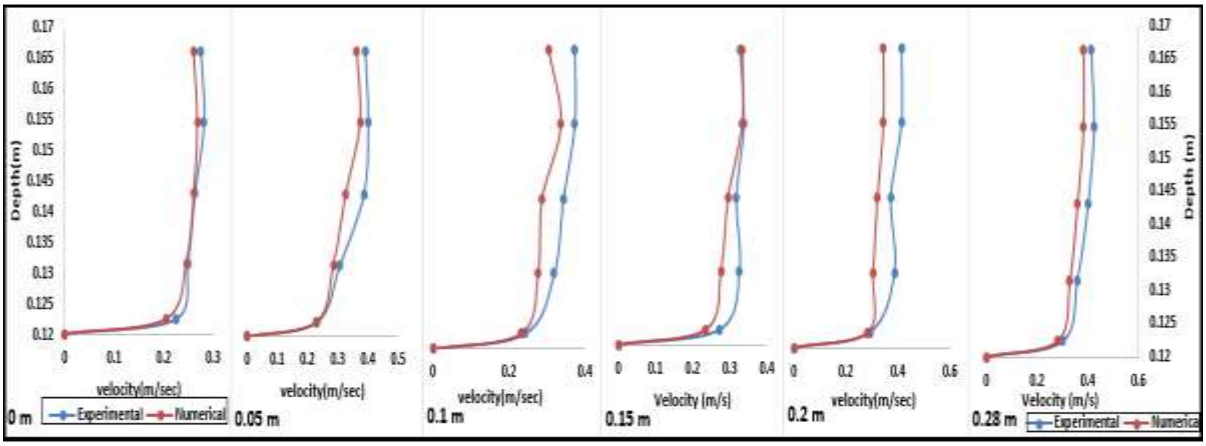


Figure 4.1: Stage VS Discharge graph

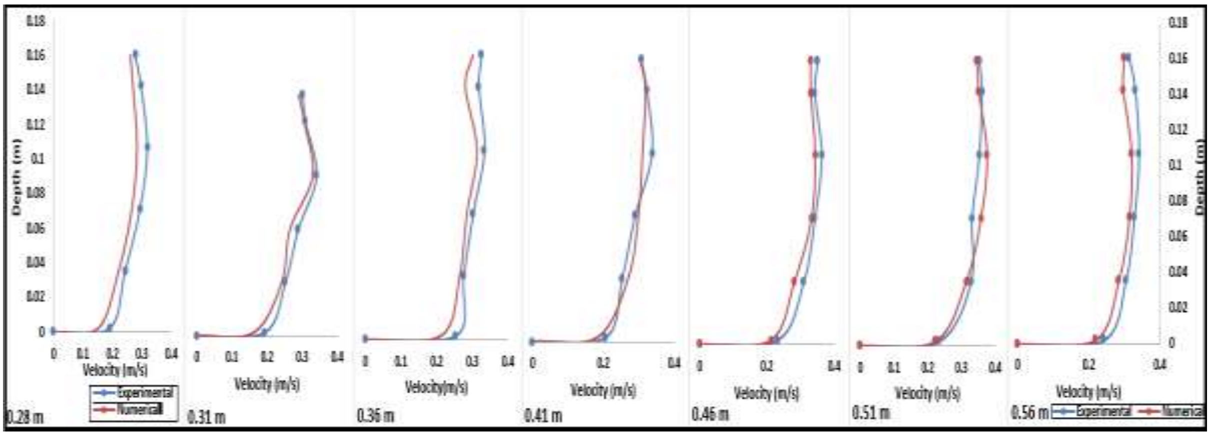
4.3DISTRIBUTION OF LONGITUDINAL VELOCITY

Longitudinal velocity is recorded by pitot-tube in the experimental meandering channels. In these channels, observations are recorded at the bend apex with a direction normal to flow direction. The longitudinal velocity distribution at bend apex for Dr 0.33 is shown below.

LEFT FLOOD PLAIN



MAIN CHANNEL



RIGHT FLOODPLAIN

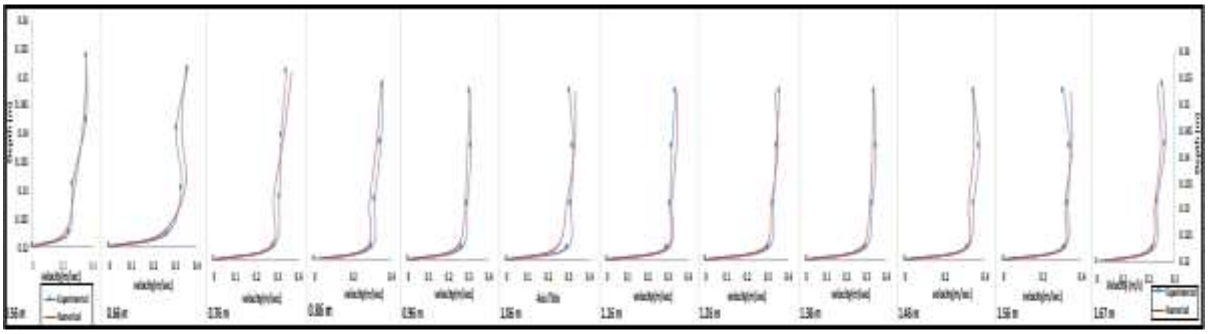
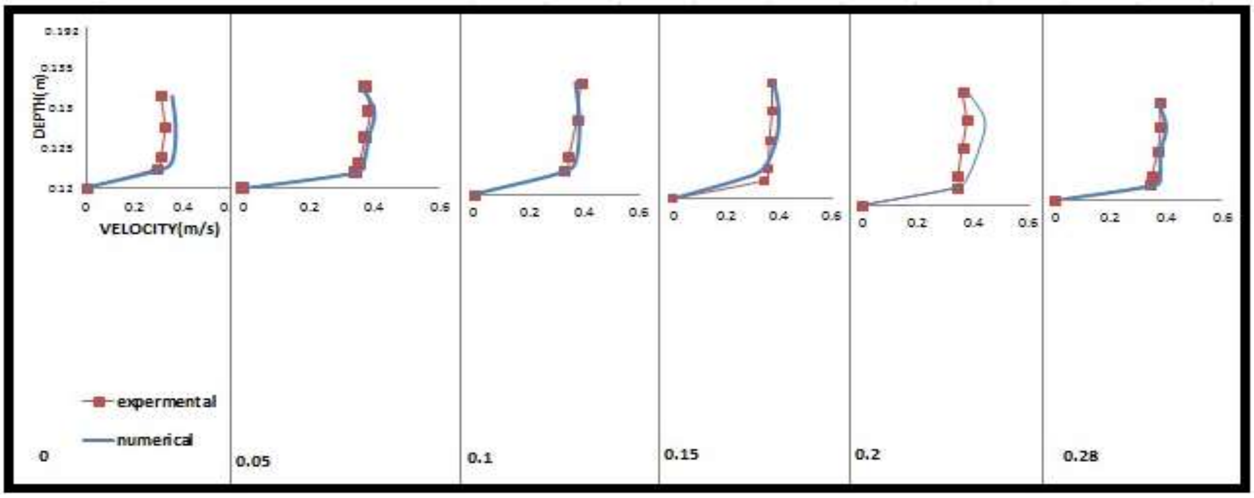


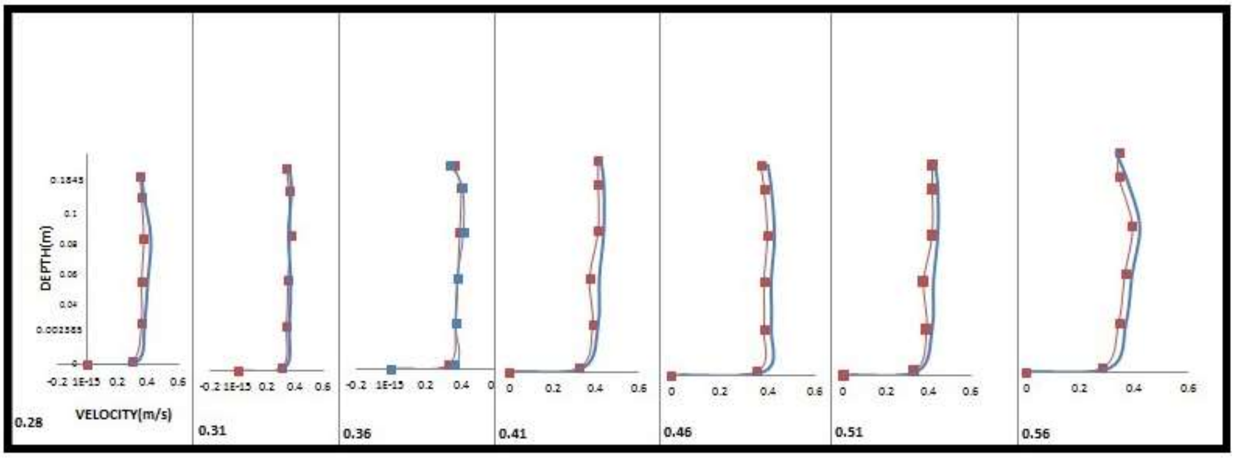
Figure 4.2 Longitudinal velocity distribution for Dr 0.33.

The longitudinal velocity distribution at bend apex for Dr 0.40 is shown below.

LEFT FLOOD PLAIN



MAIN CHANNEL



RIGHT FLOOD PLAIN

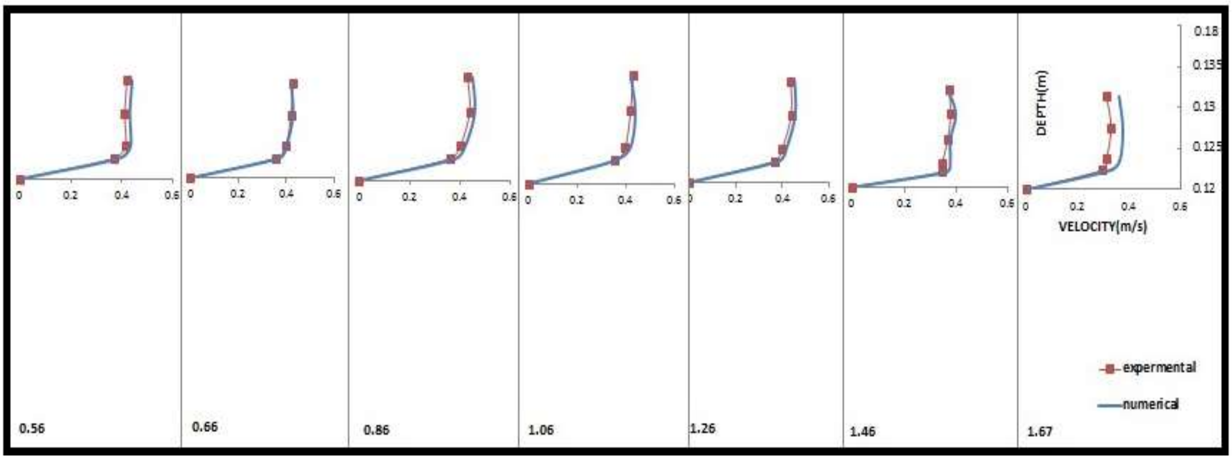


Figure 4.3 Longitudinal velocity distribution for Dr 40.

4.4 LONGITUDINAL VELOCITY CONTOUR

In this present research work velocity contours were determined for two relative depths, also the experimental results were validated with the numerical ones. The experimental results are obtained by using Surfer11 software. The Numerical Results are obtained from 3Dsimulation software ANSYS-FLUENT.

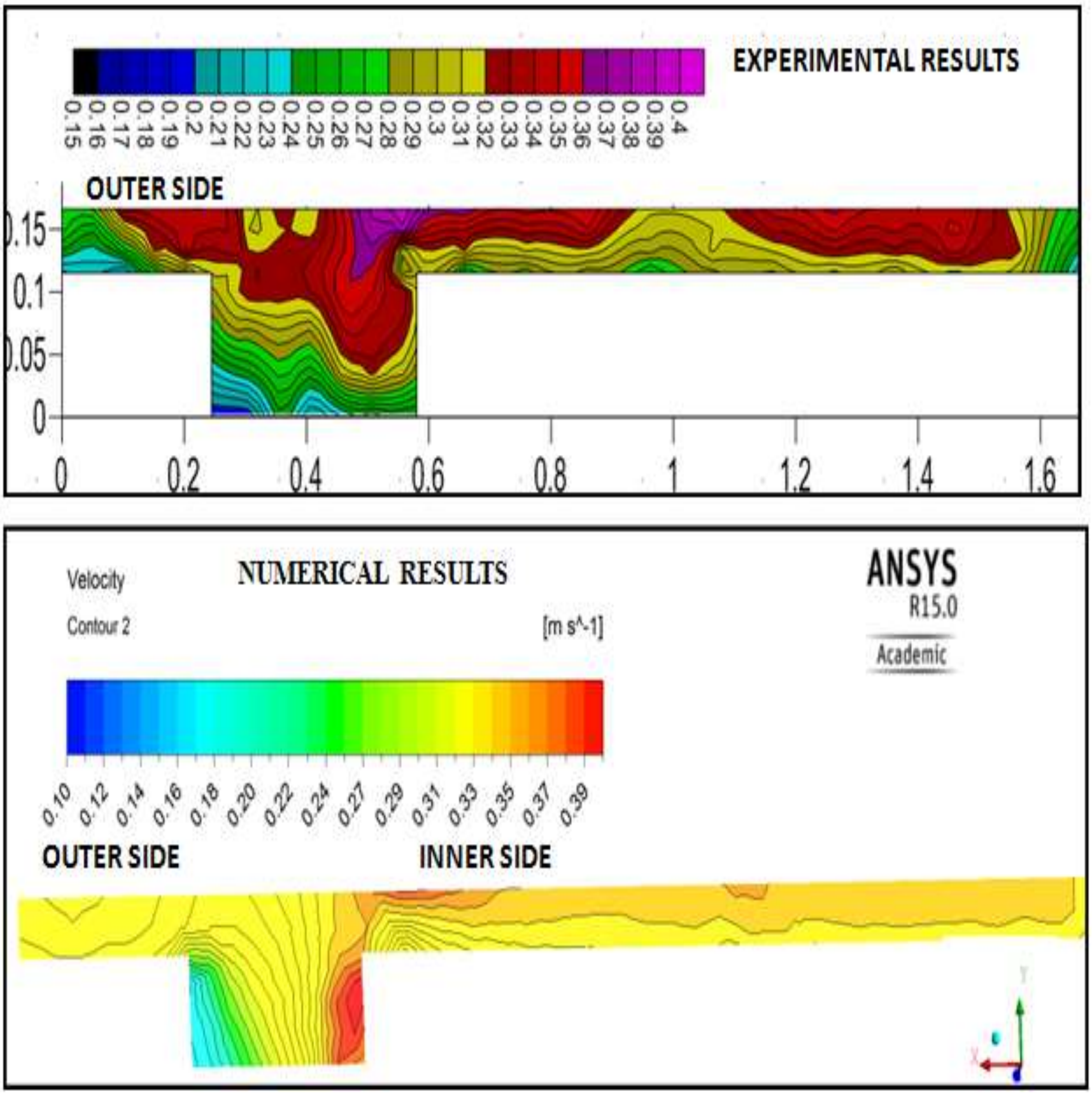


Figure 4.4 Validation of Velocity Contour for Dr 0.33.

Velocity Contours for relative depth (0.4) obtained from both numerical and experimental analysis is shown below.

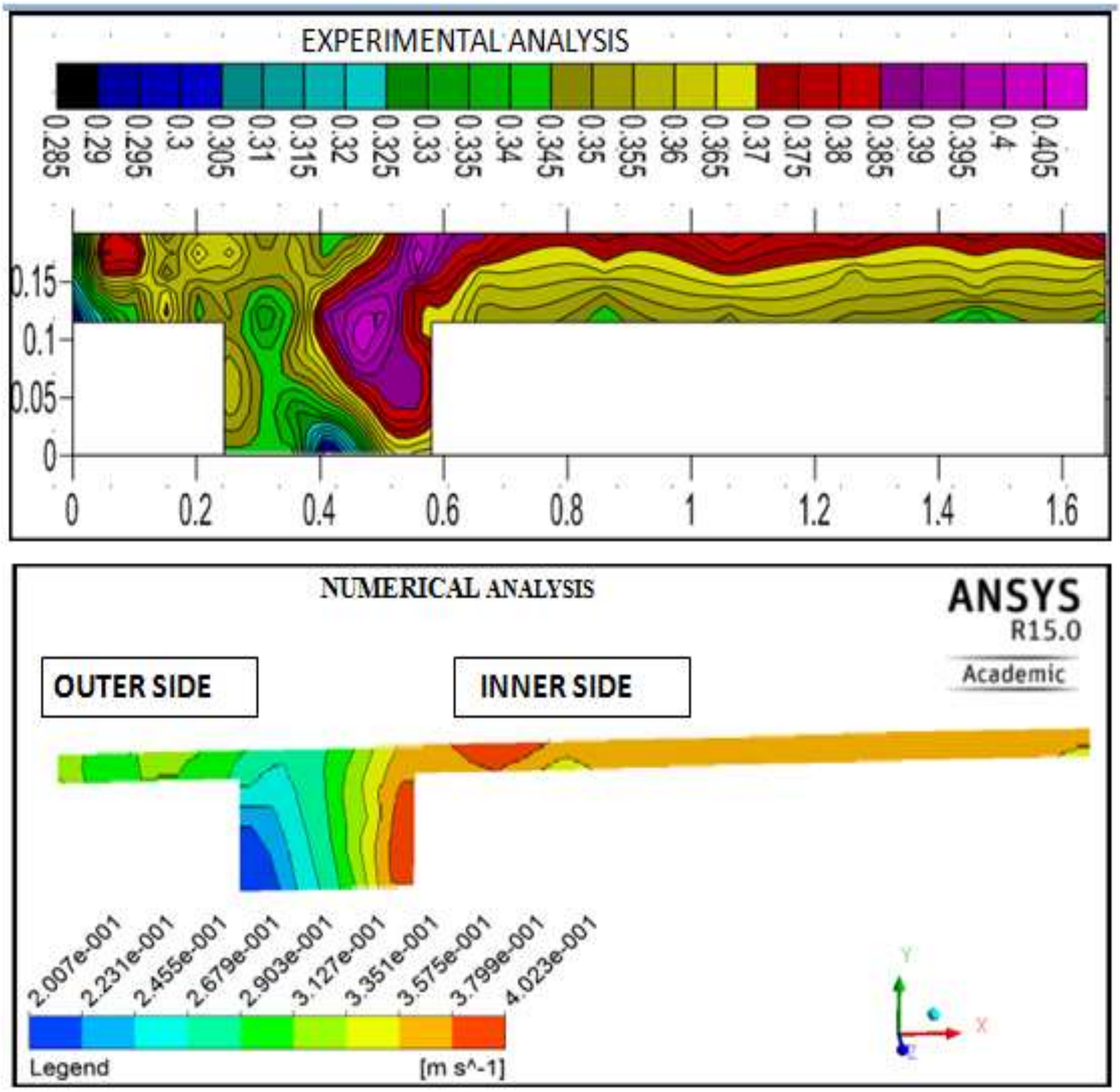


Figure 4.5 Validation of Velocity Contour for Dr 0.33

From the isovels of longitudinal velocity (Fig.4.2) to (Fig. 4.5) for the meander channel-floodplain geometry, the following features are noted. The lowest velocity contour lines are found to occur at outer main channel bottom corner and its concentration increases with the increase in flow depth over the floodplain. The maximum value of stream wise velocity lies near the free surface and towards the inner floodplain. The mean velocity exists mostly in the right flood plain region. The occurrence of higher velocity values are more in inner flood plain region than that of outer flood plain region.

4.3 DEPTH AVERAGED VELOCITY OBTAINED FROM THE RESEARCH WORK

OVERVIEW

Once normal depth conditions were established for a given discharge, point velocity measurements were made across one section of the channel at z = 0.4h from the bed. At each lateral position, a number of readings were taken at constant intervals and then averaged to reduce error.

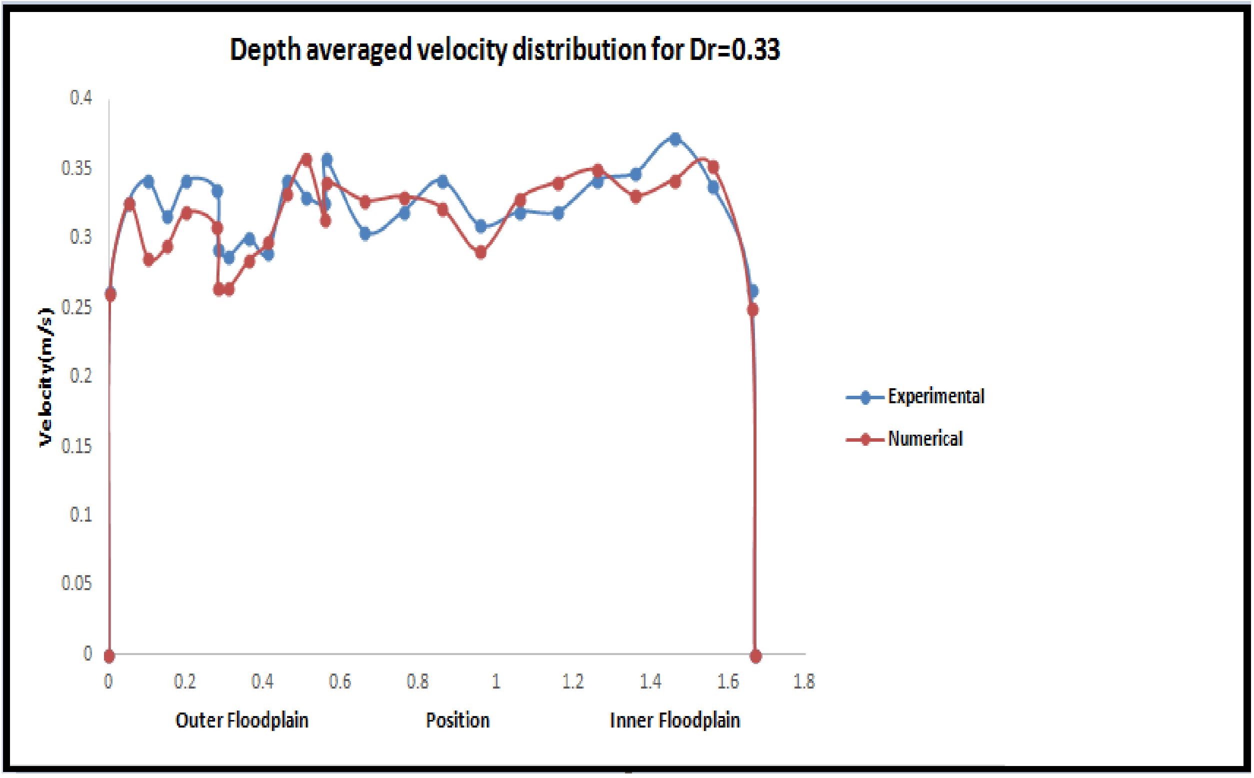


Figure 4.6: Depth averaged velocity distribution for Dr=0.33

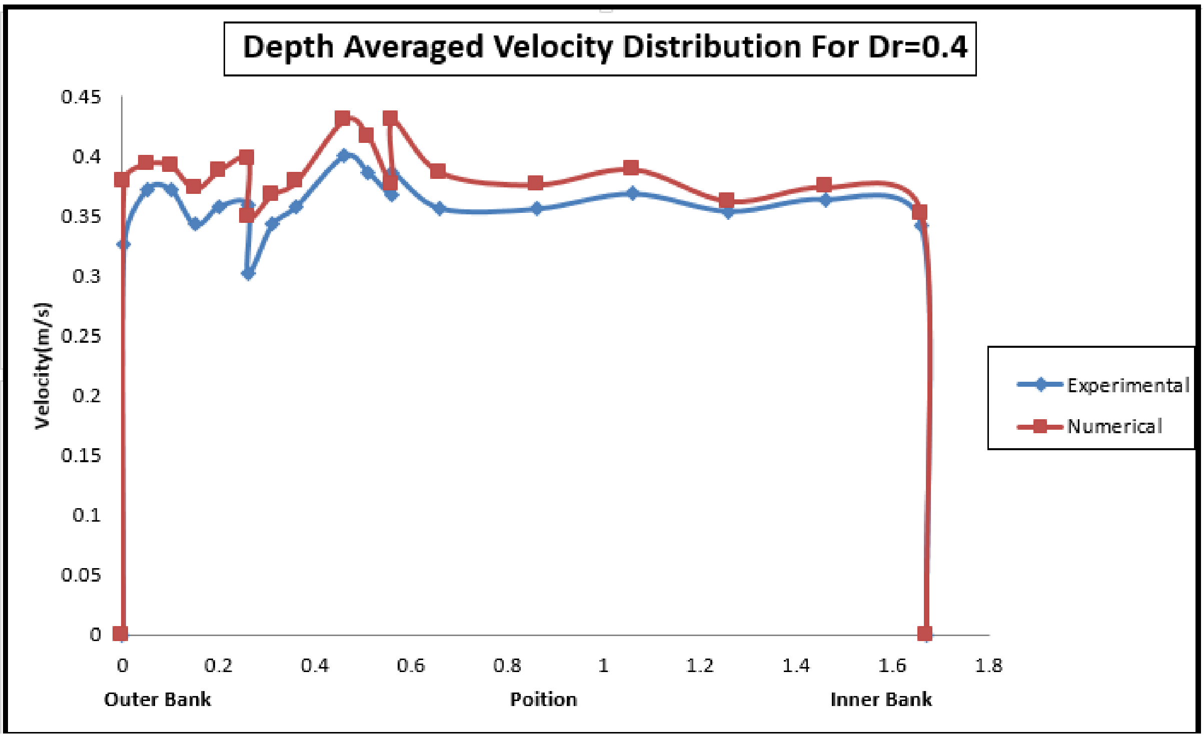


Figure 4.7: Depth averaged velocity distribution for Dr=0.4

The variation of depth averaged velocity along the width of the channel bed at floodplain depths are observed at 0.4 times the depth of flow and is validated with ANSYS data points, is shown in Figs.4.7.Series1 shows the experimental depth average values while Series 2 shows the yielded values of depth average velocity by a 3D modelling software ANSYS.

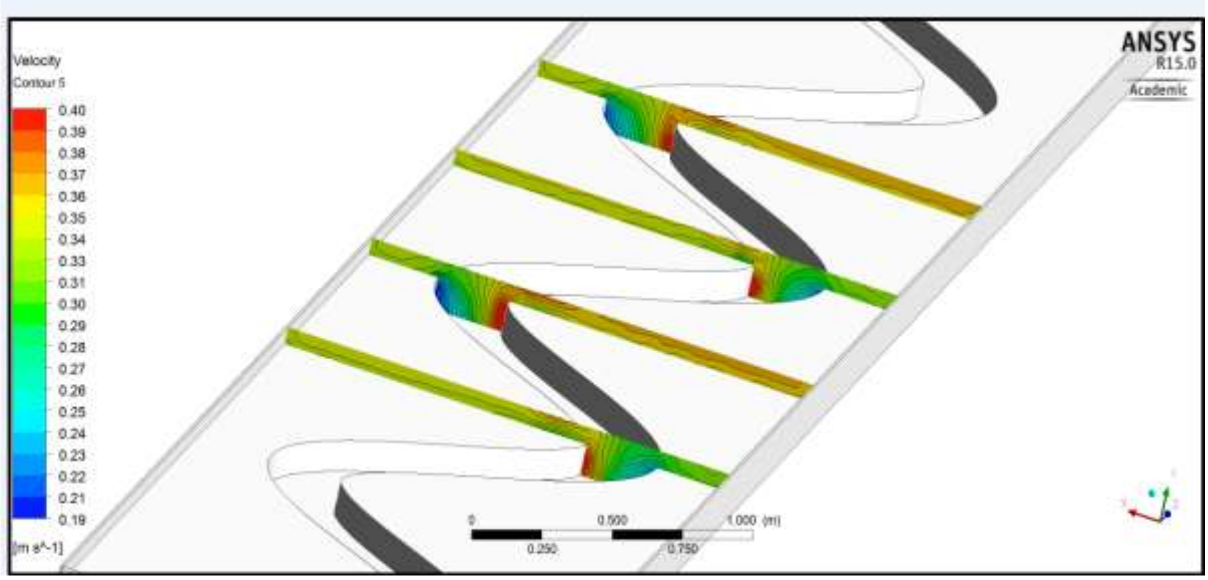


Figure 4.8: Various cross sections at bend apex points

4.4 BOUNDARY SHEAR STRESS DISTRIBUTION

OVERVIEW

Water during its motion is resisted by various forces acting on it from the bed of the channel and walls. Understanding this variation in resisting forces is of primary importance in shear studies. Due to force of gravity water is impelled downstream. The resistive force is balanced by the driving component of the flowing fluid. If the flow is uniform, velocity does not change downstream and one may conclude from Newton's first law of motion that the driving and resisting forces must be in balance.

The relevant forces are,

Driving force (W_s) = downstream component of the weight of water

$$W_s = W\,Sin\theta = \rho gAL\,Sin\theta \qquad \text{Eq.4.1}$$

Resisting force (F_0) =boundary shear stress *perimeter of the channel bed

$$F_0 = \tau_0 PL \qquad \text{Eq.4.2}$$

Now $W_s = F_0$, $\rho gAL\,Sin\theta = \tau_0 PL$ Eq.4.3

$$\tau_0 = \rho g(A/P)\,Sin\theta \qquad \text{Eq.4.4}$$

Where, (A/P) =Hydraulic Radius (R_h) in metre

Sinθ=slope

Substituting (A/P) as R_h and $Sin\theta$ as slope(s)

in equation 4.4 we get,

$$\tau_0 = \rho g\,R_hS = \gamma R_hS \qquad \text{Eq.4.5}$$

τ_0 is referred as overall mean boundary shear stress or 'depth-slope product' because hydraulic radius normally is approximated by the mean depth (h) of the channel. Equation (4.5) denotes the variation of shear stress within the section. This equation is strictly valid only for uniform flow.

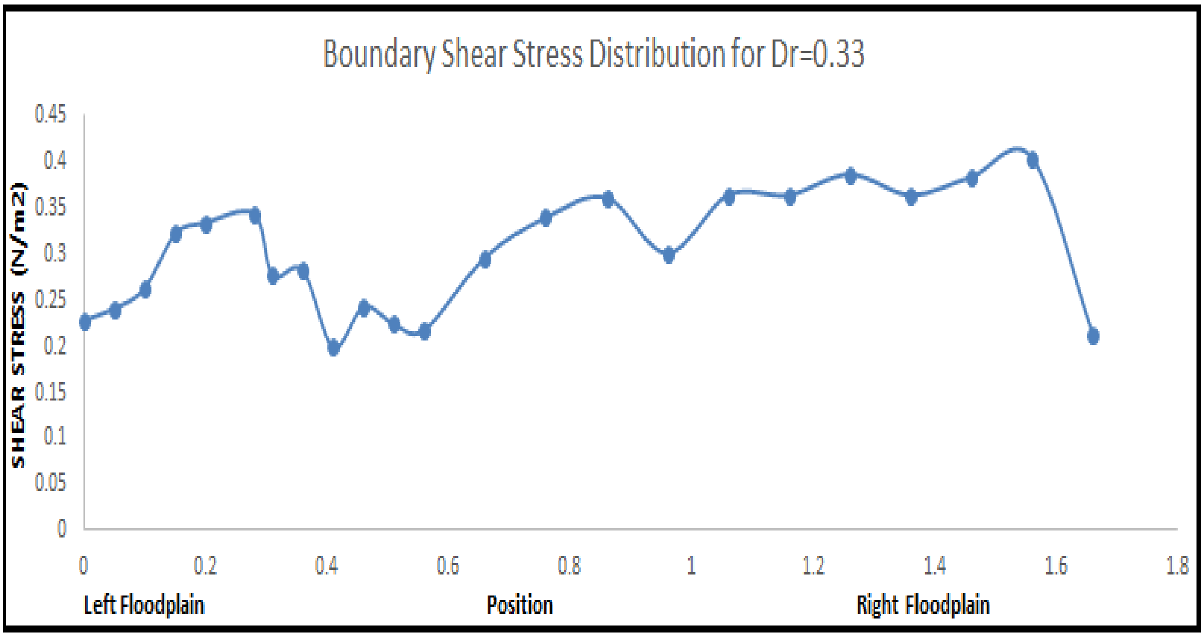


Figure 4.9: Boundary shear stress distribution for Dr=0.33

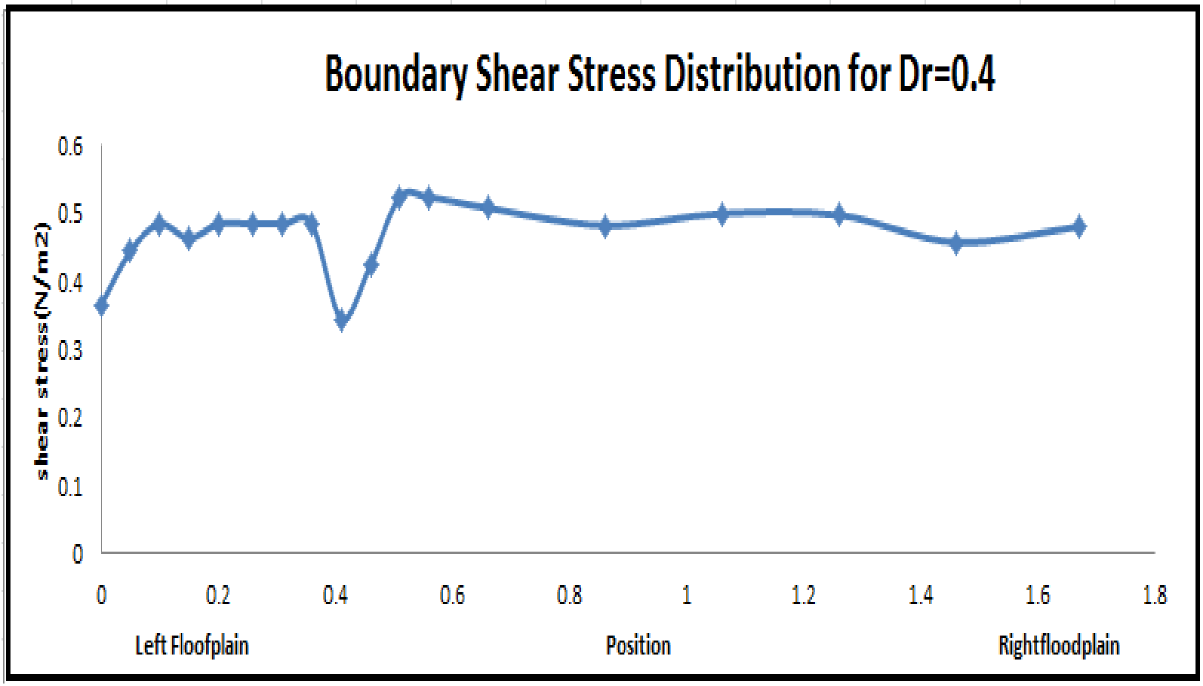


Figure 4.10: Boundary shear stress distribution for Dr=0.40

In case of the present compound meandering channel, the maximum value of boundary shear stress occurred at some distance from bend apex. In case of the present compound meandering channel, the maximum value of boundary shear stress occurred at the junction between inner main channel bank and the flood plain. However the boundary shear stress decreases in the main channel but again rises at the junction between outer main channel bank and the flood plain.

CHAPTER 5

CONCLUSIONS AND SCOPES

5.1CONCLUSIONS

Experimental investigations are carried out on a meandering river at a bend apex point for two different flow characteristics such as Stage discharge curve, velocity distribution, shear stress distribution etc. are investigated based on the analysis of the experimental investigations and numerical research certain conclusions are drawn which are discussed below:

1. Longitudinal velocity profile of a meandering channel remains higher at the inner wall of the channel section and decreases towards the outer wall.
2. Maximum longitudinal velocity from the inner bank of the bend apex sections are found to move toward the right floodplain region which is lies at the inner part of the curve. The maximum local velocity initially moves close to the surface, which later moves towards the bed.
3. From the occurrence of maximum depth averaged velocity, it is observed, that the maximum velocity always remains towards the inner wall.
4. From the stage discharge relationship we came to a conclusion that with the increase in stage the discharge increases.

5. From the boundary shear distribution it is observed that the minimum boundary shear stress occurs towards the outer bank region in the main channel. This trend of distribution of boundary shear stress gives enough indication of presence of secondary flow at main channel corner and main channel-flood plain interaction regions which is substantially affected by the large amount of momentum transportation between the main channel and flood plain

6. Depth averaged velocity in main channel region is found to decrease with increase in relative depth of flow.

7. From the result of longitudinal velocity profiles it is observed that velocity is increasing as the depth of flow goes on increasing.

5.2 SCOPE FOR FUTURE RESEARCH

The present research gives an extensive scope for future investigators to investigate other aspects of a meandering channel. The present research is limited to a single section flow analysis of the meandering flow. The research can be continued at different sections to get an overall depiction about the flow characteristics.

In this present work the experiments have done with smooth bed which can be further replaced by a rough bed.

REFERENCES

1. openchannels.’’ Proc., 13th Int. Association of Hydraulic Research, APD Congress, Singapore, Vol. 1, 76–86.
2. “Hydraulic capacity of meandering channels in straight floodway” (1956), Tech.Memorandum No. 2-429, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.
3. Inglis, C.C.(1947), “Meander and Their Bering on River Training.”, *Proceedings of the Institution of Civil Engineers, Maritime and Waterways Engineering Div., Meeting, 1947.*
4. James, M., and Brown, R. J.(1977), “Geometric parameters that influence flood plain flow”, U. S. Army Engineer Waterways Experimental Station, Vicksburg, Miss., June, Research report H-77.
5. Jarrett, R. D. (1984). ‘‘Hydraulics of high gradient streams’’, *Journal of Hydr. Engg.,ASCE*, 110, 1519–1539.
6. Javid,S., and Mohammadi,M.(2012). ‘‘Boundary Shear Stress in a Trapezoidal Channel.” IJE TRANSACTIONS A: Basics Vol. 25, No. 4, (October 2012) 365-373.
7. Jin,Y.C.,Zarrati, A. R. andZheng,Y. (2004). “Boundary Shear Distribution in Straight Ducts and Open Channels” *J. Hydraul. Eng.*, ASCE, 130(9), 924-928.
8. Johannesson, H., & Parker, G. (1989). “Linear theory of river meanders.”, *Water Resources Monograph, 12*, 181-213.
9. Khatua, K. K. (2008), “Interaction of flow and estimation of discharge in two stage meandering compound channels”. Thesis Presented to the National Institute of Technology, Rourkela, in partial fulfilment of the requirements for the Degree of Doctor of philosophy.

10. Khatua, K.K and Patra, K.C,(2010). Evaluation of boundary shear distribution in a meandering channel.Proceedings of ninth International Conference on Hydro-Scienceand Engineering, IIT Madras, Chennai, India, ICHE 2010, 74.
11. Khatua K.K., Patra K.C., (2013) “stage–discharge prediction for meandering channels”, Int. J. Comp. Meth. and Exp. Meas., Vol. 1, No. 1 80–92
12. Khatua K.K., Patra K.C., Nayak P. (2012), “Meandering effect for evaluation of roughness coefficients in open channel flow” *Sixth* international conf. on river basin management, WIT Transactions on Ecology and the Environment (ISSN 1743-3541), CMEM, WIT Press., 146(6):213-227.
13. Knight, D. W. (1981). “Boundary shear in smooth and rough channels.” *J. Hydraul. Div., Am. Soc. Civ. Eng.*, 107(7), 839–851.
14. Knight D. W. and Demetriou J.D. (1983). “Floodplain and main channel flow interaction.” *J. Hydraul. Eng*., ASCE, 109(8), 1073–92.
15. Knight, D. W., and MacDonald, J. A. (1979). “Open-channel flow with varying bed roughness.” *J. Hydraul. Div., Am. Soc. Civ. Eng.*, 105(9), 1167–1183.
16. Knight,D.W., and Sterling,M.(2000), “Boundary shear in circular pipes running partially full.”, *Journal of Hyd. Engg., ASCE* Vol.126, No.4.
17. Knight,D.W.,Yuan,Y.M.,andFares,Y.R.(1992). “Boundary shear in meandering channels.”,*Proceedings of the Institution Symposium on Hydraulic research in nature and laboratory*, Wuhan, China (1992) Paper No.11017, Vol. 118, Sept., pp. 151-159.
18. Langbein, W. B., & Leopold, L. B. (1966). “River meanders--Theory of minimum variance” (pp. 1-15). US Government Printing Office.
19. Leighly, J. B. (1932). “Toward a theory of the morphologic significance of turbulence inthe flow of water in streams.” Univ. of Calif. Publ. Geography,6(1), 1–22.

20. Mellor GL, Herring HJ. “A survey of mean turbulent field closure.”, AIAA Journal 1973; 11:590 – 599.
21. Mohanty, L.(2013), “Velocity Distribution in Trapezoidal Meandering Channel”. Thesis Presented to the National Institute of Technology, Rourkela, in partial fulfilment of the requirements for the Degree of Doctor of philosophy.
22. Mohanty, P.K., Dash,S.S. and Khatua,K.K. (2012). “Flow Investigations in a Wide Meandering Compound Channel.” International Journal of Hydraulic Engineering 2012, 1(6) : 83-94
23. Myers, W. R. C. (1978). “Momentum transfer in a compound channel.” *J. Hydraul. Res.,16(2),* 139–150.
24. Patel, V. C. (1965). “Calibration of the Preston tube and limitations on its use in pressure gradients.”, *Journal of Fluid Mechanics*, *23*(01), 185-208.
25. Patnaik, M. (2013), “Boundary Shear Stress Distribution in Meandering Channels”. Thesis Presented to the National Institute of Technology, Rourkela, in partial fulfilment of the requirements for the Degree of Doctor of philosophy.
26. Patra, K.C, and Kar, S. K. (2000), “Flow Interaction of Meandering River with Floodplains”. *Journal of Hydr. Engrg., ASCE,* 126(8), 593–604.
27. Patra, K.C., and Kar, S.K., Bhattacharya, A.K. (2004). “Flow and Velocity Distribution in Meandering Compound Channels.”, *Journal of Hydraulic Engineering, ASCE,* Vol. 130, No. 5. 398-411.
28. Preston, J. (1954). “The determination of turbulent skin friction by means of Pitot tubes.”, *Journal of the Royal Aeronautical Society, 58*(518), 109-121.
29. Rajaratnam, N., and Ahmadi, R.M. (1979). “Interaction between Main Channel and Flood Plain Flows.” *Journal of Hydraulic Division, ASCE,*Vol..105, No. HY5, pp. 573-588.

30. Rhodes, D. G., and Knight, D. W. (1994). “Distribution of Shear Force on Boundary of Smooth Rectangular Duct.”,*Journal of HydralicEngg.*, 120-7, 787– 807.
31. Saine S. Dash, K.K.Khatua, P.KMohanty(2013), “Energy loss for a highly Meandering open Channel Flow”, *Res. J. Engineering Sci.*, Vol. 2(4), 22-27, April (2013).
32. Saine S. Dash, K.K.Khatua, P.K. Mohanty(2013), “Factors influencing the prediction of resistance in a meandering channel”, *International Journal of Scientific & Engineering Research* ,Volume 4, Issue 5, May-2013.
33. Sellin R. H. J. (1961.), “A Study of the Interaction between Flow in the Channel of a River and that over its Floodplain”, Ph. D Thesis, University of Bristol, Bristol, England
34. Sellin, R. H. J. (1964), “A Laboratory Investigation into the Interaction between the Flow in the Channel of a River and that over its Floodplain”, La. Houille Blanche.
35. Shiono K., Al-Romaih I. S., and Knight D. W., (1999), “Stage-discharge assessment in compound meandering channels”, *Journal of Hydraulic Engineering*, ASCE, 125 (1), 66-77, Mar., 45-54, and discussion in 1993, 101, Dec., 251-252.
36. Shiono, K., Muto, Y., Knight, D.W. & Hyde, A.F.L.(1999), “Energy Losses due to Secondary Flow and Turbulence in Meandering Channels with Overbank Flow.”, *Journal of Hydraulic Research*, IAHR, Vol. 37, No. 5, pp. 641-664.
37. Shukry A.(1950), “Flow around Bends in an Open Flume”, Transactions ASCE, Vol. 115, pp 75L788.
38. Thomson J. (1876), “On the origins of windings of rivers in alluvial plains, with remarks on the flow of water round bends in pipes”, Proc. Royal Society of London,Vol. 25, 5-8.
39. Thomas TG. and Williams J.(1995a). “Large eddy simulation of a symmetric trapezoidal channel at Reynolds number of 430,000.” *J. Hydraul. Res.*. 33(6), pp. 825-842.
40. Thomas TG. and Williams J.(1999). Large eddy simulation of flow in a rectangular open channel. *J. Hydraul Res.* 37(3), pp. 345-361.

41. Toebes, G.H., and Sooky, A.A. (1967),“Hydraulics of Meandering Rivers with Floodplains.” *Journal of the waterways and Harbor Division, Proceedings of ASCE,* Vol.93, No.WW2, May, pp. 213-236.
42. Willetts B.B. and Hard Wick R.I. (1993), “Stage dependency for overbank flow in meandering channels”, *Proc. Instn Civ. Engrs, Wat., Marit. & Energy,* 101.
43. Wormleaton, P.R., Allen, J.,andHadjipanos, P.(1982). “Discharge Assessment in Compound Channel Flow.” *Journal of Hydraulic Engineering, ASCE,* Vol.108, No.HY9, pp. 975-994.
44. Yang, S. Q. and McCorquodale, John A. (2004) “Determination of Boundary Shear Stress and Reynolds Shear Stress in Smooth Rectangular Channel Flows.” *Journal of Hydr. Engrg.,* Volume 130, Issue 5, pp. 458-462.