AN INVESTIGATION OF VELOCITY DISTRIBUTION IN A ROUGH BED MEANDERING CHANNEL

A Thesis

Submitted by

SovanSankalp

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Dr.Kishanjit Kumar Khatua

Department of CivilEngineering

National Instituteof Technology,Rourkela

Orissa -769008,India

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DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OFTECHNOLOGY,ROURKELA

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.

SOVAN SANKALP

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OFTECHNOLOGY,ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **“Experimental And Numerical Investigation of Rough Bed Meandering Channel”** is a bonafide record of authentic work carried out by **SovanSankalp**under my supervision and guidance for the partial fulfilment of the requirement for the award of the degree of Master of Technology in hydraulic and Water Resources Engineering in the department of Civil 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: **22.05.2015**

Place: Rourkela

Prof. K.K. Khatua
Associate Professor
Department of Civil Engineering
National Institute of Technology, Rourkela

A Few lines dedicated to my parents and my guide

Guru Brahma

Guru Vishnu

Guru DevoMaheshvara

Guru Sakshat

Param Brahma

Tashmai Shri GuruveyNamaha

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ABSTRACT

An investigation of flow and velocity distribution of a simple meandering channel with rough bed is portrayed experimentally and numerically. Experimentation of fluvial flows are actively dominated by geometric complicacy along with variation in measurable property such as velocity distribution on sectional parameters like width ratio, aspect ratio and hydraulic parameter such as relative depth. Generally rivers have a tendency to meander their flow path for minimization of energy loss throughout their way.

The geometric section selected here for experimental analysis is a rough bed sine generated trapezoidal main channel except the wide flood plain circumscribed on both sides of main channel. A series of experiments were conducted in this study for the evaluation of longitudinal velocity distribution along the width and depth of the channel at different cross-sections (13 sections) along the meander path selected of a highly sinuous channel of cross-over angle 120 degree. Meander course experimented is from one bend apex to the subsequent bend apex which changes its path on the cross-over. Bend apex is just similar to a bend on a road or race circuit i.e. a function of highest curvature. Cross-over defines the part where the sinuous channel alters its sign.

The study explores the varying velocity profiles from one bend apex to the other with higher velocity always remaining on the inner bank of main channel, which hence moves from one bend to another as the meander path changes its course at the crossover. The experimental results were also compared with another researcher’s work having the same geometrical parameters, with a smooth bed and different aspect ratio.

As a reciprocal study to this experimental examination attempted in this work, a numerical hydrodynamic tool viz. CCHE (Centre for Computational Hydroscience and Engineering) developed by NCCHE, University of Mississippi, US is applied to simulate the inbank flow velocity distribution and validate the experimental result. The 2D and 3D version of the hydrodynamic tool mentioned above were formulated to the meandering channel for getting a statistical comparison between the experimental and numerical analysis of the velocity profile variation.

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SYMBOL	DESCRIPTION
A	Cross-sectional Area of Channel
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
W	Width of Channel
λ	Wavelength of a Sinuous Channel
υ	Kinematic Viscosity
V_w	Volume of Water
v	Point Velocity

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The term “water”, for all we know is the most elemental and essential wealth available to mankind. It is visualized on land in the form of rivers which are a natural feature of our landscape and form an integral part of the water cycle. Rivers are the most beautiful thing gifted to mankind as it provides peace and serenity to human beings. They are the major natural resource for the growth and prosperity of nations or states through which they travel alongside. The supply of both good quality and quantity of water is fruitful in many means to the livelihood of thousands of people. A better understanding of river mechanics remains a busy task for river engineers to achieve vital information for flood control, channel design, channel stability and the effect of transport of pollutants and sediments in the river. Rivers are divided into three types of flow pattern such as (i) Straight river (ii) Meandering river and (iii) Braided river. In general rivers hardly flow straight and uniform, they are always seen in a typical curved or meandering channel forms. The planimetric expansion of meandering rivers, followed by the progressive growth and shift of river bends and by the occurrence of bend short cuts, is one of the primary river plan form phenomena. Meandering rivers are so common channel forms on this planet that they are seen in numerous situations from alluvial situations to bedrock and cold melt water systems. Under normal weather conditions the flow in meandering rivers is restricted to its main channel only. Occasionally in harsh weather conditions they are filled up with more volume and jumps out of the main channel in the form of most common disaster i.e. flood. The research studied and presented both experimentally and numerically here in this thesis work is limited to the variation of flow characteristics in the main channel only.

1.2 MEANDERING

The term ‘meandering’ derives its nomenclature from a river located in present-day Turkey and known to the ancient Greeks as Μαίανδρος *Maiandros* (Latin: *Maeander*), characterised by a very convoluted path along the lower reach. In the early sixties the term ‘meandering’ was defined as flow in a winding course. Then in the eighties it was modified with a comparison stating flow similar to a person wandering aimlessly. But later it was technically defined as a sinuous curve, bend or loop along the course of a stream or river. Today this term meandering rivers is identified globally among most scientists and researchers because it is the mostcommon river planform style in populated areas. Almost all rivers meander to its own extent depending on its geometry and other natural effects.

Figure 1-Photograph of a Meandering River

A **meander**, in general, is a bend in a sinuous watercourse or river. A meander forms when moving water in a stream erodes the outer banks and widens its valley, and the inner part of the river has less energy and deposits silt. A stream of any volume may assume a *meandering* course, alternately eroding sediments from the outside of a bend and depositingthem on the inside. The result is a *snaking* pattern as the stream meanders back and forth across its down-valley axis.

Meandering of river is an exceptionally convoluted procedure including stream association amid curves, disintegration and silt transport. Inglis (1947) said that the river turns disintegrate during flood on account of amplitude turbulent vitality for which it develops and reefs. With fluctuating releases and residuum arrangement, there is a slant for residue to store at one twist and move towards the other.Levliasky (1955) deliberated the impact of centrifugal force to be a fundamental explanation behind meandering of a river, because of the helicoidal cross-momentum development.Chang (1984) conveyed that "as we know in general, the channel slant can't surpass the valley incline under the state of equalization. If the discharge and load are such that the channel slant so conveyed surpasses the valley incline, the dynamic changes as aggradations will happen, realizing steepening of the valley incline.As the channel slant can't surpass the valley incline under the state of equlibrium, it should either be equivalent or not exactly the valley slant.

The meander channel case addresses a level of channel alteration so that a river with a compliment direct slope can exist in a more compelling valley incline". Stream reliably alters itself with respect to its ability to conform the water discharge and sediment weight supplied from the watershed. These alteration, likely changes in the channel geometry, side slope, meandering pattern, roughness, are made such that the stream encounters minimum imperativeness use in transportation of its heap.

1.3 MEANDERING CHANNEL

Flow in meandering channel is quite synonymous for natural flow systems such as in rivers. Rivers generally follow this outline for minimization of energy loss. 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 before a channel is called meandering.

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. Meandering channels are equilibrium features that represent the most probable channel plan geometry, where single channels deviate from straightness. Meander plan geometry is simply describable by a sine function of the relative distance along the channel bend. It is basically formed by sediment erosion from the outer wall of bend and depositing them on the inside as a result widens its valley.

The various parameters of meandering channels are as follows:

(a) Meander wavelength

(b) Meander width

(c) Channel width

(d) Channel depth

(e) Bend radius

(f) Sinuosity

Sinuosity is used to describe a meandering channel. When sinuosity is greater than 1.5, the channel is classified as meandering (Knighton 1998). Equation 1 describes the method used for calculating channel sinuosity:

$\textit{Sinuosity} = L_c / L_v$ Eq.(1)

Where, Lc = the channel length; and Lv = the straight line valley length. There are two methods available to analyse meander geometry (Knighton1998). The first method focuses on the individual bend statistics: meander wavelength (L) and radius of curvature (r_c), which are averaged over a series of bends.

The second method is a series approach method that spans sequences of bends and treats the stream trace as a spatial series of flow direction (arc angle θ) or differential change of flow direction ($\Delta\theta$) along the reach (Knighton 1998). For meandering channels, Knighton (1998) states that the second method provides more flexibility for flow characteristics analysis and theoretical model development. Figure 2 presents the geometry of meandering channel.

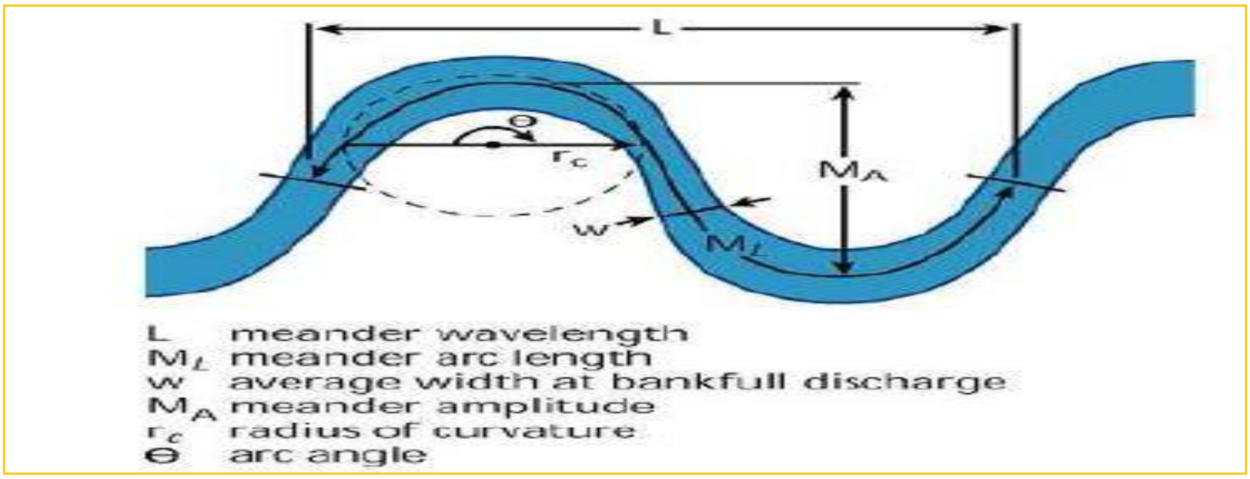

Figure 2 Description of Sinuosity

A sine-generated curve is used to develop a simple model of meandering channel, as described by equation 2.

$\theta = \omega \sin kx$ Eq.(2)

Where, θ= channel direction; x = flow distance along the reach; ω = the maximum angle between a channel segment and the mean down valley axis; and k = the ratio of 2p to the meander wavelength.

The meandering channel adopted here for experimental analysis is a highly sinuous channel with sinuosity 4.11. The channel is made available in the laboratory of National Institute of

Technology, Rourkela in Hydraulics Machines Lab. The meandering channel considered here is a rough bed meandering channel which is well explained further in the next chapters. For making the channel bed rough an appropriate size of small size aggregates which are sieved properly and washed out are laid down throughout the channel section.

1.4 MEANDERING PATH

Meandering path is a course pathway assumed by a river during its flow . The meandering path considered here for experimentation is taken from the second bend apex to the subsequent third bend apex. The bend apex is defined as the segment at which the stream has the greatest arch. A channel while moving from one bend apex to the next bend apex proceeds through the cross-over. Cross-over is a segment at the purpose of articulation where the meandering path changes its course as displayed in Fig. 3. The curved bank or the external bank turns into the raised bank or the inward bank after the cross-over and comparably the arched bank or the internal bank turns into the sunken bank or the external bank. In the Fig 3 W speaks to the width of the channel, λ speaks to the wavelength, L speaks to the length of channel for one wavelength and rc speaks to the radius of the channel.

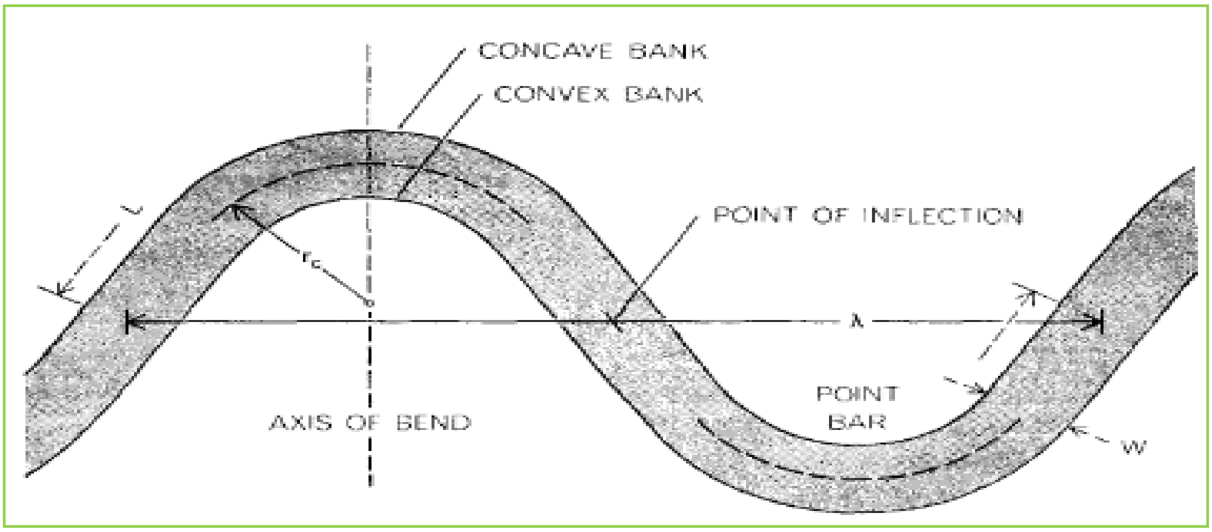

Figure 3-Geometrical Parameters of a meander path

1.5 LONGITUDINAL VELOCITY DISTRIBUTION

Longitudinal velocity is the speed of flow in the longitudinal direction relative to each section. In the main channel this is typically the stream wise velocity aligned to the main channel, while on the floodplain it is the velocity in the direction of flow. Appropriation of flow and velocity in a simple meandering channel are critical subjects in river mechanics to be researched from a commonsense perspective in connection to the bank protection, route, water admissions, and residue transport-depositional examples. Information on velocity distribution in a channel likewise serves to focus the vitality consumption, bed shear stress circulation, furthermore, the related heat and mass transport issues.

Specialists, Planners and Analysts are exceptionally keen on anticipating precisely and assessing quantitatively and dependably the longitudinal velocity distribution in a simple meandering channel. The information of velocity distribution serves to know the speed extent at every point over the stream cross-segment. Kiely (1990) found that velocities in the main channel of meandering channels can be reduced by up to 50 percent of those in equivalent straight channels. Marriott (1999) found that with very sharp bends where flow separation occurred, the overbank flow increased the conveyance of the in bank zone, but for other cases the overbank flow reduced the velocity in the main channel below the bank full level.

Kiely (1990) also stated that the maximum velocities in the main channel, above and below bank level, are close to the inner bend. Sellin and Willetts(1996) showed that the maximum velocity remains close to the inner bend at the apex, but then weakens and moves across to the outside of the bend further downstream.

Notwithstanding a few inquires about on different features of velocity distribution in meandering rivers, no precise exertion has yet been made to set up the relationship between the predominant meander wavelength, discharge and the distribution of velocity. In straight channel velocity distribution varies with different width-depth ratio, whereas in meandering channel velocity distribution varies with aspect ratio, sinuosity, meandering making the flow more complex to analyse. In the case of meandering river extreme velocity is seen to occur at inward divider or the curved side of the channel.

Because of the practical difficulty in obtaining sufficiently accurate and comprehensive field measurements of velocity and shear stress in compound channelsunder unsteady flood flow conditions (Bhowmik and Demissie, 1982), well designed laboratory investigations under steady flow conditions are still preferred as a trusted method to provide the information concerning the details of the flow structure. Such information is important in the application and development of numerical models aimed at solving certain practical hydraulic problems (i.e. to understand the mechanism of sediment transport, analysis of river migration, to prevent bank erosion in river channel, design stable channels, flood risk management, etc.).In this study undertaken the experimental channel changes its path of flow, and both the clockwise and anticlockwise curves of the meandering channel are examined.

Consequently the development of velocity can be considered from one bank of the channel to the next bank.In this thesis work the experimental channel considered i.e. a rough meandering channel point velocity information have been collected utilizing pitot tube arrangement for different depth and width ratio at thirteen different locations of a simple rough meandering channel.

The customary force law speaks to a vertical dispersion of longitudinal velocity in open channel with most extreme quality at free surface and with zero at the channel bed. The longitudinal velocity distribution of a simple meandering channel demonstrates two qualities for all cases and profundity proportions. In the bend area, velocity increments is seen in the internal curve (arched) and diminishes in the external twist (curved).

1.6NUMERICAL HYDRODYNAMIC TOOL

Despite lots of experimental work done in meandering channels and various theoretical studies done by the researcher about numerous channels, a numerical analysis is always examined to verify the efficiency of the experimental work and theoretical knowledge with those simulated results from the desired software.

The base for any kind of numerical analysis is based on CFD i.e. Computational Fluid Dynamics, which approached a bit late but is widely pursued in the field of river hydraulics with the advancement of modern high speed digital computers. CFD was not the substitute for those experimental or theoretical studies rather it nicely and reciprocally complemented the other two approaches. All the three approaches are interdependent to each other in various analysis. CFD is a numerical tool which solves complex differential and partial differential equations of fluid dynamics problems on computers with the help of a set of algorithms. As a complementary study to the experimental research undertaken in this work, a numerical hydrodynamic tool viz. CCHE2D developed by NCCHE, University of Mississippi, US is applied to simulate the flow in a highly sinuous meandering channel.

The CCHE2D model is a two-dimensional depth-averaged, unsteady, flow and sediment transport model. The flow modeling is examined on the basis offormulation of depth-averaged Navier-Stokes equations. This is an united collection for simulation and analysis of free surface flows, sediment transport and morphological processes. This family includes a pair of components: Mesh Generator (CCHE2D MESH) and a Graphical Users Interface (CCHE2D-GUI), which will help you use CCHE2D model more easily and efficiently.

1.7 AIM AND OBJECTIVES OF THE RESEARCH

The present work is meant to investigate the distinctive flow characteristics of a meandering way of a 120° cross-over purpose of a rough bed simple meandering channel. Although great investigation has been finished on flow distribution of open channel flow with unmistakable focuses, yet next to no exploration has been done along the path of a roughmeandering channel which is anteceded and followed by the meandering channel of same sinuosity.The meandering path being a bit of a more drawn out meandering channel serves to secure more correct information about its flow qualities which can then be associated with certified field conditions.

The objectives of the present work are outlined as:

- Experimental examination of longitudinal velocity along the width of the channel. The level profiles are examined at the bed, 0.2H, 0.4H, 0.6H and 0.8H above the channel bed. H being the average depth of flow of water at the corresponding section. The level profiles serves to dissect the development or position of most extreme velocity at each area along the meander path.
- Calculation of vertical profile of longitudinal velocity along the depth of the channel. The vertical profiles are examined at equivalent gaps of 4cm along the width of the channel at each area. The study serves to comprehend the definite normal for velocity distribution all through the channel area furthermore along the meandering path considered for experimentation.
- Comparison of vertical profiles of the longitudinal velocity of the highly sinuous channel with smooth and rough beds. The comparison is made with respect to inverse aspect ratio.
- To apply the 2D numerical hydrodynamic software tool CCHE2D developed by NCCHE, University of Mississippi, USA to validate the results of the rough meandering channel. Comparison of the numerical results with the experimental results.

1.8 LAYOUT OF THESIS

The thesis consists of seven chapters. General introduction is given in Chapter 1, literaturesurvey is presented in Chapter 2, and numerical tool is described in Chapter 3, experimental framework and mechanism are outlined in Chapter 4 and analysis based on experimental results are done in Chapter 5, Chapter 6 outlines theconclusion and finally the references are presented in Chapter 7.

Section 1 is the ‘INTRODUCTION’ chapter which gives a general view on rivers and its nature of flow along with a brief foundation on the meandering channel, itsfeatures and issues are described, and the aim and objectives of the research work undertaken is well explained.

Section 2 is the ‘LITERATURE REVIEW’ chapter which explains shortly the definite writing study by numerous prominent researchers that identifies with the present work from the earliest starting point till date.This chapter serves to arrange one's information and contemplations by gathering and grouping a huge collection of the database and the ability grew by past specialists while likewise distinguishing the issues and difficulties confronting the examination.

Section 3 is the ‘NUMERICAL TOOL AT A GLANCE’ chapter which gives a brief introduction of the numerical tool, its features, and its working environment. This chapter gives an explanatory idea about the working of the numerical tool.

Section 4 is the ‘EXPERIMENTAL FRAMEWORK AND ITS MECHANISM’ chapter which elaborates the experimental programme in details. This section explains the experimental setups, the arrangement made for experimentation and basically the instruments used during the experimental analysis at different locations of the channel.

Section 5 is the ‘RESULT ANALYSIS AND DISCUSSION’ chapter that deals with the outcome of the experiment conducted in the laboratory. In this section some basic comparisons are done to analyse the difference in work of two different researchers. The significant contribution of the numerical tool to the simulation of the experimented results is also pictured with several figures.

Section 6 is the ‘CONCLUSIONS’ chapter which summarizes the conclusion reached by the present research work and the scope for future research is listed out. This chapter explains the all above theoretically and experimentally explained research work in a nutshell.

‘REFERENCES’ is the last section which has listed down serially the name of the work of other researchers whose papers were referred to gain some ideas for the betterment of my research work both theoretically and experimentally.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter emphasizes on the short description of the previous command of many engineers, scientists and researchers in the field of open channel flow and various river related issues. They have widely mulled over open channel flow and a huge number of research publications are accessible at present on open channel flow. The complete writing audit covering the host of perspectives on open channel flow would be extremely thorough and extensive to be incorporated in any thesis work. The survey of writing exhibited here is exceptionally particular and focuses basically on the spearheading investigates in the field of hydraulics engineering basically related to flow attributes in a meandering channel .Research in the field of science and innovation gets a uniform flow where research discoveries and data of the past are imparted to the cutting edge in manifestation of distributed writing. So a definite literature review is essential to any significant and productive research in any subject. The present work is no exemption and thus a centred and concentrated survey of writing was completed covering different perspectives concerning the meandering channel. An essential stride in getting a superior comprehension of river systems is to study its velocity distribution along its width, depth and also along the meander path with greatest precision. Distribution of flow velocity in longitudinal and lateral direction is one of the essential angles in open channel flow. It specifically identifies with various flow highlights like water profile estimation, shear stress distribution, secondary flow, channel conveyance and host to other flow elements. The flow attributes of a river is basic for flood control, channel configuration, channel adjustment and rebuilding tasks and it impacts the transportation of toxins and silt. Flow in meandering channels is of expanding significance as this kind of divert is normal on account of regular streams, and research significant work with respect to surge control, discharge estimation and stream rebuilding need to be led for this sort of channel. Scientific interest in meandering rivers has existed for a long time (e.g. Einstein, 1926), and a considerable amount of effort has been made towards provide a mechanistic framework for the quantitative determination of many key parameters in meander development. These efforts have led to the development of models that establish the intrinsic ability of meander trains to evolve from incipient meander formation to neck cut-off.

2.2Previous Research on Velocity Distribution:

Bhowmik and Demissie (1932) studied data from two rivers in the United States and it is observed the rating curves obtained from these two rivers. It can be seen that, for both rivers there is a significant reduction in the main channel velocity during overbank flow.

Coles (1956) proposed a semi-observational mathematical statement of velocity distribution, which can be connected to external region and divider district of plate and open channel. He summed up the logarithmic recipe of the divider with attempted wave capacity, w(y/8). This is essential detailing towards external layer region.

The U.S. Army Corps of Engineers (Hydraulic 1956)considered a progression of analyses on meandering channels at the Waterways Experiment Station in Vicksburg. This paper explores the stage-discharge and the impact of geometric parameters like radius of curvature of the bends, sinuosity of the channel, flow depth, roughness added to the channel and so on transport limit in meandering channels.

Chow (1959) demonstrates the tables determining roughness coefficients for regular channels with consistent roughness attributes along a full stream reach. However in any one achieve these qualities may differ significantly.

Spitsin (1962) explained about the behaviour of a trapezoidal channel with a channel bed widthof 1.66 meters during overbank flow. To compare the flow in the main channel under interactingand isolated conditions, a glass wall at the channel/flood plain junction is inserted.

Also he wasable to calculate the energy existing in the channel and flood plain under isolated and interactingconditions.

Chang (1984) showed his experimental skill on the meander curvature and other formal features of the channel using energy methodology. It clearly explains the variations in bend radius lengthways of a channel. The modified Chang (1984) method is established on the assumption that the channel is quite wide as matched to its depth. This paper shows that it is problematic to apply this methodology to natural channels because of their flexible alignment.

Johannesson and Parker (1989 a)exhibited a logical model for figuring lateral distribution of depth averaged primary flow velocity in meandering rivers. With the use of a surmised "moment method" they represented the secondary flow in the convective transport of essential stream energy, yielding attractive aftereffects of the redistribution of essential flow velocity. They finalized a model which can be applied for channels with laterally flat or sloping in erodible beds. Their analysis can easily be compared to the case of a fully-erodible bed, so as to encompass the "resonance" of Blondeaux and Seminara (1985), and the over deepening of Straiksma et al. (1985) which will be demonstrated at a later date.

James and Wark (1992) considered the step function described above with a linear function to evade the discontinuity at the definiteconfines of the defined sinuosity ranges with consequent ambiguity. To overcome from this difficulty the existing equation was further liberalized known as the LinearisedSCS (LSCS) Method [1992] and this method was easy to apply and yields a significant result.

James (1994) analysed the numerous approaches for bend loss in meandering channel anticipated by different investigators. He confirmed the results of the procedures using the data of FCF, trapezoidal channel of Willets, at the University of Aberdeen, and the trapezoidal channels measured by the U.S. Army Corps of Engineers at the Waterways

Experiment Station, Vicksburg

Shiono, *et. al*. (1999) studied the effect of bed slope and sinuosity on discharge estimation of a meandering channel. Conveyance capacity of a meandering channel was derived using dimensional analysis and consequently helped in finding the stage-discharge relationship for meandering channels. The study showed that the discharge increased with an increase in bed slope and decreased with increase in sinuosity for the same channel.

Patra, Kar and Bhattacharya (2004) demonstrated that the flow and velocity distribution in meandering channels are firmly administered by flow interaction. By taking sufficient consideration of the interaction effect, they proposed mathematical statements that are discovered to be in great concurrence with common rivers. The proposed equation had good command over the interaction effect. Results from the details, reproducing the three-dimensional velocity field in the main channel and in the floodplain of meandering compound channels are contrasted with their separate experimental channel data that were acquired from a progression of symmetrical and unsymmetrical test channels with smooth and rough segments.

Afzal *et al*. (2007)dissected power law velocity profile in completely created turbulent pipe and channel flows regarding the envelope of the friction component. This model gives great estimate for low Reynolds number in outlined procedure of genuine framework contrastedwith log law.

Jovein et al (2009) examined flow structure for the control of erosion in strongly curved open channel bends. Lateral momentum and secondary flow induced in bends, causes maximum velocity transfer from centre line, super elevation, which results in erosion in outer bank and depositing sediment in inner bank. It was seen that the maximum velocity in all discharges is about the centre line of channel before the bend on the first section. The reason for the maximum velocity changes is that water depth decreases near the internal wall in this part of the bend, therefore, the maximum velocity increases. In comparison, after the middle of the bend, the water surface slope starts to decrease, and the secondary flow keeps away the maximum velocity from the internal wall. As a result, the maximum velocity decreases.

Khatua (2008) mulled over the appropriate distribution of energy in a meandering channel. It is come about because of the variety of the resistance variables Manning’s n, Chezy’s C, and Darcy-Weisbach’s f with depth of flow. Stage-discharge relationship from in-bank to the over-bank flow, channel resistance constants were established for meandering channel.

Pinaki (2010)examined a progression of research facility tests for smooth and rigid meandering channels and created numerical comparison utilizing dimension analysis to assess roughness coefficients of smooth meandering channels of less width proportion and sinuosity.

Khatua and Patra (2012) performed a progression of research center tests for smooth and rigid meandering channels and created numerical modelsutilizingmeasurement investigation to asess roughness coefficients. The imperative variables considered in influencing the stage-discharge relationship were velocity, hydraulic radius, viscosity, gravitational acceleration, bed slope, sinuosity, and aspect ratio.

Moharana (2012) contemplated the impact of geometry and sinuosity on the roughness of a meandering channel. ANFIS was utilized to forsee the roughness of a meandering channel utilizing a huge information set.

Dash (2013)examined the vital parameters influencing the flow conduct and flow resistance in term of Manning’ n in a meandering channel. Elements influencing roughness coefficient are non-dimensionalized to forsee and discover their reliance with distinctive parameters. A mathematical model was planned to forsee the roughness coefficient which was connected to anticipate the stage-discharge relationship.

Mohanty (2013)anticipated lateral depth-averaged velocity distribution in a trapezoidal meandering channel. A nonlinear type of comparison involving overbank stream profoundity, main channel flow depth, approaching discharge of the main channel and floodplains etc. was detailed. A quasi1D model Conveyance Estimation System (CES) was connected to the same experimental compound meandering channel to accept with the experimental analysis of depth-averaged velocity.

Pradhan (2015) experimented to calculate depth-averaged velocity along a highly sinuous channel. He has considered 13 individual sections along the meander path for his experimental analysis. He concluded with the fact that horizontal velocity profile of a highly sinuous meandering channel remains higher at the inner wall rather than outer wall.

2.3 PREVIOUS RESEARCH ON ROUGHNESS COEFFECIENT:-

Jarrett (1984)summarized and compared several methods of determining roughness coefficients of streams in Colorado. He has presented two equations for calculation of roughness for natural stable channels in which roughness changes dramatically with depth of flow. He also concluded that roughness coefficients and hydraulic computations may not be applicablefor sediment-laden flows, including mudflows and debris flows, on streamswith slopes greater than 0.05, and in scoured reaches.

Rice et al (1998) conducted a study on calculation of roughness of rock rip laid on steep slopes. They developed empirical relationships to anticipate Manning’s roughness coefficient as a component of D_{50} and S_0.He also formulated the Darcy-Weisbach equation as a function of d/D_{84}.He concluded stating that roughness increases with increase in bed slope and rip-rap size.

Hin and Bessaih (2004) examined velocity distribution, stage-discharge relationship and the impact of momentum transfer in a straight compound channel havinga rougher floodplain than the main channel. They artificially roughened the floodplain by utilizing wire network.

Yang et al. (2007)concentrated on the resistance attributes of inbank and overbankflows by leading a progression of experimental trials in a large symmetric compound channelhaving a rough main channel and rough floodplains. They analyzed the effectiveresistance coefficients (i.e. Manning's *n*, Darcy–Weisbach's*f*, Chezy's C) and therelative Nikuradse roughness height and inferred that these flow resistance coefficients shift with varying flow depth in a confounded manner for the overbank flow in the largecompound channels with a rough bed.

Kim et al (2010)estimated Manning's roughness coefficient for a gravel-bed river reach using field measurements of water level and discharge. Results showed that the roughness coefficient tends to decrease with increasing discharge and water depth, and over a certain range it appears to remain constant. Comparison of roughness coefficients calculated by field measurement data with those estimated by other methods showed that, although the field-measured values provide approximate roughness coefficients for relatively large discharge, there seems to be rather high uncertainty due to the difference in resultant values.

Khatua, Patra and Nayak (2011) studied the meandering effect for calculating roughness coefficient in an open channel flow. They have analyzed the change in roughness coefficient with varying meandering channel of respective slope, sinuosity and geometry of the channel. They have modeled a distinct equation for roughness coefficient based on dimensional analysis and tested with experimental data.

2.4 PREVIOUS RESEARCH ON CCHE2D:-

Today in this period of PC's, numerical models have become the most widespreadimplements for researching flow and silt transport in open channels. One-dimensional models demand small extent of groundstatistics, and the mathematicalorders, which are needed for calculating, then let computation be more stable than two-dimensional and three-dimensional models. Two-dimensional and three-dimensional models can conduct flow analysis and sediment transport calculation in limited Natural River, because of the computing time demanded and the vast of field data for calibration and verification.

Scott and Jia (2006) demonstrated CCHD2D model capability for addressing sediment transport problems in the Mississippi (L=25 miles). The quasi-unsteady simulation in CCHE2D option was used to simulate long-term analysis. Evaluation of sedimentation in the point bar dike for a ten-year period of record flow was conducted in the Catfish point reach (L=25 miles) and the effect of a series of dikes were constructed to reduce dredging in the Redeye Crossing reach (L=5.5 miles).

Hasan et al (2007) applied 2D modelling for Muda River using CCHE2D.Their main objective was to ensure that the design cross-section and alignment of river channel are economic, effective and environmental sound. They also examined long term river behaviour with the help of model studies. Tidal influence on the study reach were observed along with velocity contour in the channel and floodplain. They concluded that these models are useful in studies where local details of velocity and depth distributions are important.

Hossain, Jia and Chao (2008)examination approves the CCHE2D hydrodynamic model flood replication results utilizing a progressionof satellite imagery and a few advanced digital image processing procedures. In this study, remotely detectedstatistics has been tested to provide continuous truth data to evaluate the CCHE2D model simulation results for flood engendering due to levee rupturing.

He et al. (2009) used CCHE2D model to examine how much large wood structures affected the flow, sediment transport, riverbed change, and fish surroundings in the Little Topashaw Creek (L=2 km), North Central Mississippi. Five structures made of trees were put in the study area. Habitat assessment for two fish species, blacktail shiner and largemouth bass, were conducted using before and after the large wood structure (LWS) construction and as a result of that, both fish species were increased in case of the LWS installation. In other words, LWS had a positive effect on fish habitat.

Fathi et al (2012) applied a powerful two dimensional numerical model which is named CCHE2D, to simulate the river flow pattern of a meandering river rich by a 180_channel bend, which is named Khoshk-e-Rud River of Farsan, at the 30th Km of west of ShahreKord. They analyzed to have a standard calculated mesh, different calculated meshes must be analyzed sensitively. Thus, the optimum calculated mesh could be selected. They simulated the flow pattern by the CCHE2D model for each two cases and the simulated results of model were compared to estimate data's. Finally, the results showed that, the best and closest predicted results pertain to the made calculated mesh by 48*200 dimensions and fined width by canceling of flood plain.

Kim Z (2013) studied the changes in the bed of Geum River (L=130 km from Daechung regulation dam to Geum River estuarial bank) in South Korea were predicted using the 1-D HEC-RAS model and the 2-D CCHE2D model. Inflow data of sub basins were calibrated with daily runoff data generated by PRMS based on a hydrologic unit map, short-term riverbed changes were predicted with CCHE2D for 11 days in the problem area, depending on the results of 1-D model, and the effect of dikes was examined.

Kamanbedast,Nasrollahpour and Mashal (2013) worked on the prediction and estimation of sediment transport in rivers using CCHE2D model. They researched on the unsteady figure of Karkheh River in Iran as well as variations of river bed elevation and sediment transport due to two flood events utilizing CCHE2D.They concluded stating that velocity, Froude number and shear stress for 50-year flood are more than 25-year flood.

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CHAPTER 3

DESCRIPTION OF NUMERICAL TOOL

3.1 INTRODUCTION

The CCHE2D (National **C**enter for **C**omputational **H**ydroscience and **E**ngineering's **2-D**imensional Model) is a hydrodynamic model for unsteady turbulent open channel flow and sediment transport simulation developed at the National Center for Computational Hydrosciences and Engineering (NCCHE), School of Engineering, the University of Mississippi. The CCHE2D model is a two-dimensional depth-averaged, unsteady, flow and sediment transport model. The flow model is based on depth-averaged Navier-Stokes equations. This is an integrated package for simulation and analysis of free surface flows, sediment transport and morphological processes. The model is capable of simulating unsteady open channel flows with the steady state solution as a special case. Both subcritical and supercritical flows as well as transitions of the two states can be simulated. Large scaled natural channel flows, small scaled laboratory flume flows have been used to verify the model's capability, the results for the main flow and near field details are both satisfactory.

In addition to the numerical model itself, this family includes two more members: a mesh generator (CCHE2D Mesh Generator) and a Graphical Users Interface (CCHE2D-GUI), which will help you use CCHE2D model more easily and efficiently.

The CCHE2D mesh generator allows the rapid creation of complex structured mesh systems for CCHE2D model with several integrated useful techniques and methods.

The CCHE2D-GUI is a graphical user's environment for the CCHE2D model with four main functions: preparation of initial conditions and boundary conditions, preparation of model parameters, run numerical simulations, and visualization of modelling results.

The CCHE2D Mesh Generator provides meshes for CCHE2D-GUI and CCHE2D numerical model, while the CCHE2D-GUI provides a graphical interface to handle the data input and visualization for CCHE2D numerical model.

The computational code is developed based on the FORTRAN 90 64bit version. The program fully takes the advantages of dynamic array allocation capability and module programming capability to allocate memory for arrays automatically according to the requirement of the application and add new functionalities. The 64bit version allows users to simulate cases with a very large number of nodes on PCs.

The following models are also attached to the simulation process of CCHE2D in addition to the hydrodynamic model:

1. FLOOD MODEL

2. SUSPENDED SEDIMENT TRANSPORT MODEL

3. BEDLOAD SEDIMENT TRANSPORT MODEL

4. BANK EROSION MODEL

5. BANK MASS FAILURE MODEL

6. COHESIVE SEDIMENT TRANSPORT MODEL

7. POLLUTANT FATE AND TRANSPORT MODEL

8. WATER QUALITY MODEL

9. COAST MODEL

3.2 MAIN FEATURES OF THE FLOW MODEL

The CCHE2D flow model has the following main features:-

a. The model strictly enforces the mass conservation within the computational domain through the user of control volume approach. This property is of fundamental importance in achieving reliable and accurate results.

b. Wetting and drying of the domain as the nodes are submerged under high flows and exposed during low flows. This feature is particularly important during unsteady flows. The wet and dry nodes are distinguished based on the critical depth specified by the user. During the simulation process any node having flow depth less than the critical depth is considered dry.

c. The turbulent eddy viscosity is approximated using three different approaches. The first one is based on the depth average parabolic eddy viscosity model; the second approach employs depth-averaged mixing length model; and the last approach is based on depth-averaged.

d. The last two approaches are particularly suitable for re-circulation flows and flow around hydraulic structures. The user has the option to simulate a given case with any of the above turbulent closure scheme.

e. The user can provide no-slip, total-slip, partial-slip, or log-law boundary condition at the no-flow boundaries. The log-law approach results in an accurate prediction of shear stresses near the hydraulic structures that are important for computing flow and sediment transport in the vicinity of hydraulic structure.

f. The model supports both steady and unsteady boundary conditions for flow with multiple inlets and outlets. At any inlet the user can specify specific discharge, total discharge, or discharge hydrograph boundary condition. At an outlet the model accepts open boundary, water surface level, stage-discharge relationship, or stage hydrograph as a boundary condition.

g. In case of open boundary the model uses kinematic wave approximation to assess the water surface level at the outlet. This condition should be applied judiciously and is useful in cases when water surface level at the outlet is not available.

h. The model is capable of handling supercritical flow. In addition, mixed flow regime (combination of subcritical and supercritical flow) in a channel reach can be simulated using the CCHE2D model.

3.3 CURRENT STATUS OF CCHE2D MODEL

The CCHE2D model is available free of charge to the researchers and engineers that sign Beta-Testing Agreement with the NCCHE. Both the mesh generator and the CCHE2D-GUI are developed for the Microsoft Windows system and can run on Windows 95, 98, 2000, and XP. The CCHE2D model is bundled with the CCHE2D-GUI and can run independently on the client machine. However, the user can also apply for a login and password to run the model on the NCCHE’s server.

3.4 GOVERNING EQUATIONS

Because many open channel flows are of shallow water problems, the effect of vertical motions is usually of insignificant magnitude. The depth integrated two-dimensional equations are generally accepted for studying the open channel hydraulics with reasonable accuracy and efficiency. The momentum equations for depth-integrated two-dimensional turbulent flows in a Cartesian coordinate system are:

1. MOMENTUM EQUATION

$$\frac{du}{dt} + u\frac{du}{dx} + v\frac{du}{dy} = -g\frac{dz}{dx} + \frac{1}{h}\left[\frac{d(h\tau_{xx})}{dx} + \frac{d(h\tau_{xy})}{dy} - \frac{\tau_{xy}}{\rho h} + f_{cor}v\right. \qquad (3.a)$$

$$\frac{dv}{dt}+u\frac{dv}{dx}+v\frac{dv}{dy}=-g\frac{dz}{dx}+\frac{1}{h}[\frac{d(h\tau_{xx})}{dx}+\frac{d(h\tau_{xy})}{dy}-\frac{\tau_{by}}{\rho h}-f_{cor}u \qquad (3.b)$$

where *u* and *v* are depth-integrated velocity components in *x* and *y* directions, respectively; *t* is the time; *g* is the gravitational acceleration; is the water surface elevation; is the density of water; h is the local water depth; is the Coriolis parameter τ_{xx}, τ_{yy}, τ_{yx} andτ_{yy} are depth integrated Reynolds stresses; andτ_{nx}, τ_{ny} and $\tau_{bx,}$ τ_{by} are shear stresses on the water surface and bed surface, respectively. The shear stress terms at the water surface are dropped since wind shear driven effect is not considered in this version of the model.

2. CONTINUITY EQUATION

Free surface elevation for the flow is calculated by the depth-integrated continuity equation:

$$\frac{\delta h}{\delta t}+\frac{\delta uh}{\delta x}+\frac{\delta vh}{\delta y}=0 \qquad \text{Eq. (4)}$$

Assuming the bed elevation, ζ, would not change in the flow simulation process: $\partial\zeta/_{\partial t}=0$

the continuity equation is then simplified to

$$\frac{\partial\eta}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \qquad \text{Eq. (5)}$$

Where η is the free surface elevation, *h* is the water depth. Because bed morphological change is a much slower process than hydrodynamics, this equation is widely accepted and utilized for computing free surface elevation with two-dimensional models. One may note in cases when the bed elevation changes fast due to erosion or deposition, in cases of dam break process, for example, Eq. (4) should be applied.

The turbulence Reynolds stresses in Eq. (5) are approximated according to the Bousinesq’s assumption that they are related to the main rate of the strains of the depth-averaged flow field with a coefficient of eddy viscosity:

$$\tau_{xx}=2v_t\frac{\partial u}{\partial x} \qquad \text{Eq. (6)}$$

$\tau_{xy} = v_t \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$ Eq. (7)

$\tau_{yy} = 2v_t \frac{\partial v}{\partial t}$ Eq. (8)

$\tau_{yx} = v_t \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$ Eq. (9)

3.5 EDDY VISCOSITY MODELS

There are two zero-equation eddy viscosity models adopted in the CCHE2D model. The first one is the depth-integrated parabolic model, in which the eddy viscosity $v_t$is calculated by the following formula:

$v_t = A_{xy}/6 \times ku_* \times h$ Eq.(10)

Where A_{xy} represents a coefficient to adjust the value of eddy viscosity. $\kappa$is the von Karman constant, and U***** the shear velocity. The second eddy viscosity model is the depth-integrated Mixing Length model. The eddy viscosity $v_t$is calculated by the following equation.

$v_t = l^2 \sqrt{2\left(\frac{du}{dx}\right)^2 + 2\left(\frac{dv}{dy}\right)^2 + 2\left(\frac{du}{dx} + \frac{dv}{dx}\right)^2 + \left(\frac{dU}{dz}\right)^2}$ Eq. (11)

$l = \frac{1}{h}\int kz \sqrt{\left(1 - \frac{z}{h}\right)}\, dz = kh \int_0^1 \lambda\sqrt{1 - \lambda d\lambda} \approx 0.267kh$ Eq. (12)

$\frac{\partial U}{\partial z} = C_m \frac{U}{kh}$ Eq. (13)

Where U is the total velocity, U_* is the total shear velocity, and C_m is a coefficient. The C_m instead of direct calculation is assigned a value of 2.34375 in such a way that Eq.2 will recover Eq.1 during the absence of all the horizontal velocity gradients (uniform flow).

3.6 GENERAL METHODOLOGY

The numerical modeling based on solving the depth averaged Navier-Stokes equations is an initial-boundary value problem. It is necessary to provide initial conditions and the boundary conditions. The general technical analysis of the numerical simulation can be simply listed as follows:

1. Mesh Generation
2. Specification of Boundary condition
3. Parameter setting
4. Simulation
5. Results visualization and interpretation

3.6.1 Mesh Generation

A mesh represents a computational domain and the way the governing equations are discretized. To have a successful simulation, one has to prepare the mesh carefully, so that the following concerns are taken into consideration:

I. The interested zones has sufficient resolution;
II. Transition between areas of different densities is smooth;
III. Inlet(s) and outlet(s) should be sufficiently far away from the zones of interest;
IV. The mesh should be smooth and orthogonal as much as it allows.

Mesh generation particularly for practical problems takes a lot of time, however, the time shall be paid off if good quality is achieved. In many cases, the simulation code will run with a low quality mesh but the results may be less reliable.

For meeting the above and creating the mesh for the different physical domains the module CCHE-MESH available in the package can be used by following a step by step procedure. Usually CCHE-MESH creates a structured mesh which consists of families of mesh lines with the property that members of a single family do not cross each other and cross each member of the other families only once. A file is imported to the CCHE MESH window as per the limitation of the type of file prescribed by the module. The imported file then processed through an Algebraic Mesh Generation which is done by a two boundary method.

Define the outer boundaries and the inner boundaries by placing the boundary control points. Distribute the equal number of boundary points along the top and the bottom boundaries. Each pair of the boundary points forms a control line. The boundaries so created is saved as boundary file option for further use. For algebraic mesh definite I_{max} i.e. no of I lines and J_{max} i.e. no of J lines to be meshed inside the boundary lines created are specified by the user. Fast computation and direct control of mesh nodes are the two main advantages of the algebraic mesh generation which interpolates the interior mesh nodes directly from the boundaries. The nodal distributions can be well controlled by the stretching functions.In CCHE-MESH, a more flexible and powerful two-direction stretching function EDS is proposed.E (= -1, 0, 1) is the exponential parameter; D (0<D<1) is the deviation parameter; S (>0) is the parameter used to control the degree of stretching, called scale parameter. The exponential parameter determines the characteristic of the distribution: contraction to a point, repulsion from a point, or uniformity. If E = -1, the distribution is contracting to the point; if E = 1, the distribution is repulsing from the point; and if E = 0, the distribution is uniform. The deviation parameter provides the relative location of this point along AB. For example, if D = 0.5, this point is located at the centre. The scale parameter S controls the degree of stretching. The larger S is, the more the distribution is stretched. If S = 0, the distribution is uniform. Then the process is followed by generating numerical mesh for smoothening the algebraic mesh created with the required no of iterations as given by user. Then the mesh file is evaluated i.e. the quality of mesh is evaluated quantitatively by several indicators, such as Maximum Deviation Orthogonality (MDO), Averaged Deviation from Orthogonality (ADO), Maximum grid Aspect Ratio (MAR), and Averaged grid Aspect Ratio (AAR). Finally the mesh file is saved as geometry (.geo) file for further working in the window of CCHE GUI.

3.6.2 Specification of Boundary Condition

Boundary conditions are the user defined options which oversee or guide the flow in the recreated zone. It must be deliberately chosen speaking to the genuine physical conduct of the flow occurring. Fundamentally the inlet and outlet flow conditions are to be specified by the user for the beginning of simulative analysis. The .geo file is opened in the CCHE GUI window.

The initial conditions are set i.e. the initial bed elevation which can be to applied to whole domain or to a user specified domain, next the initial water surface which is provided at the upstream and the downstream side of the channel is given, next is the bed roughness value for the whole domain or selected site.

Every conditional process is followed by an interpolation either in the I-direction or in the J-direction for the application of the value of initial conditions to the whole of the channel. Now the boundary condition is set i.e. the inlet and outlet values set at the upstream and downstream respectively.

At the inlet user can specify either total discharge or the discharge hydrograph whichever is available. At the outlet we need to specify the water surface level or rating curve or stage hydrograph whichever is available. Now the boundary condition is set for further analysis and inputs.

3.6.3 Parameter Setting

There are a number of groups of parameters which must be then set after setting the initial and boundary conditions. In the parameter setting the flow parameter is to be set.

Under this flow parameters there are three groups of parameters to be set viz. simulation parameters, bed roughness parameters and advanced parameters.

Under the heading of simulation parameter one has to choose the simulation time and the time step with the total time step being formulated automatically i.e. simulation time divided by the time step given, then from the turbulence model option one has to choose the desired model option required for his analysis and some other numerical parameters like wall slipness coefficient, method of iteration, depth to consider dry. We can choose to compute the flow as quasi uniform flow.

Similarly in the bed roughness group there are a number of options to choose or specify the bed and wall roughness values such as Manning‘s *n* value or out of those from Wu &Wang (1999) or van Rajin (1989) formula as applicable to the case at hand.

In the advanced group Coriolis force coefficient, gravitational acceleration, von Karman constant, and kinematic viscosity of fluid, with default values that suffice for most cases, are available. However the user can change the above given parameters for different run cases simulated by user for the analysis with different variables in each parameter.

3.6.4 Simulation

After specifying all required conditions i.e. initial conditions, boundary conditions, setting the flow parameters the model simulation can be started with an option called Run Simulation.

This is the final process before the outcome of results from simulation. For this ‘run simulation’ tab with a number of options such as steady flow, unsteady flows etc. are available and the user may choose depending on the user’s need. Also multiple runs may be necessary with some changes in flow parameters to get the desired results as numerical simulation is often a trial and error process.

3.6.5 Result Interpretation and Visualization

After the simulation is run for the desired no. of time steps the command window inside the GUI of CCHE2D indicates that the simulation is successful and ask for any key to continue. Now the final result files are ready.

Now choose the intermediate file option to get down a list of attributes of the flow results which can be viewed individually by clicking on them from the variable view space.

There are a number of output variables such as water surface; water depth; u velocity; v velocity; velocity magnitude; u specific discharge; v specific discharge; total specific discharge; u and v components of shear stress; total shear stress; Froude no; eddy viscosity.

Also if the user provides time interval to extract history results of simulation before setting up the simulation then CCHE2D can give history results at predetermined time intervals of 100 or 1000 time steps to analyse the progress of simulation in case an unsuccessful simulation. The simulation results and the initial conditions can be exported as data file with xy coordinate and all other variables from data export option

CHAPTER 4

EXPERIMENTAL FRAMEWORK AND MECHANISM

4.1 OVERVIEW

It still remains a dilemma for most engineers, researchers etc. to take measurements of various flow related parameters in a natural river because the flow in a river is always unpredictable. You cannot trust the flow in a river just by looking at its geometry as it is so rightly said “A river is the author of its own geometry” and you cannot challenge nature for your research related issues. This puzzling of rivers creates deficiency in the collection of real field data. To overcome such complicacy in the experimentation on natural rivers, the flow attributes of a river can be experimented by analyzing them on a manmade channel designed quite synonymous to natural rivers. Rivers usually follow the path of least resistance which tends to be referred as the meander path, in brief rivers are meandering in character having particular sinuosity all throughot their movement. Flow sequence are contemplated on test models for distinctive sinuosity and can then be utilized to model them on regular channels. The flow developments and behaviour pattern found within the laboratory flumes can be utilized in better working out of the mechanism of glide in a meandering channel and so for the solution of many practical river issues.

Experimental investigations for my research work were led under controlled research centre conditions in the Fluid Mechanics and Hydraulics Laboratory of the Civil Engineering Department at the National Institute of Technology, Rourkela, India. Experiments are carried out in the existing highly sinuous flume with the bed of the channel being considered as rough (roughened manually by laying a certain size of aggregates along the meander path) instead of those smooth perpex sheets of which the channel was built.

Within the present work the velocity distribution has been studied through a sequence experimental runs in a meandering channel of better sinuosity existing within the laboratory. Subtle elements of hydrodynamics and geometric parameters of meandering channel, equipment’s and measuring hardware's utilized, managing methodology received, roughness elements designed along with its properties and determination of n value of the roughness element used has been laid out on this chapter of thesis work.

4.2 FRAMEWORK OF THE EXPERIMENTAL CHANNEL

4.2.1 GEOMETRY SETUP

The experimental channel i.e. a compound meandering channel was built which was fabricated inside a large steel tilting flume. The tilting flume is 15m long having a rectangular cross-section of 4m wide and 0.5m deep, made up of deep metal frame with glass walls. The positioning of flume is directed through some hydraulic jacks so as to deliver unusual bed inclines on tilting. This complete setup of experimental geometry is made accessible at the Fluid Mechanics and Hydraulics Laboratory of NIT, Rourkela.

For the fabrication of meandering channel strong quality perpex sheets were cut into proper sizes to shape up the curvy channel for rigorous experimentation. The perpex sheets used for designing the complete meandering channel were about 6 to 10 mm thick.

The meandering channel designed inside the steel flume has two straight flood-plains within which the main channel was fabricated having a bank full depth of 0.065m with a bottom width of 0.33m and 1:1 side slopes.

For the present research work we have considered the flow in the main channel only in exception to the two flood plains. Fig 4 displays the plan metric view of the channel setup developed with help of AUTOCAD software. Fig 5 displays the colourful view of the channel setup present in the laboratory of NIT, Rourkela. The fabricated curvy trapezoidal main channel seems quite synonymous to a sine generated bend of one and half wavelength.

At the beginning of the flume just after inlet and before head gate (called stilling chamber), a series of baffle walls were installed for energy dissipation purpose, i.e. to reduce turbulence and make water body still before passing over the channel.

Head-gate reduces the waves if formed in the water body before it passes over the channel and in this way head-gate plays a vital role in having uniform flow.

Water jumps smoothly from the notch, falls over a wire mesh placed just below the notch, and maintains a steady flow. Water then starts flowing into the main channel through a smooth bell mouth transition section so as to maintain a more steady flow throughout the channel section and to reduce head loss for a flawless analysis of its basic flow parameters. A movable bridge (approx.1m width and 4m long) was provided across the flume in both axes over the channel area so as to make experimentation handy and easy over a 4m wide channel. The measuring instruments such as point gauges and pitot tubes are arranged on the bridge such that each section along the meander path is accessible for measurements. Tailgate was provided just before end point of the flume for analysis of the bed slope. Rectangular notch was installed at the end of the flume to calculate discharge for each constant flow of water in the channel.

All the experimental calculations are observed from the second bend apex to the next corresponding bend apex of the experimental channel from the upstream end. The following figures shows a schematic plan of the channel and the actual photograph of channel.

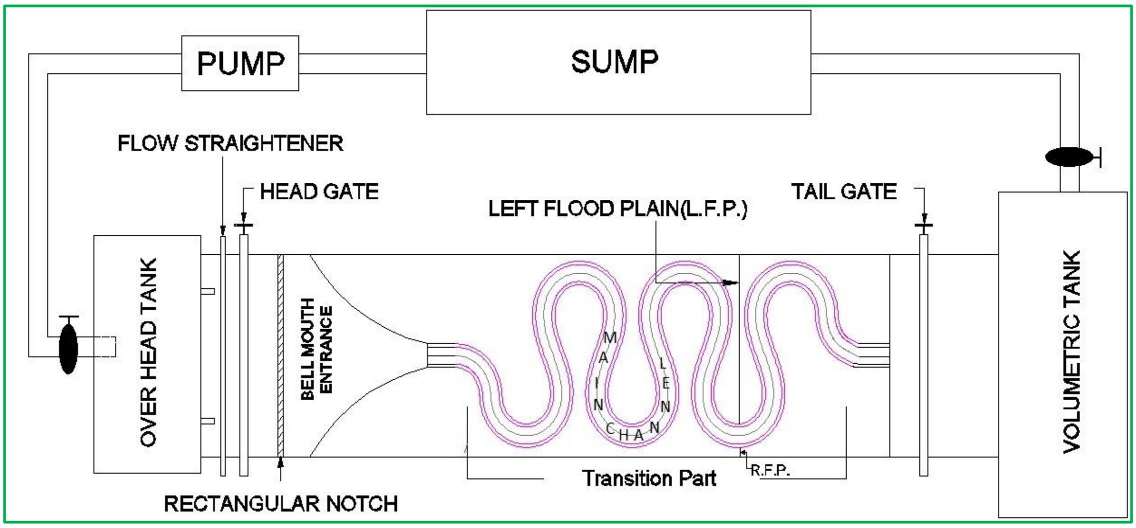


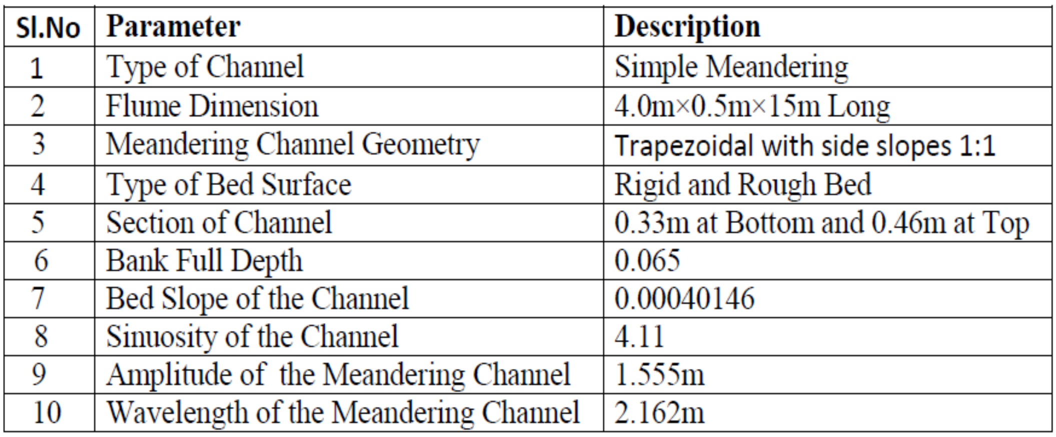
Figure 4 Planimetric view of the experimental meandering channel

Figure 5 Meandering channel at NIT, Rourkela

4.2.2 Experimental simple meandering channel

The simple meandering channel considered for investigation constituted a main trapezoidal channel of 330 mm wide at bottom, 460 mm wide at top having depth of 65 mm and side slopes of 1:1.The bed of main channel was made rough by laying down a layer of uniform size small aggregates for considering it as rough bed meandering channel. The details of aggregates is discussed later in this chapter. The details geometric features of the main channel are given below in tabular form in Table 1.

Table1:Details Geometry of Meandering Channel



Sl.No	Parameter	Description
1	Type of Channel	Simple Meandering
2	Flume Dimension	4.0m×0.5m×15m Long
3	Meandering Channel Geometry	Trapezoidal with side slopes 1:1
4	Type of Bed Surface	Rigid and Rough Bed
5	Section of Channel	0.33m at Bottom and 0.46m at Top
6	Bank Full Depth	0.065
7	Bed Slope of the Channel	0.00040146
8	Sinuosity of the Channel	4.11
9	Amplitude of the Meandering Channel	1.555m
10	Wavelength of the Meandering Channel	2.162m

Figure 6 Rough Meandering Channel

4.2.3 WATER SUPPLY FACILITY

Water rushing into the meandering channel is just a cyclic process as we experience it in nature’s water cycle process i.e. recycling in general. The cycle here involves water moving from an underground sump to an overhead tank with the assistance of centrifugal pumps continuously whenever there is flow in the channel and vice-versa.

An extensive R.C.C overhead tank is built on the upstream side of the channel inside the laboratory. The overhead tank is quite useful for experimentation as it helps to maintain a constant head of water to get an efficient steady discharge .It is designed in such a way that in a state of overflow in the tank the excess water rolls down to the sump directly through huge pipes.

A stoned volumetric tank is designed at the downstream side of the flume for the purpose of discharge calculation and to retain the running water from the channel which again flows back to the underground sump for re-supplying of water to the overhead tank.

A large underground sump is positioned outside to maintain a continual water supply to the overhead tank for experimentation. Two parallel pumps of 15Hp and 10Hp respectively fitted with suction and delivery pipes complete the process of pumping water from the underground sump to the overhead tank.

Water rushes into the flume from the overhead tank through regulating pipes that are handled manually to uphold the required amount of discharge for your experimentation.

This water falling into the flume is first reserved in a stilling tank. Then it is allowed to flow through an regulating vertical gate into a series of baffle wall ahead of the rectangular notch. These arrangements are implemented to minimize the turbulence of the incoming water.

Water jumping from the notch falls over a wire mesh positioned manually just below the notch, to further steady the flow. On the downstream side a tail gate is fitted to maintain the flow depth and to achieve Quasi-Uniform flow in the channel.

The following figures show a flow chart description of the experimental water supply facility considered in the lab. The figures are well arranged with respective arrow marks displaying the direction of water flow.

Figure 7 Flow Chart of the Water Supply System

4.3APPARATUS AND EQIPMENTS USED

During the present experimental analysis following described equipment's and apparatus were used efficiently and handled carefully with proper precautions to avoid any inconvenience during the work. The traveling bridge setup is fitted with five pitot tubes which are unevenlyspaced with an external dia of 4.7mm and also a pointer gauge of least count 0.1mm. The moving bridge is navigated across the meander path to every section and respective reading are taken. The pointer gauge is utilized to analyse the water surface profile across the channel width at every segment. The set of pitot tubes determine the pressure difference at every predefined location across every section. Velocity at those points is the calculated from the pressure difference. All the pitot tubes are connected to five different manometers which are setup on a vertical board having a spirit level. The spirit level assists in maintaining the verticality of the manometers. In the experiments structures like baffle walls, stilling chamber, head gate, travelling bridge, sump, tail gate, volumetric tank, overhead tank arrangement, water supply devices, two parallel pumps etc. are used. A rectangular notch arrangement is positioned at the upstream side of the channel to uphold the flow of water and calculate discharge . For rough bed selection an appropriate size of aggregates are used. Different sizes of sieve i.e. 10mm, 8mm, and 6.7 mm sieve were used for attaining a proper size of aggregate. The retaining of 8mm and 6.7mm were used in the channel for rough bed analysis. For further understanding of the aggregates laid on the channel bed a cylinder was used to calculate the angularity number of the aggregates in the transportation laboratory. The following photographs display the measuring devices used for data collection and the devices used for aggregate selection.

Figure 8.1 Stilling Chamber

Figure 8.2 Depth Measuring Scale

Figure 8.3 Pitot tube Arrangement

Figure 8.4 Manometer Arrangement

Figure 8.5 Moving Bridge Arrangement

Figure 8.6 Pointer Gauge

Figure 8.7 Tail Gate

4.4 EXPERIMENTAL PROCEDURE

4.4.1 POSITION OF MEASUREMENT

All experimental examinations are detailed along a meandering path from the second bend apex to the next bend apex going through the cross-over of the meandering channel. A segment at cross-over perpendicular to both the inner and outer curves of the meandering channel is outlined and amplified unto the extended bend apex line, as shown in Figure 9. An angle of 120^0 is formed for both the bends. This is the cross-over edge of the bend point. The bends are separated into 6 similar sections of 20^0 each to the centreline of the meandering channel. Channel segments along the width i.e. perpendicular lines stretched to both the curves from these points. Sections A and M are the bend apex while section G is the cross-over section.

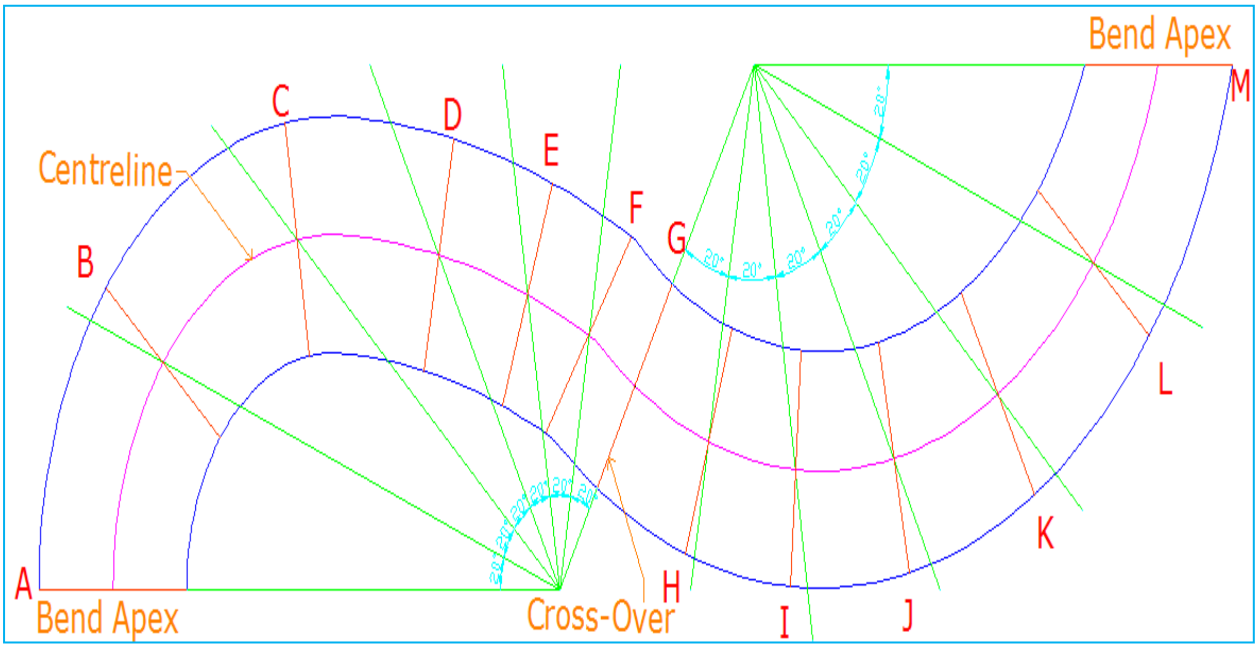


Figure 9 Plan geometry of meandering path

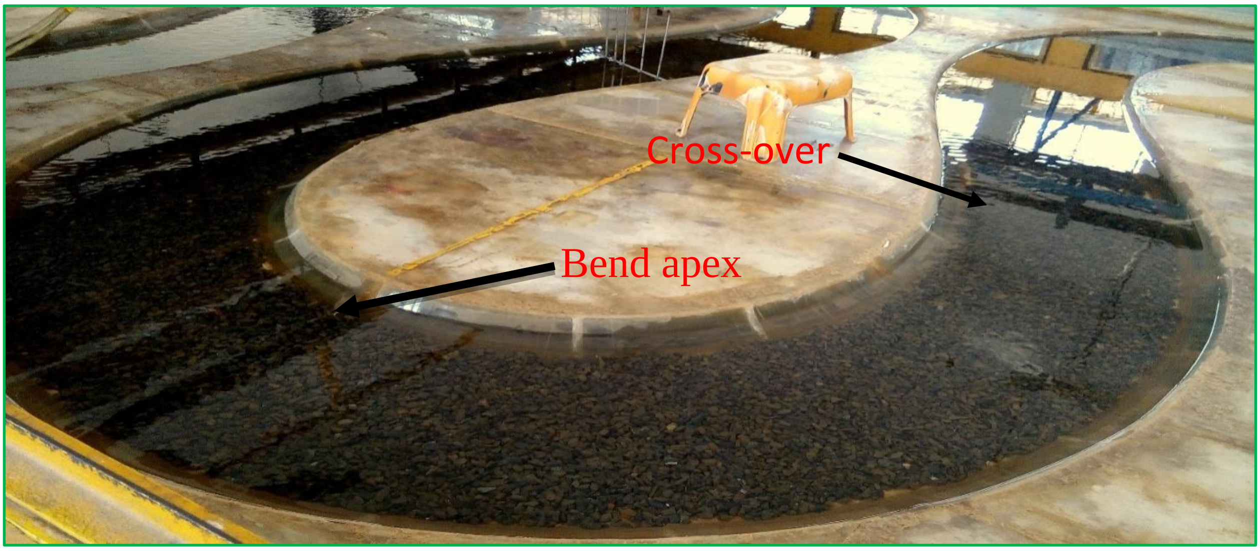


Figure 10 Photograph of meandering path

A steady discharge is kept up while taking the readings for the whole meandering path. Arrangement of Pitot-tubes with moving extension course of action are made to gauge the velocity at diverse purpose of the flow entry of the channel.

The estimations are taken at diverse reaches along the meander path for each area. Experimentation is done from left edge to the right edge of the main channel in the path of flow. The parallel dispersing of the grid points has been considered as 4cm on either side of the centerline.

The Pitot tube is navigated upwards from the bed of the channel. The bed of the channel characterised here is the position of radius of the Pitot tube which is 0.2385cm from the bed. This is accomplished by setting the Pitot tube at the surface of the channel. Readings are noted down at the bed and then moved up by $0.2H$, $0.4H$, $0.6H$, and $0.8H$ from the bed. H here is the average depth of water at the every corresponding section along the meander path. Figure 11 displays the grid diagram worked for the experimental analysis.

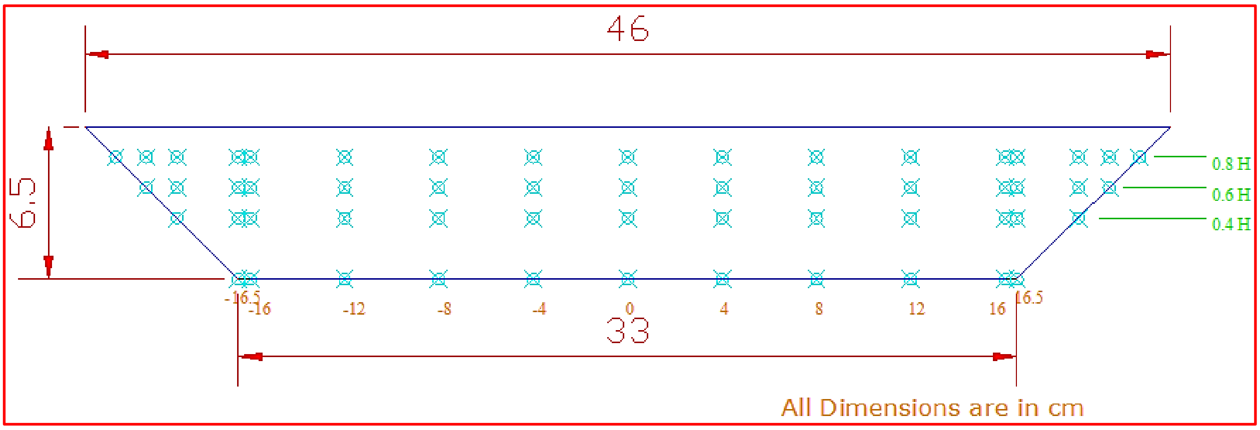


Figure 11 Grid arrangement for velocity measurement

4.4.2 MEASUREMENT OF BED SLOPE

For estimation of bed slope, water level piezometric tube is utilized. The water level taken is from the bed of the flume without considering the thickness of the Perspex sheet. Difference in the two corresponding points was measured. Slope is measured by dividing this level difference with the distance between the observed points. Experimental observation was taken for five points and average was taken for further formulation. The slope calculated is 0.00165, this shows the slope of the flume. To compute the slope of the main channel, the sinuosity of the main channel is divided from the slope of the flume. The sinuosity of the meandering channel being 4.11, the channel slope of the main channel is computed to be 0.00040146.

4.4.3 NOTCH CALIBRATION

Rectangular notch of the flume is used to compute the theoretical discharge into the channel. Before computing the discharge, the notch needs to be standardised with respect to actual discharge from the volumetric tank . The volumetric tank with a cross-sectional area of 208666cm^{2}and has a piezometer connected to it for measurement of the rate of rise in water level. Actual discharge is computed by recording the time taken for rise in unit increase in height of water level in the piezometer.

The volume of water collected at the volumetric tank is given by,

$V_w = A \times h_w$ Eq. (12)

Actual discharge of water collected at the volumetric tank is given by,

$Q_a = V_w / t$ Eq. (13)

Theoretical discharge is given by,

$Q = \frac{2}{3} \times Ln \times \sqrt{2gHn}^{3/2}$ Eq. (14)

Where Hn is the height of water above notch and Ln is the length of the notch(here Ln is 3.4).

The coefficient of discharge is given by,

$C_d = Q_a / Q_{th}$ Eq. (15)

Where, $Q_a$is the actual discharge, $Q_{th}$is theoretical discharge, A is the area of volumetric tank, Vwvolume of water, t time in sec, $C_d$is the coefficient of discharge calculated from notch calibration, $hw$is the height of water in the volumetric tank, and g is the acceleration due to gravity.

From the notch calibration, coefficient of discharge C_d of rectangular notch was found to be 0.66. The discharge is maintained at 5.2 x 10-3 m3/s throughout the experiment.

4.4.4 STAGE DISCHARGE CORRELATION

Stage-Discharge relationship is one of the most vital analysis done by most of the river engineers for betterment of their design and flood management responsibilities. During the present analysis in the meandering channel present in laboratory it was not an easy task to maintain a uniform and steady flow throughout the channel section for experimentation because of the resistance offered from the curvature of channel and the impact of number of unknown geometrical and hydraulic limitations. Regardless of all those deficiencies faced in the channel and for the purpose of analysis an overall uniform flow is assumed to be exist in the channel. A few trial and error attempts were made to maintain the flow depth in the channel run so that the water surface slope remains parallel to the valley slope. In most of the experimentation this simplified method of attaining uniform flow is attempted to achieve which is also synonymous to the work of Shino, Al-Romaih and Knight (1999). By analysing this relationship we are able to relate the efficiency of the meandering channel. The stage of flow here is considered as a normal depth. The stage discharge curves plotted for the rough bed meandering channel of sinuosity 4.11 is shown below in Figure 12. The graph shown below concludes that discharge is directly proportional to the stage in the channel.

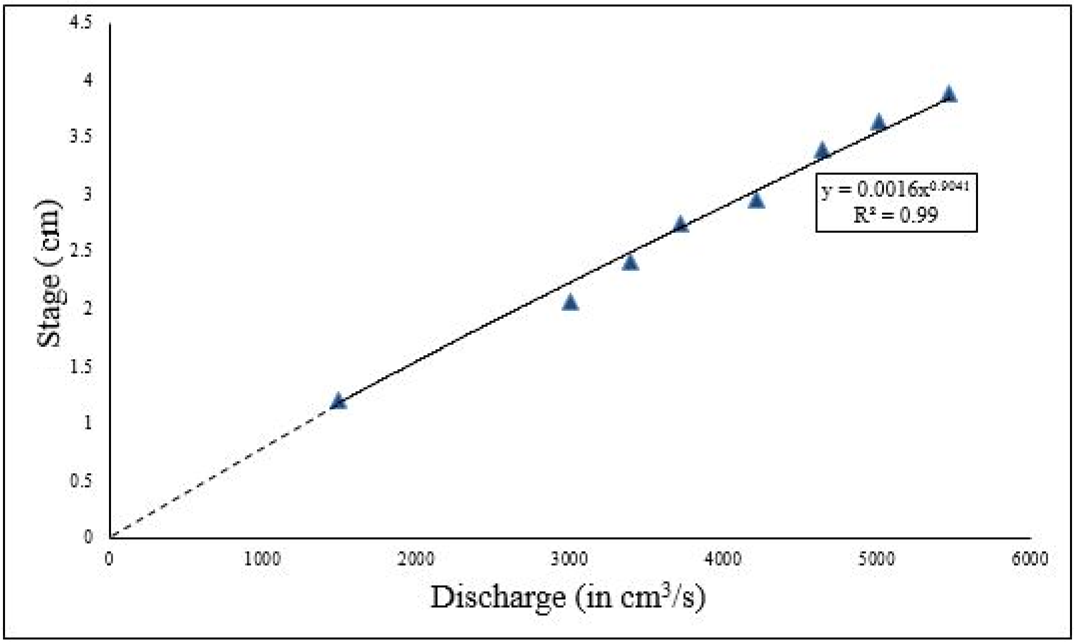


Figure 12 Stage Discharge Relationship

4.4.5 ROUGH MATERIAL USED AND ITS Manning’s *n* CALCULATION

The rough material used in the bed of the experimental simple meandering channel was an appropriate size of aggregate. The aggregates used were sieved thoroughly in the Transportation laboratory of NIT, Rourkela. For sieving purpose we have taken three different size of sieves from the lab. The sieves applied were of size 10mm, 8mm, and 6.7mm. The sieves were arranged in a descending order with a waste retaining pan below.

The aggregates were allowed to pass through those sieves arranged in descending order. For this experimental research we have taken the aggregates those were being retained in the sieve of 6.7mm size. The aggregates were washed properly and laid in the bed of the simple meandering channel with the help of adhesives and maintaining a uniform height throughout the channel. Given below are the photographs of the sieve analysis done for the aggregates.

Figure 13- Photo of 8mm sieve

Figure 14- Photo of 6.7mm sieve

Figure 15- Photo of 10mm sieve

Figure 16- Photo of aggregate

For Manning’s *n* calculation the selected size of aggregates that was to be used in the experimental research was arranged in the main channel of a straight channel. The aggregates were uniformly laid in the straight channel maintaining a proper height with respect to the main channel height throughout the channel.

The dimensions of the straight channel comprises of main channel width being 0.33m and depth of main channel is0.11m with side slope of 1:1 and bed slope being 0.0002.

A depth of flow was maintained along the main channel and the corresponding actual discharge was calculated from the volumetric tank. 10 such depths were maintained along the channel and their respective actual discharges were calculated. Knowing the actual discharge the Manning's *n* was formulated using the below given equations,

$$Qa = V \times A \qquad \text{Eq. (16)}$$

$$V=1/n \times R^{2/3} \times S^{1/2} \qquad \text{Eq. (17)}$$

$$R= A/P \qquad \text{Eq. (18)}$$

$$\text{So, } Qa = 1/n \times (A/P)^{2/3} \times S^{1/2} \times A \qquad \text{Eq. (19)}$$

From the above equations it was efficiently calculated and the average value of those ten calculated Manning's *n* was found to be 0.013.

4.4.6 LONGITUDINAL VELOCITY MEASUREMENT

Pitot tubes are operated for the computation of velocity. Five Pitot-tube setup is used for the experimental analysis. The Pitot tubes are connected to individual manometers positioned on a vertical board. The spirit level keeps themanometers in the vertical level .

The Pitot-tubes and manometers are connected with the help of small dia pipes. Air bubbles in the small pipes are driven out manually.

Pitot tubes are positioned in the opposite direction of flow perpendicular to it. The pressure difference at each position decided previously of the channel section along the meander path is obtained.

The point velocity computed by $v = \sqrt{2}gh$ where g is acceleration due to gravity and h is the difference in pressure noted down from manometers.

Here the tube coefficient is considered as unit and the error due to turbulence assumed negligible while computing velocity.

The velocity data are obtained at the bed (0.2385cm from bed) and then moved up by $0.2H$, $0.4H$, $0.6H$ and $0.8H$ from the bed. Here H is the average flow depth of water at the every corresponding section along the meander path. No slip condition is considered and the velocity at surface is assumed to be zero.

Figure 17 Photograph during Velocity Measurement

Figure 18 Depth Adjustment from Moving Bridge

CHAPTER 5

RESULTAND DISCUSSION

5.1 GENERAL

This chapter is the cream among rest of the chapters described thoroughly in this thesis work. The aim of this chapter is to clarify the fruitful outcome of the rigorous experimentation done in the laboratory and to assess the capability of the computational model in reproducing the flow characteristic and mechanism associated with the simple rough bed meandering channels inbank flow. This current section will show the consequences of the experimental tests done in the form of stage-discharge relationship, longitudinal velocity distribution along the width and depth of the rough bed channel.

The statistical and graphical results of the vertical velocity profiles observed along the thirteen sections of the rough bed meandering channel is compared with other researchers graphical analysis on smooth bed meandering channel.The computational outcome of the experimental results used in the software CCHE is well portrayed with respective figures showing output of the experimental data used in the numerical model as boundary condition.

5.2 DISTRIBUTION OF LONGITUDINAL VELOCITY

Precise expectation of velocity distribution in channels is vital for flood related studies and estimation of stage discharge relationship in normal channels. Regularly for straight forwardness in river engineering design practice the velocity is viewed as uniform and investigation is done considering momentum or energy approach. In the present scenario for experimentation in the rough meandering channel for velocity calculation along the meander path we have considered a discharge of 5.2 x 10^{-3} m^3/s during the complete analysis .The most common method of experimentation is done here to calculate the longitudinal velocity along the path at each sections i.e. 13 sections. To calculate the point velocities at the defined sections a device commonly used is the Pitot static tube. A set of pitot tubes i.e. five pitot tubes are positioned unevenly within the bank of the channel. The Pitot tube arrangement is moved at 4cm intervals on either side of the centreline of the meandering channel. The detailed velocity distribution is carried out experimentally from one bend apex to its subsequent bend apex for a better understanding of the flow characteristics of a highly sinuous rough meandering channel with sinuosity 4.11. The longitudinal velocity distribution is analysed along the depth of the channel at 9 positions along the width of the channel.

The following figures from 19.1 to 19.13 represent the vertical velocity profile along the channel depth at nine positions along the width of channel of all the 13 sections of the meandering path graphically.

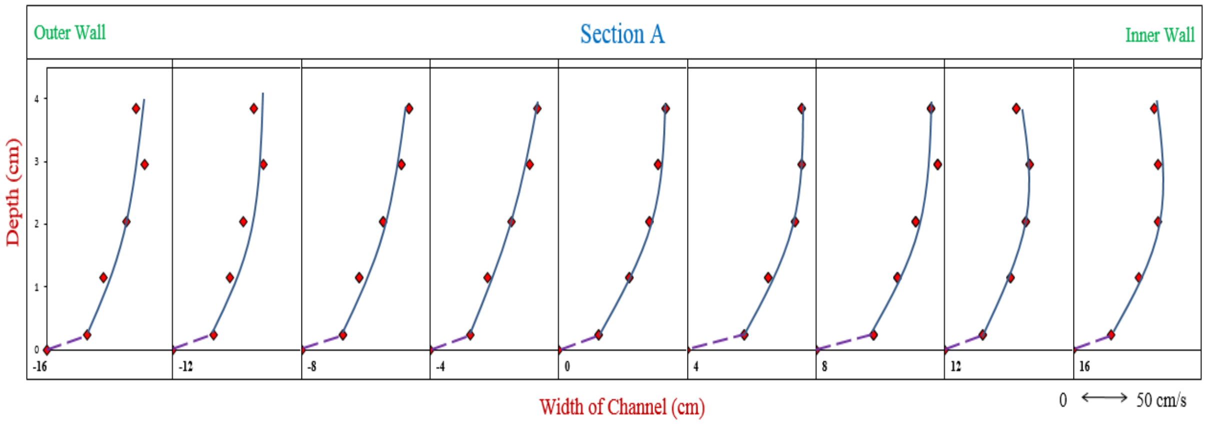


Figure19.1

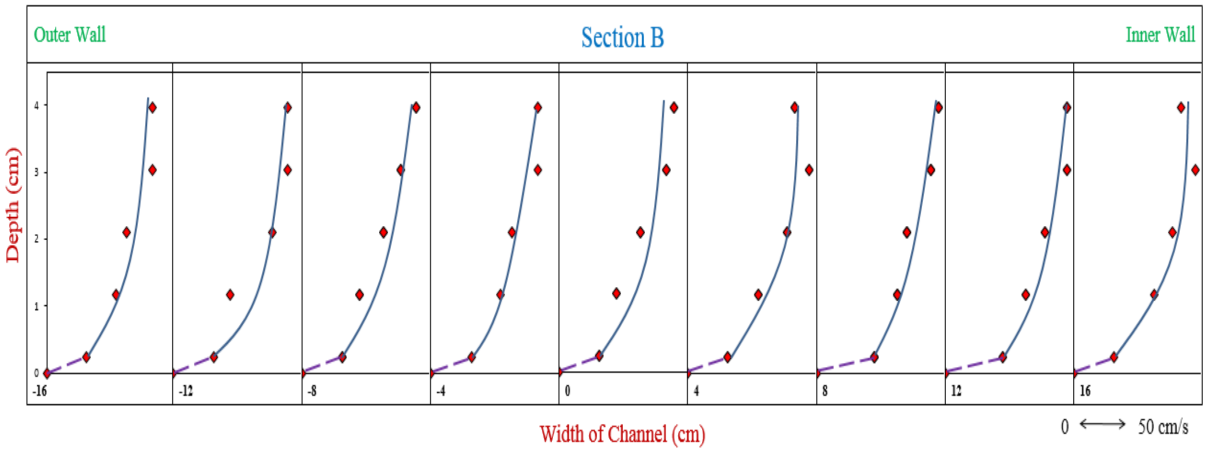


Figure 19.2

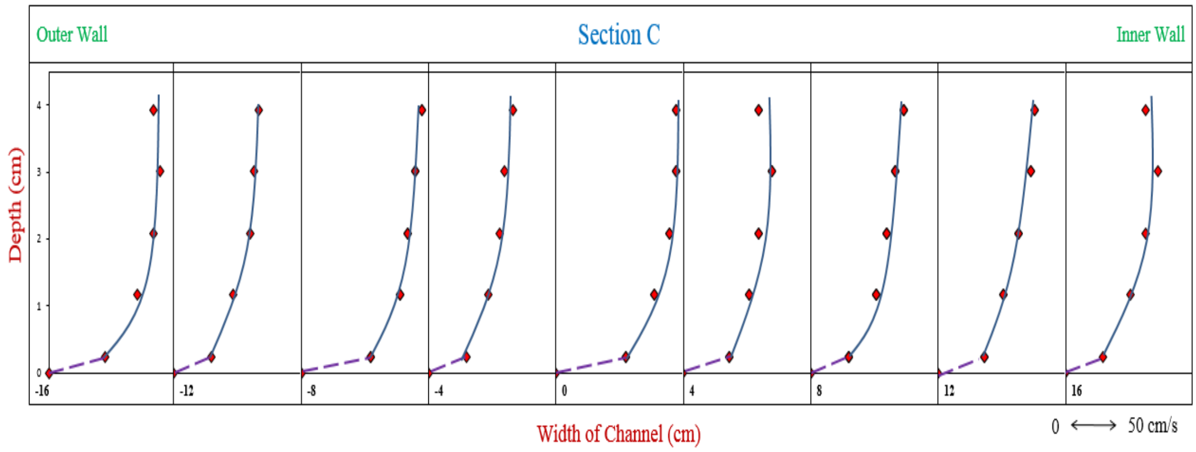


Figure 19.3

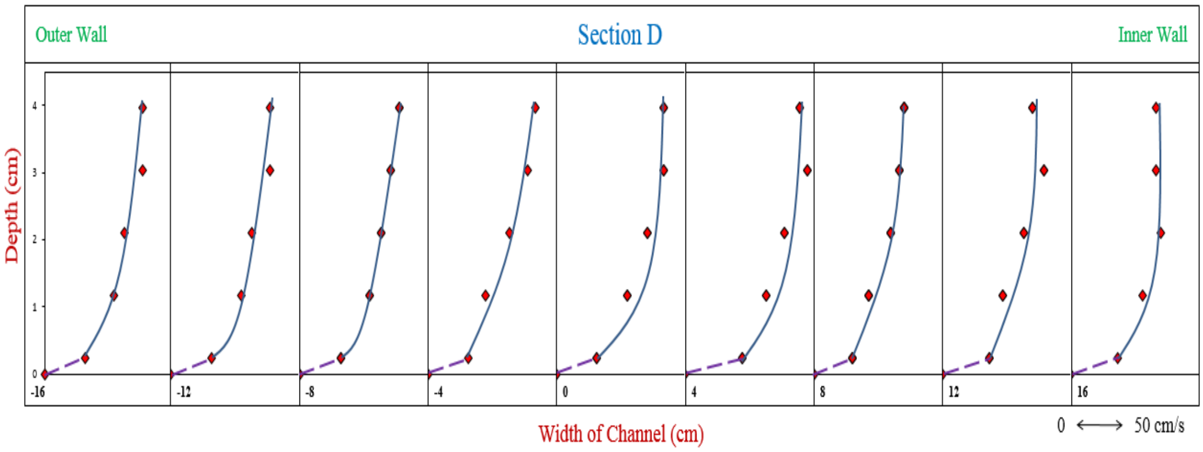


Figure 19.4

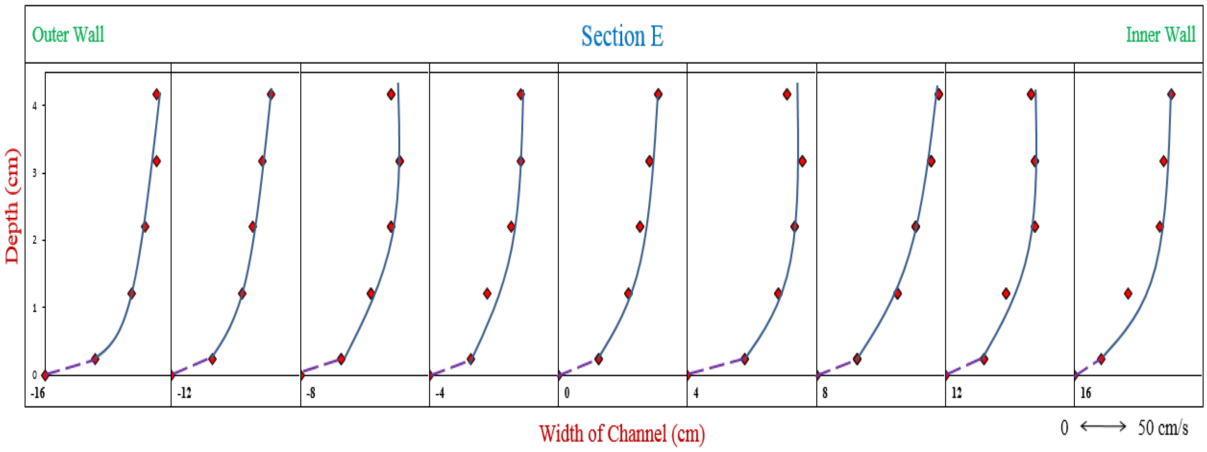


Figure 19.5

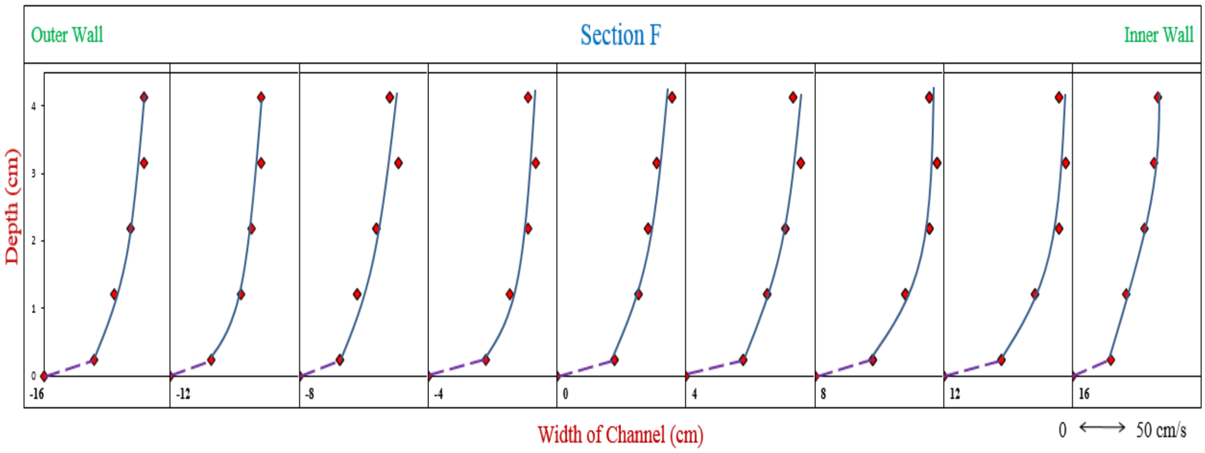


Figure 19.6

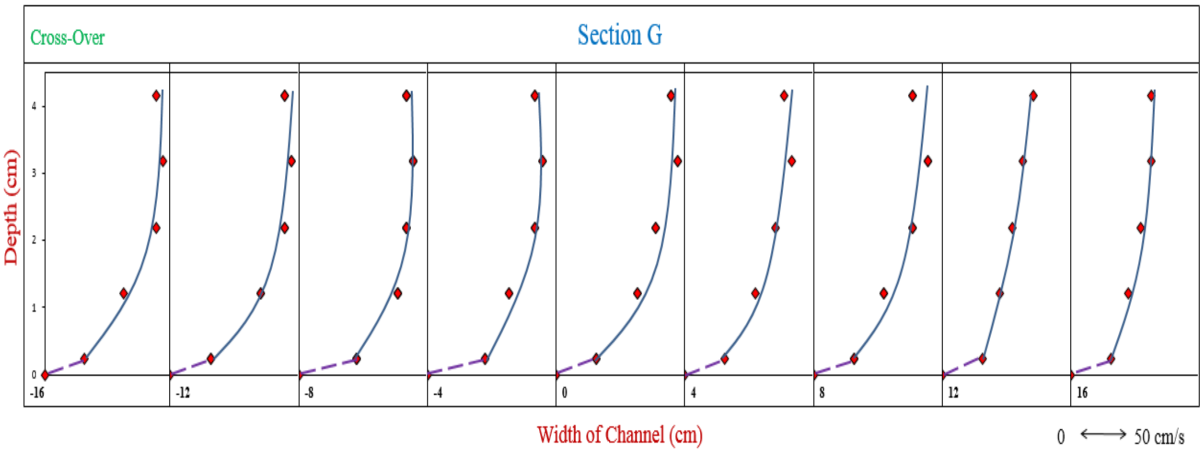


Figure 19.7

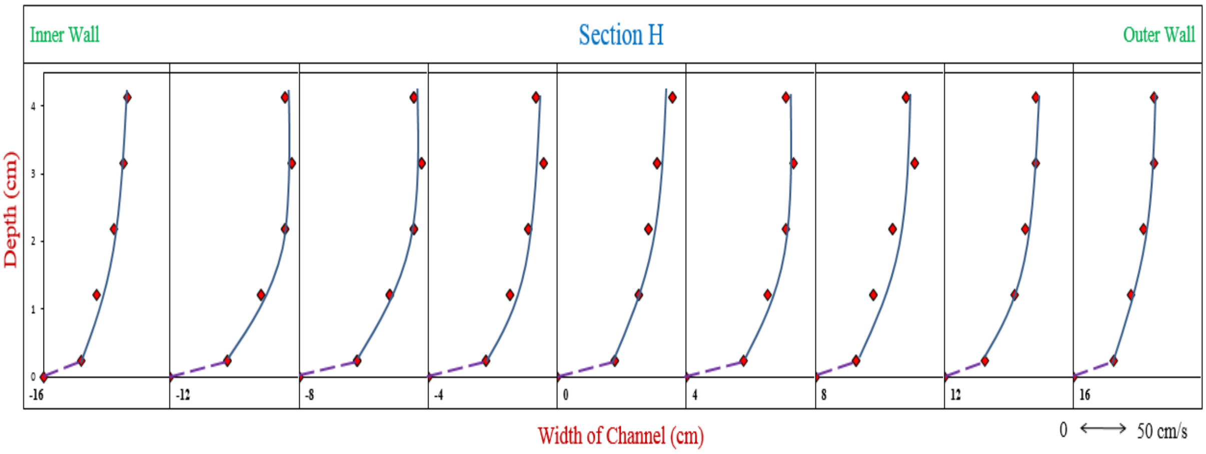


Figure 19.8

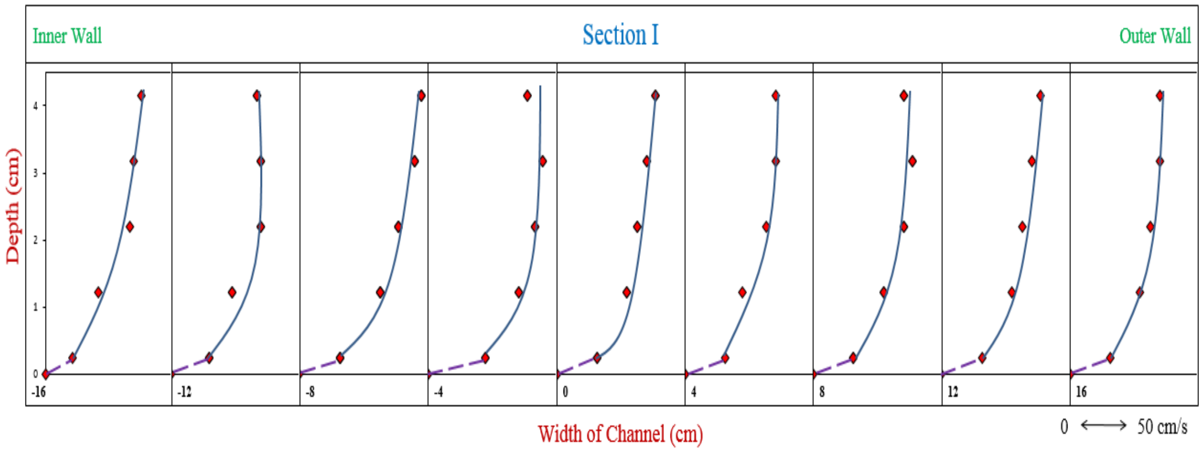


Figure 19.9

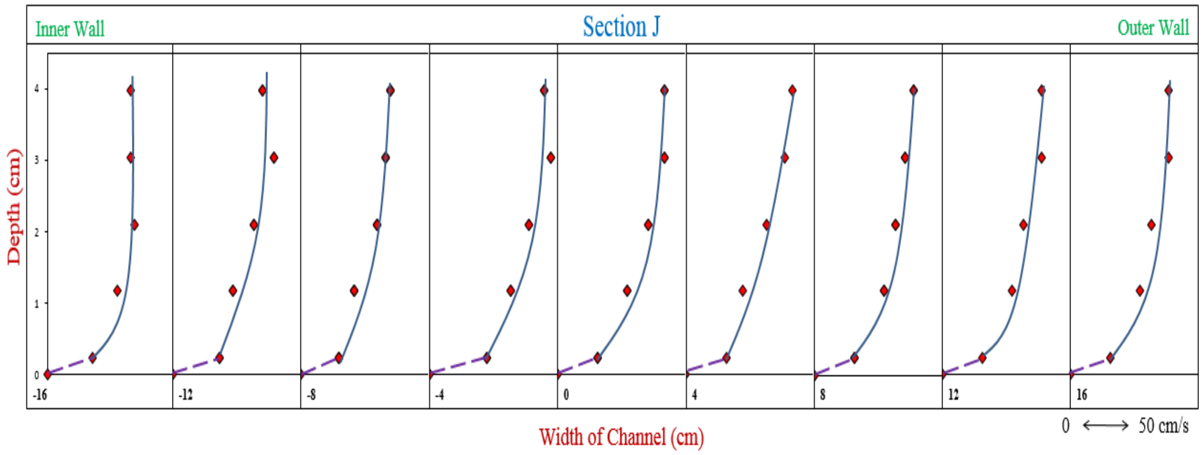


Figure 19.10

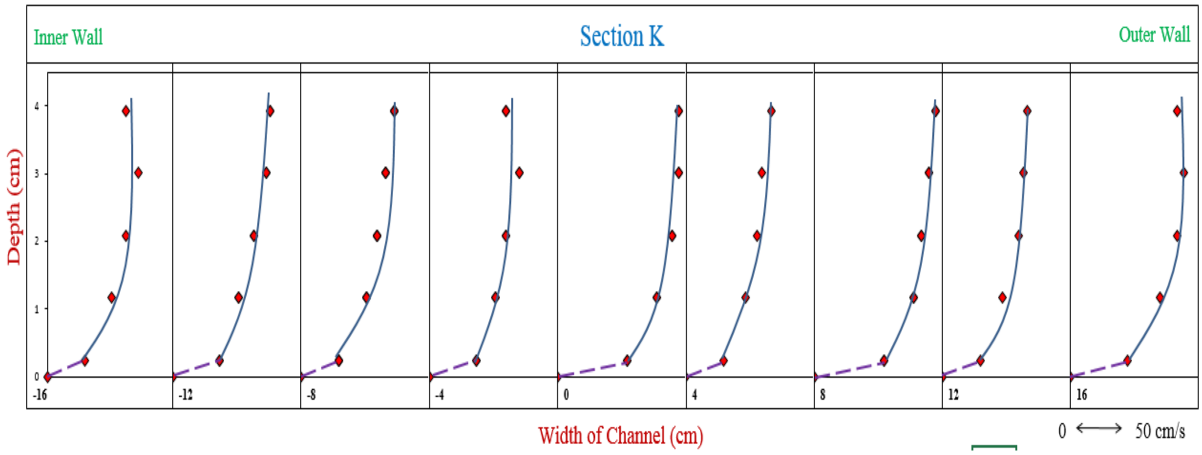


Figure 19.11

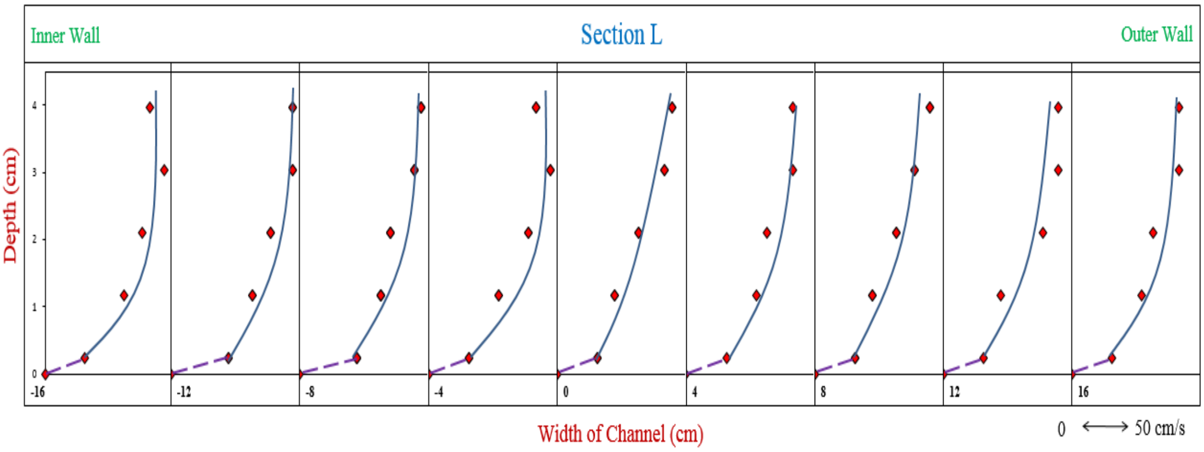


Figure 19.12

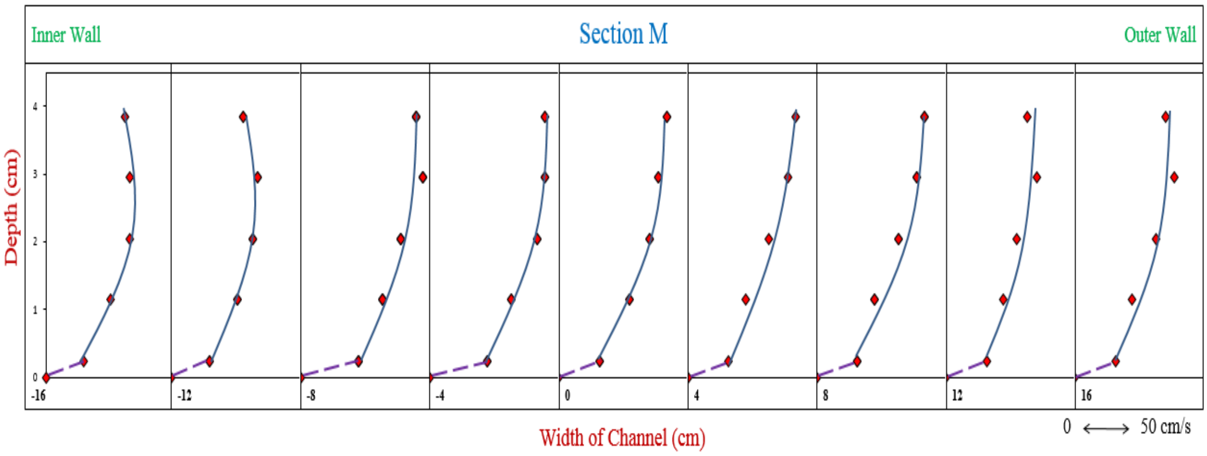


Figure 19.13

Figure 19.1-19.13: Vertical Velocity Profile Plots for all 13 sections along the Meander Path

5.2.1 VELOCITY CONTOURS

To view a clear and colourful picturisation of the distribution of vertical velocity profiles in the outer and inner wall of the channel of all the 13 sections velocity contours are plotted. Velocity contours are made with the help of Surfer software. Velocity contours are plotted by taking velocity in the x-direction and depth of flow in the y-direction.

The following figures from 20.1 to 20.13 represent the contour plots shown in alphabetic manner from the experimental observation taken along the depth of channel.Each section shown below has the vertical velocity profiles at 9 positions across the channel section taken 4cm from either side of the centerline. The plots shown below is a result of the experimental velocity data recorded at bed and points on 0.2H, 0.4H, 0.6H, and 0.8H from bed along the channel.

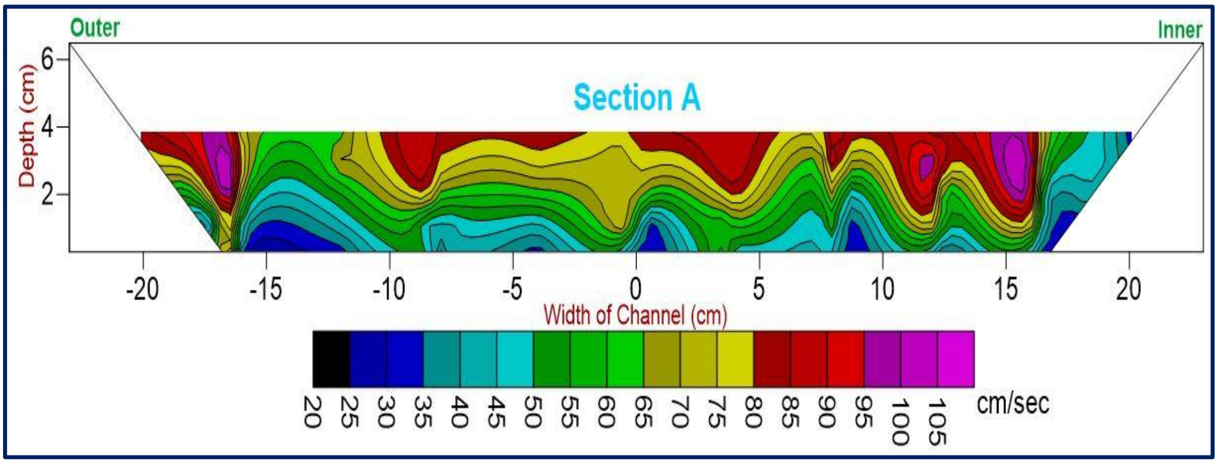


Figure 20.1

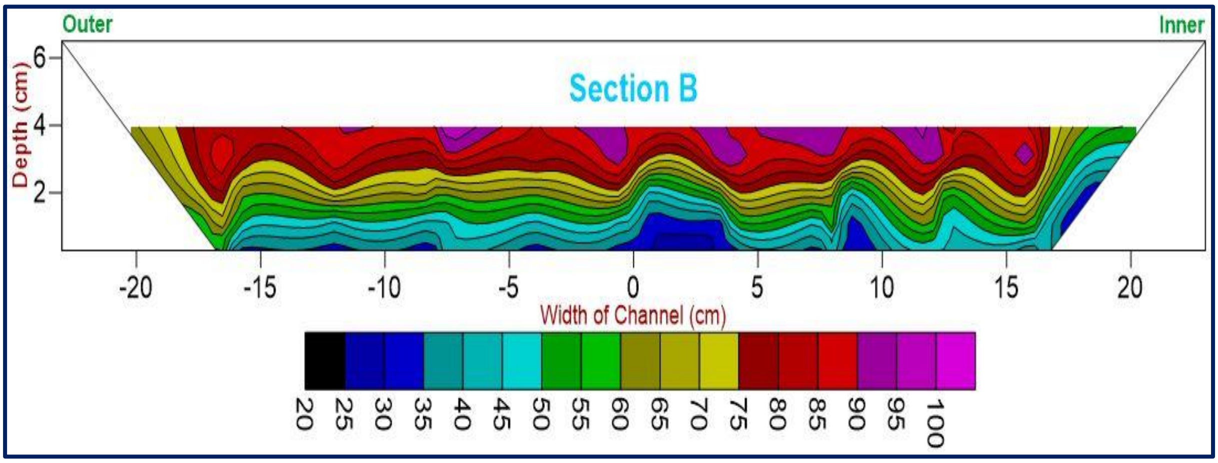


Figure 20.2

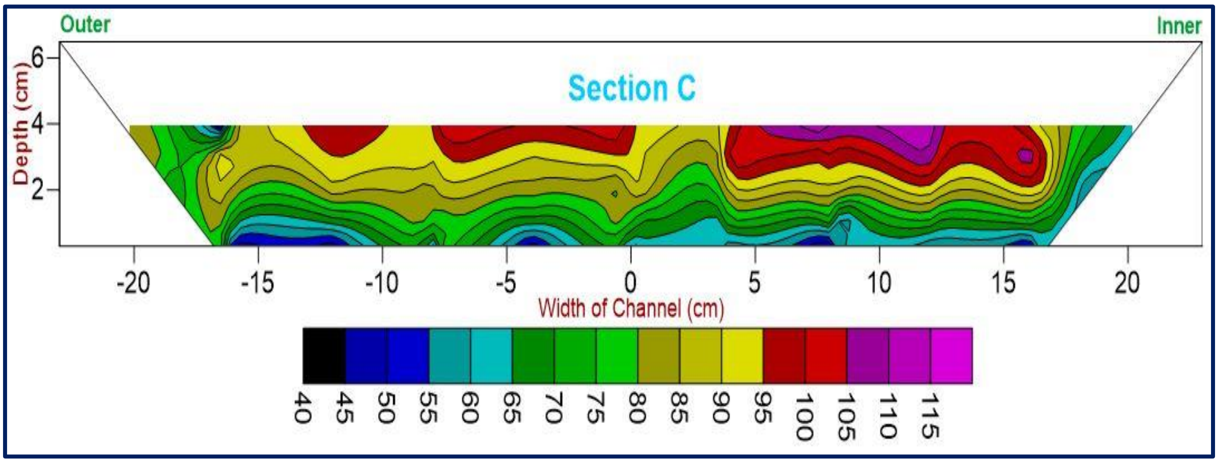


Figure 20.3

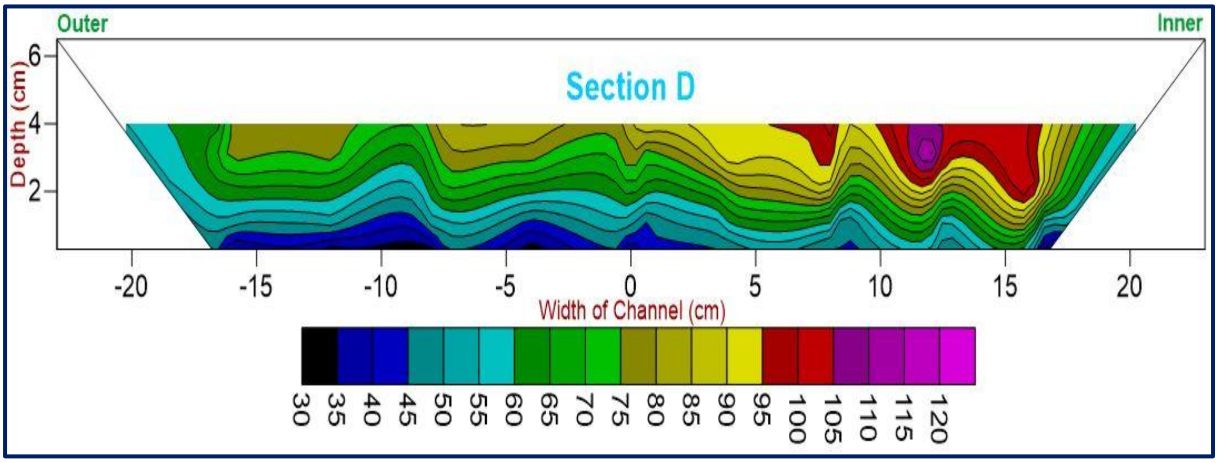


Figure 20.4

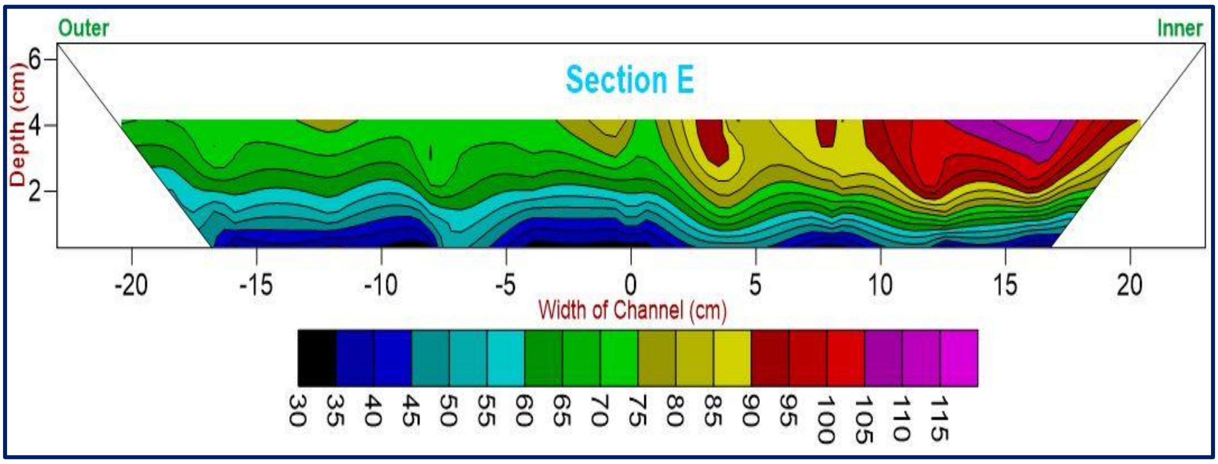


Figure 20.5

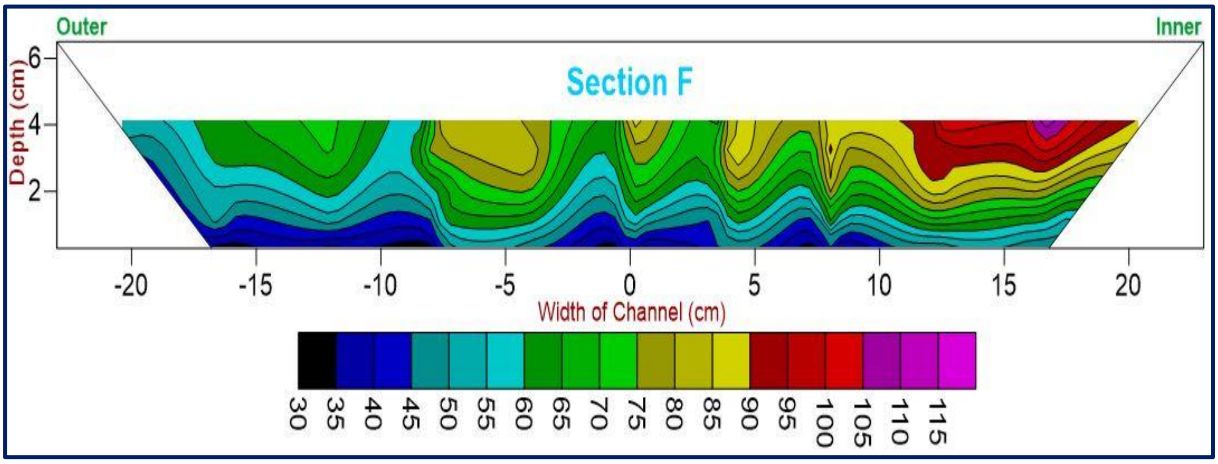


Figure 20.6

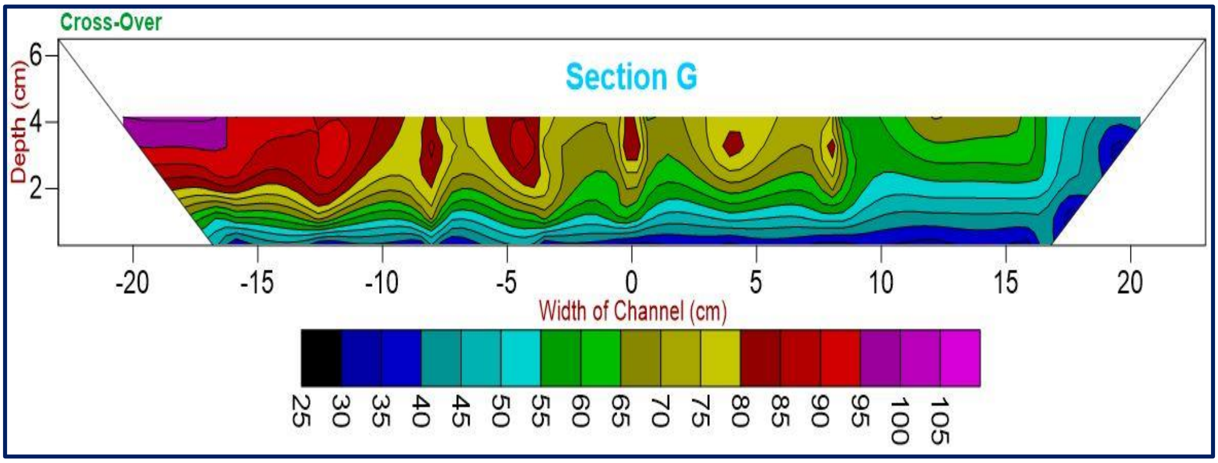


Figure 20.7

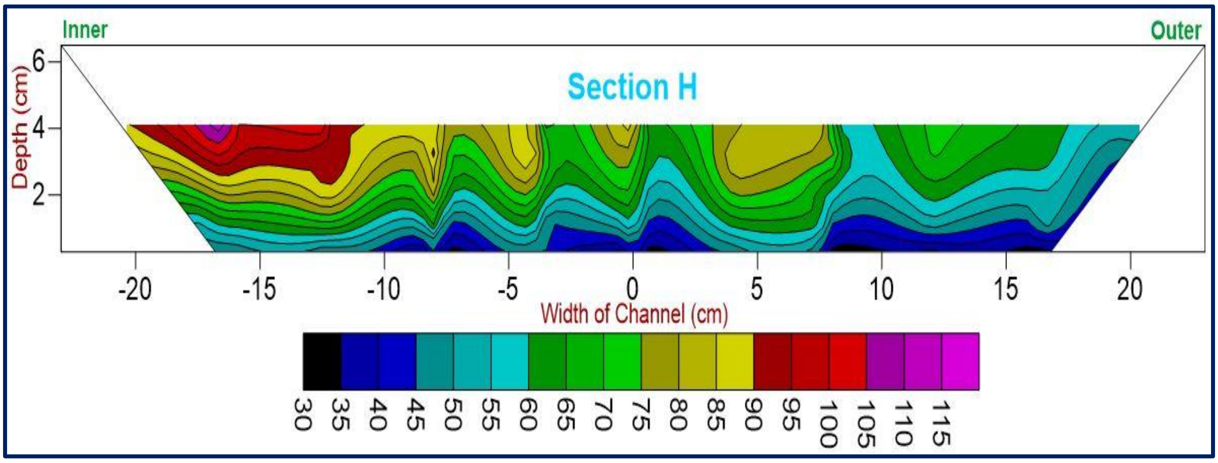


Figure 20.8

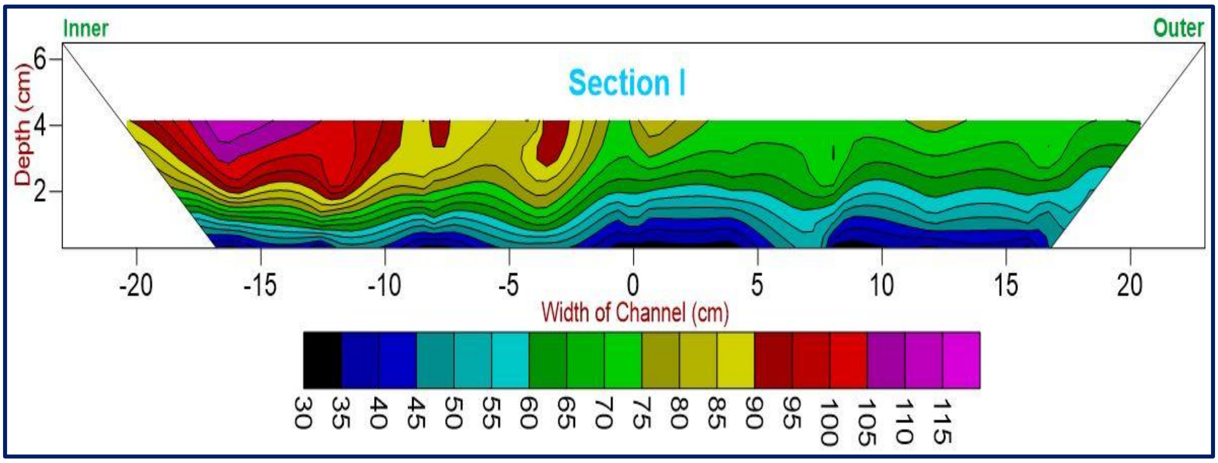


Figure 20.9

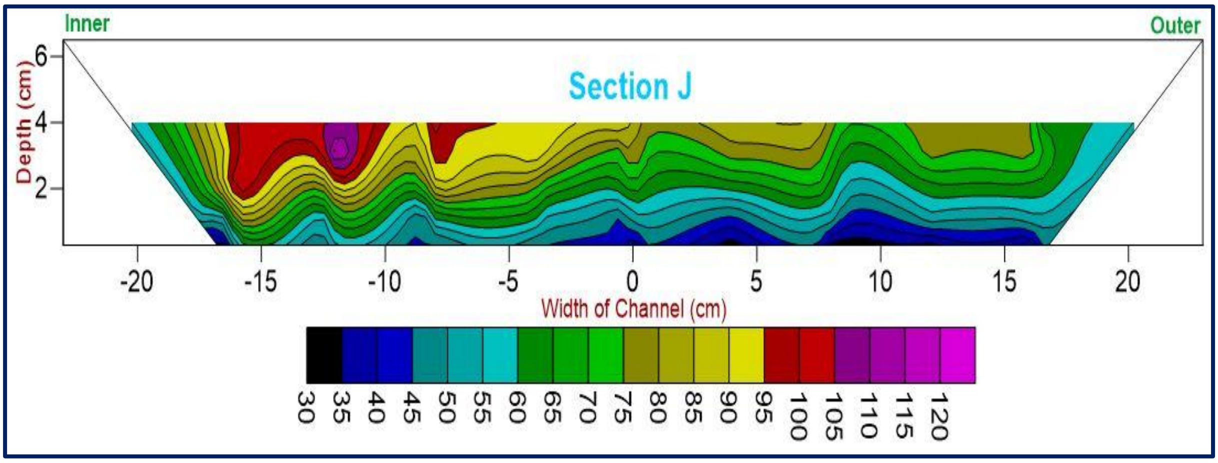


Figure 20.10

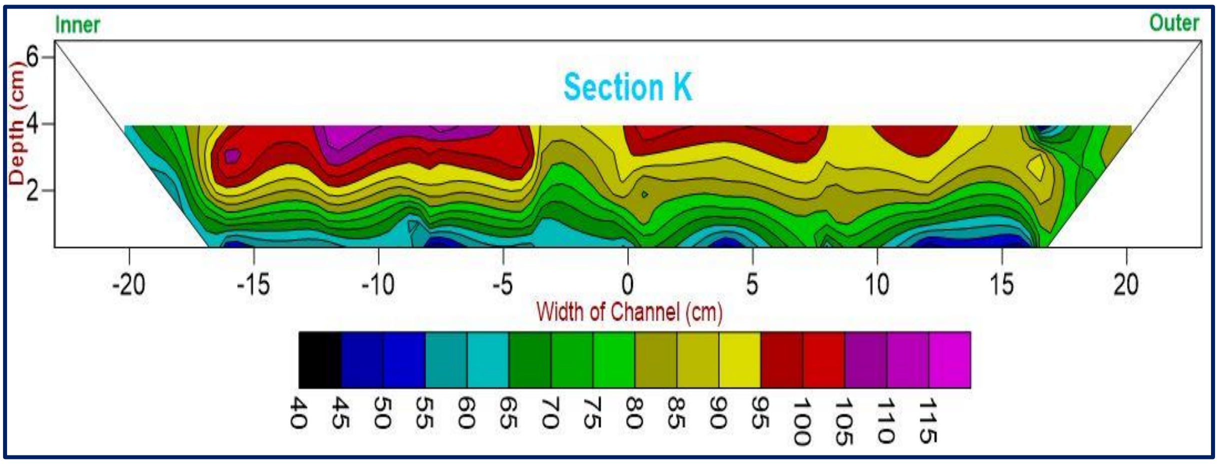


Figure 20.11

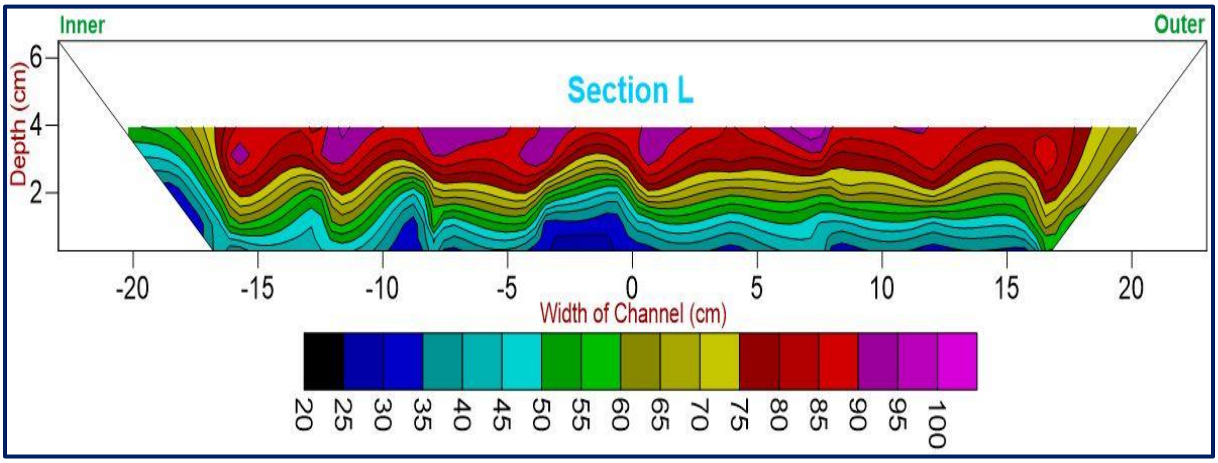


Figure 20.12

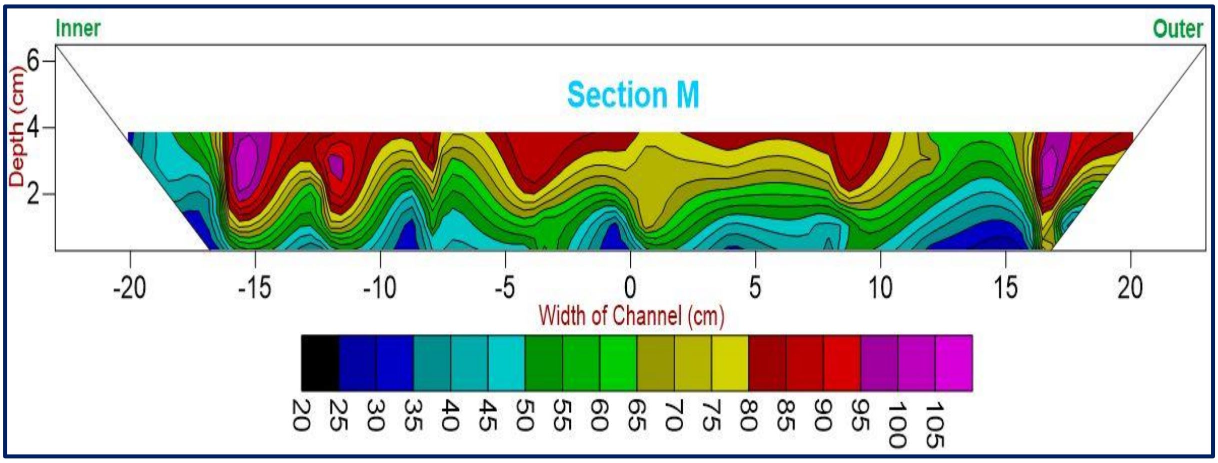


Figure 20.13

Figure 20.1-20.13: Velocity Contour Plots for all 13 sections along the Meander Path

The following inferences can be made from the vertical velocity profile plots shown above both graphically and with contour plots.

1. The velocity contour diagram of section A, as given in Fig. 20.1 shows that higher longitudinal velocity lies towards the right bank or the inner wall of the channel section. The vertical velocity profiles at the same section (Fig. 19.1), depicts the similar pattern. It was seen the velocity profile to be bulgier at the inner wall than at outer wall.

2. From figure 20.1 to 20.3 it is seen the maximum velocity moves from section A to section C. The maximum local velocity initially moves close to the surface, which latter moves towards the top surface of section C.
3. The maximum velocity at section C is found to be always higher, i.e. close to 120 cm/s as compared to the other sections until the cross-over in the meandering path.
4. From fig. 19.1 to 19.6, i.e. from section A to F, it is seen that the velocity remains higher in the inner bank as related to the outer bank. Non-uniformity in velocity is observed in these sections.
5. In fig. 20.7 and 19.7 it is seen that the change of velocity between the inner and outer walls is very less at the cross-over section G. However, the local maximum velocity of about 110 cm/s is found to be somewhere towards the outer region.
6. The bend apex sections A and M have the maximum degree of curvature. Here it is seen the maximum velocity to be lying close to the inner wall.
7. The sections D and J as seen in Fig. 20.4 and 20.10, have maximum velocity throughout the channel, close to 125 cm/s. Such observation is due to the curvature of the meander path, moving towards the cross-over.
8. The sections B and L which are incidentally closer the bend apex region as seen in figure 20.2 and 20.12 the velocity seems to be higher at the regions closer towards the free surface along the width of the channel.

5.3 VERTICAL VELOCITY PROFILE TRENDS OF A MEANDERING CHANNEL

Analysis was done to observe the trend by longitudinal velocity profiles as represented in above figures . The “logarithmic law” formulation for the velocity profile in turbulent open channel flow which is based on Prandtl’s (1926) theory of the “law of the wall” and the “boundary layer” concept is commonly adopted for velocity distribution. An alternative function for the velocity distribution is the “power law”. The general form of this law is proposed as (Barenblatt and Prostokishin, 1993; Schlichting, 1979):

$$u+ = C_4(z+)^m \qquad \text{Eq. (20)}$$

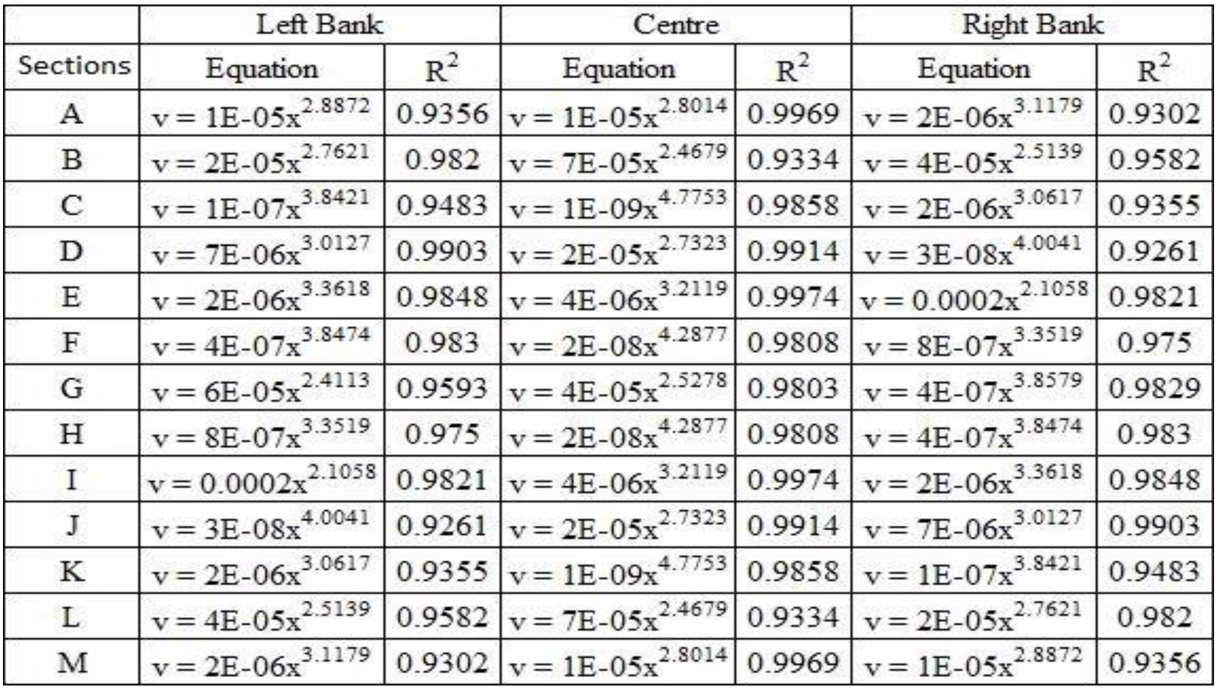
Where C_4 and m are the coefficient and exponent of the power law. In this graphical analysis of longitudinal velocity in a rough meandering channel the velocity distribution was found to obey the power law.

Each section experimented comprised of nine velocity profiles along the width, of which the centre, left bank, and right bank profiles were considered. A best fit curve for each such profiles at every section along the meander path were examined. The best fit curve for each such profiles were found to be power function. The R^2 value calculated in relation to the power function was found to be varying between 0.9261 to 0.9974. So the vertical velocity profile may be considered by the equation given below as,

$$\mathbf{v = a \times x^n} \qquad \text{Eq. (21)}$$

The vertical velocity profile of the rough meandering channel seems to be very different as compared to smooth meandering channel. Given below are the power equations of individual sections of the meander path considered for experimentation in the rough channel. The proposed equations take adequate care of the effect of longitudinal velocity during the flow in rough meandering channel. The equations are so formed to be in good agreement with the experimental data. The following table displays equations formulated for each section considered in the meander path during experimentation.

Table 2 EQUATIONS FORMULATED FOR EACH SECTION



	Left Bank		Centre		Right Bank	
Sections	Equation	R^2	Equation	R^2	Equation	R^2
A	$v = 1E\text{-}05x^{2.8872}$	0.9356	$v = 1E\text{-}05x^{2.8014}$	0.9969	$v = 2E\text{-}06x^{3.1179}$	0.9302
B	$v = 2E\text{-}05x^{2.7621}$	0.982	$v = 7E\text{-}05x^{2.4679}$	0.9334	$v = 4E\text{-}05x^{2.5139}$	0.9582
C	$v = 1E\text{-}07x^{3.8421}$	0.9483	$v = 1E\text{-}09x^{4.7753}$	0.9858	$v = 2E\text{-}06x^{3.0617}$	0.9355
D	$v = 7E\text{-}06x^{3.0127}$	0.9903	$v = 2E\text{-}05x^{2.7323}$	0.9914	$v = 3E\text{-}08x^{4.0041}$	0.9261
E	$v = 2E\text{-}06x^{3.3618}$	0.9848	$v = 4E\text{-}06x^{3.2119}$	0.9974	$v = 0.0002x^{2.1058}$	0.9821
F	$v = 4E\text{-}07x^{3.8474}$	0.983	$v = 2E\text{-}08x^{4.2877}$	0.9808	$v = 8E\text{-}07x^{3.3519}$	0.975
G	$v = 6E\text{-}05x^{2.4113}$	0.9593	$v = 4E\text{-}05x^{2.5278}$	0.9803	$v = 4E\text{-}07x^{3.8579}$	0.9829
H	$v = 8E\text{-}07x^{3.3519}$	0.975	$v = 2E\text{-}08x^{4.2877}$	0.9808	$v = 4E\text{-}07x^{3.8474}$	0.983
I	$v = 0.0002x^{2.1058}$	0.9821	$v = 4E\text{-}06x^{3.2119}$	0.9974	$v = 2E\text{-}06x^{3.3618}$	0.9848
J	$v = 3E\text{-}08x^{4.0041}$	0.9261	$v = 2E\text{-}05x^{2.7323}$	0.9914	$v = 7E\text{-}06x^{3.0127}$	0.9903
K	$v = 2E\text{-}06x^{3.0617}$	0.9355	$v = 1E\text{-}09x^{4.7753}$	0.9858	$v = 1E\text{-}07x^{3.8421}$	0.9483
L	$v = 4E\text{-}05x^{2.5139}$	0.9582	$v = 7E\text{-}05x^{2.4679}$	0.9334	$v = 2E\text{-}05x^{2.7621}$	0.982
M	$v = 2E\text{-}06x^{3.1179}$	0.9302	$v = 1E\text{-}05x^{2.8014}$	0.9969	$v = 1E\text{-}05x^{2.8872}$	0.9356

5.4 A COMPARATIVE ANALYSIS OF SMOOTH AND ROUGH MEANDERING CHANNEL

In this thesis work a comparison is made between the flow analysis done in a smooth and rough meandering channel. For the comparison I have considered the graphical analysis of a smooth bed meandering channel along the meander path experimented by Pradhan (2014) having same geometrical parameters.

The velocity profile is studied against reverse aspect ratio at each section along the meander path. The results of both the analysis were studied graphically and are presented over here in the following figures.

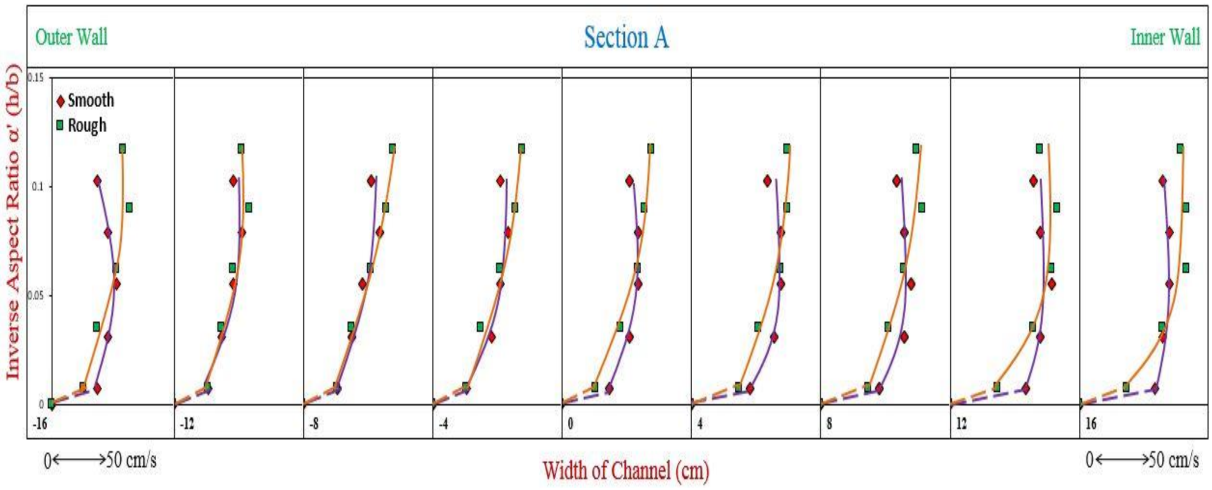


Figure 21.1

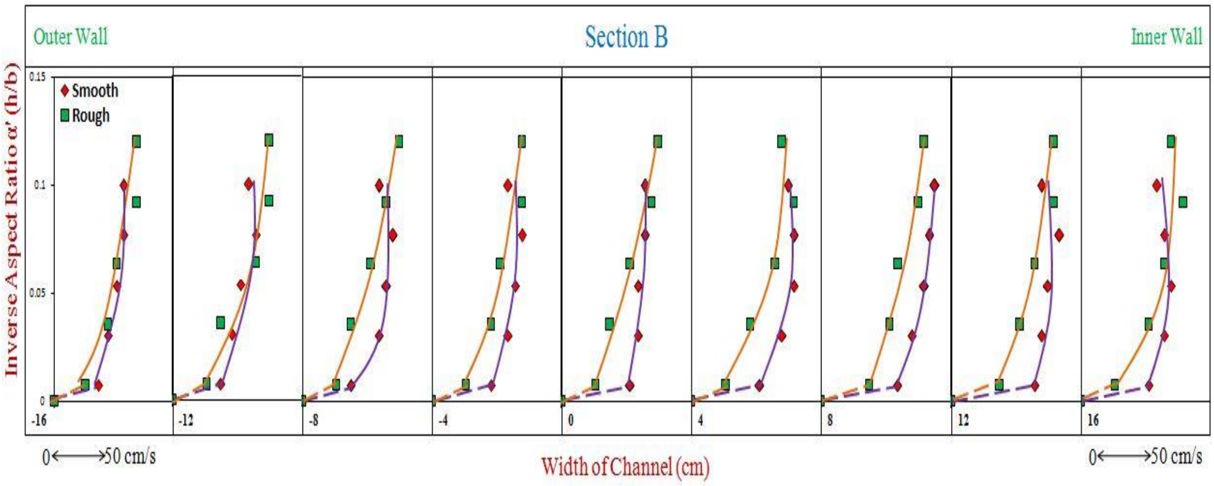


Figure 21.2

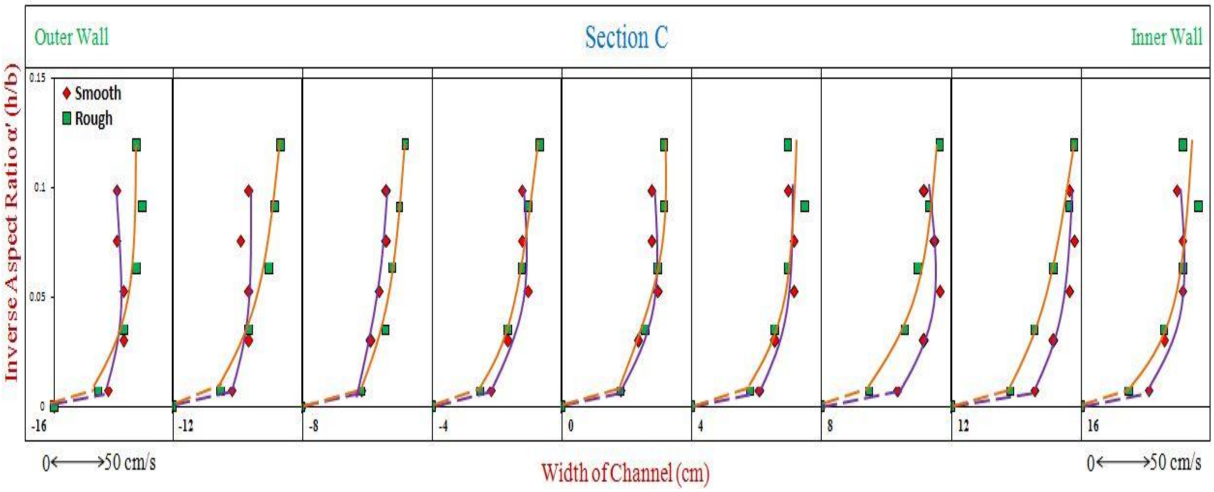


Figure 21.3

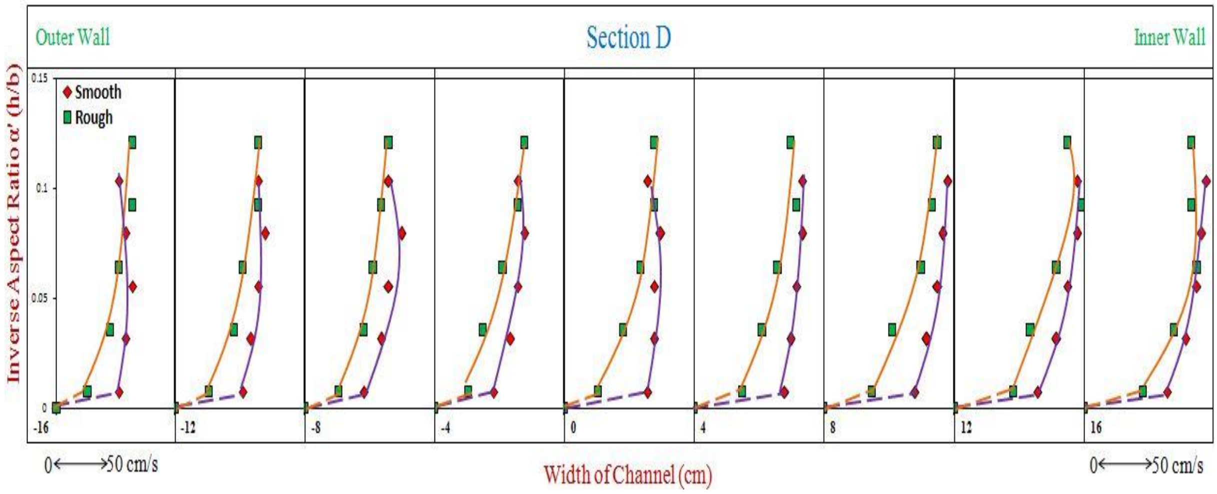


Figure 21.4

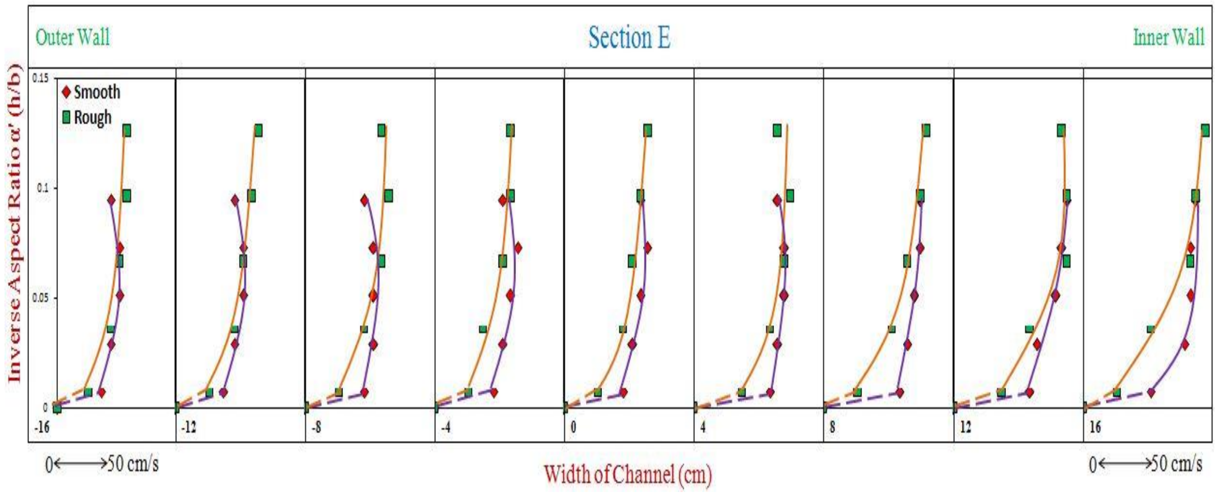


Figure 21.5

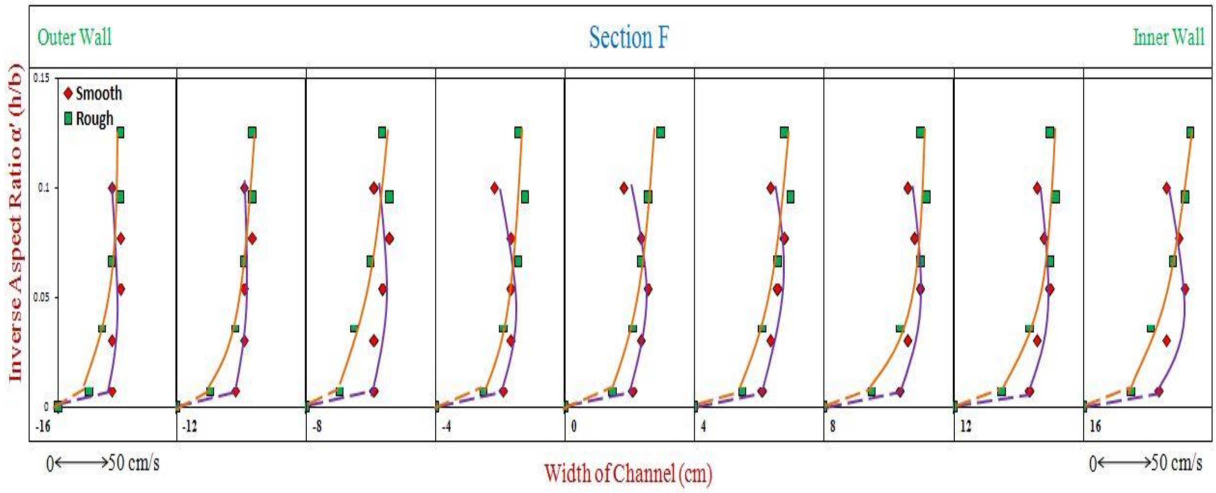


Figure 21.6

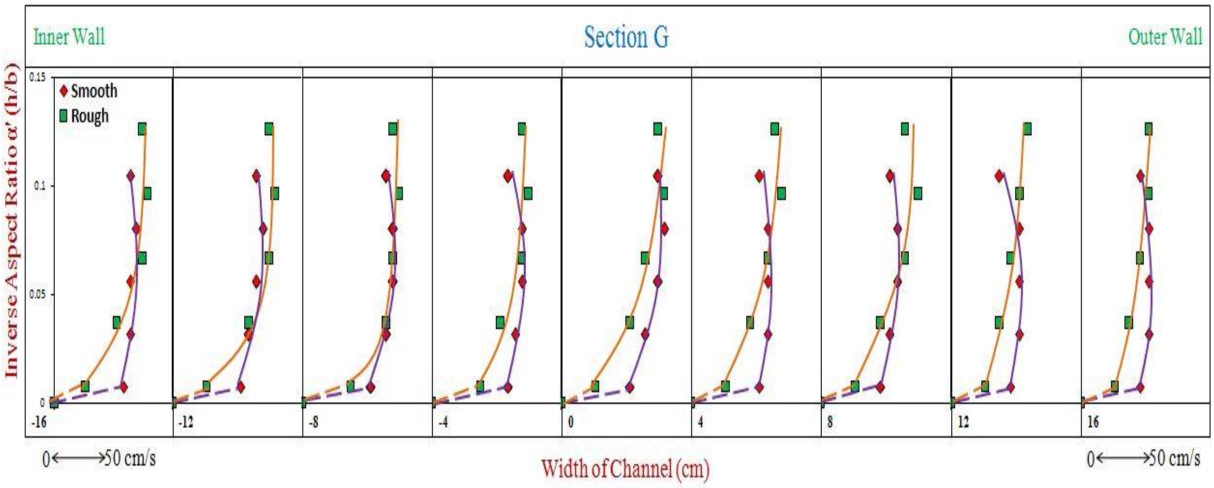


Figure 21.7

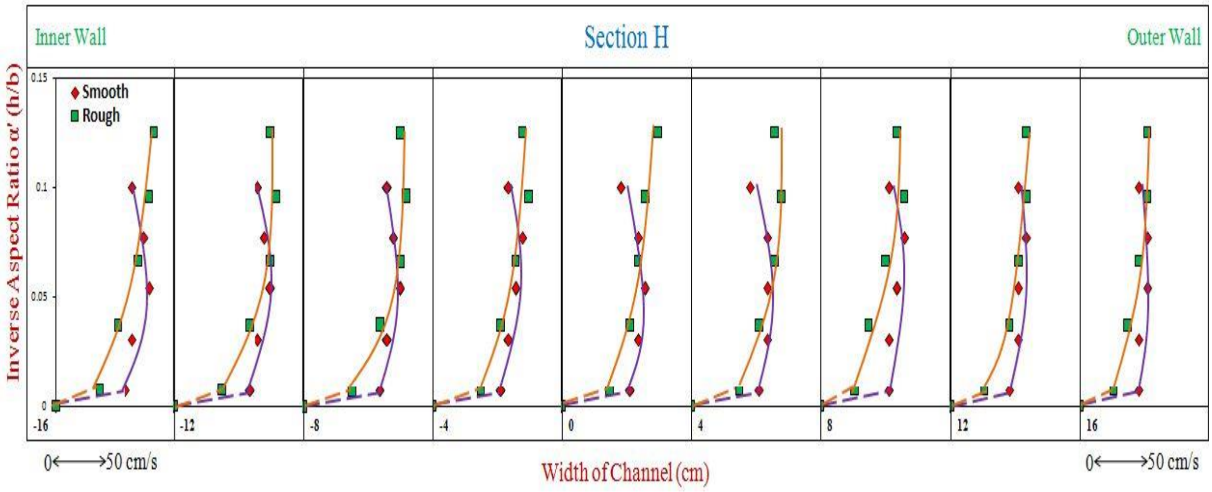


Figure 21.8

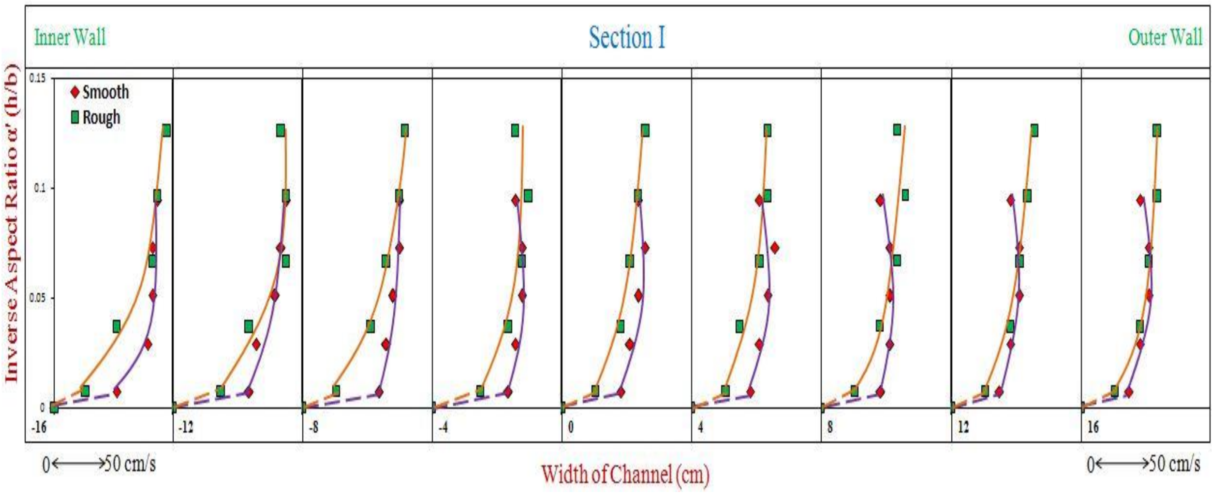


Figure 21.9

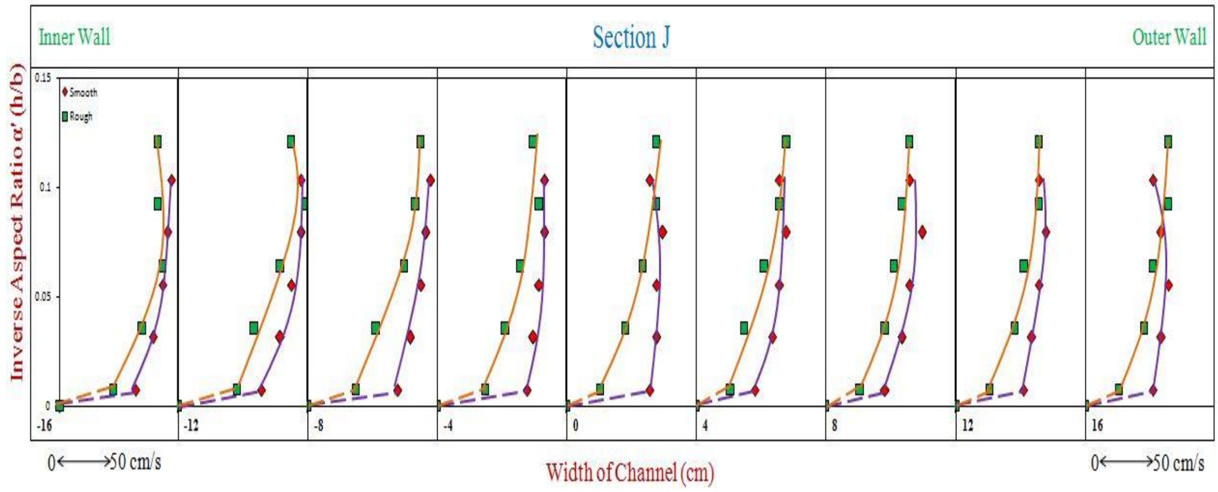


Figure 21.10

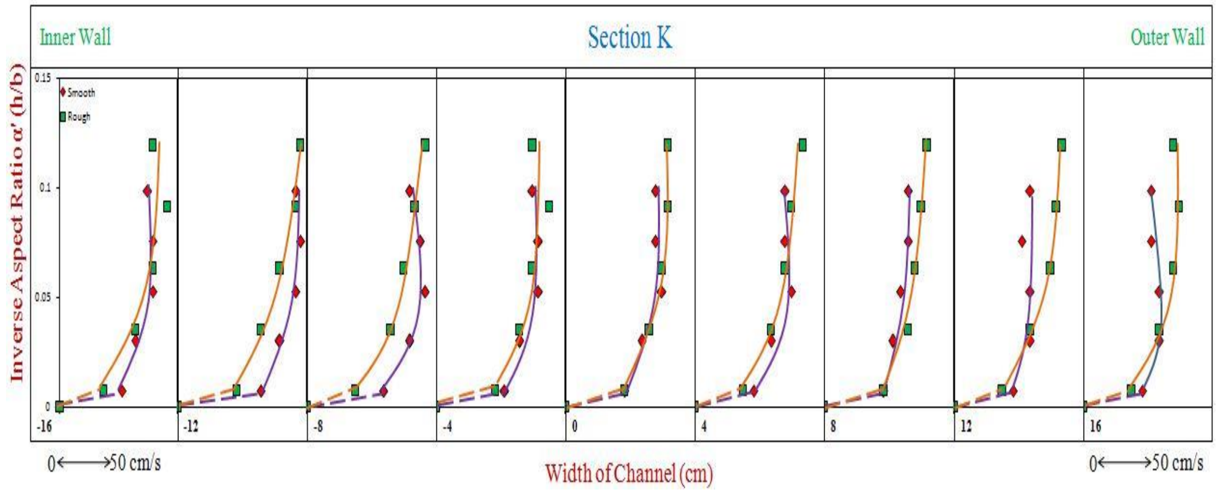


Figure 21.11

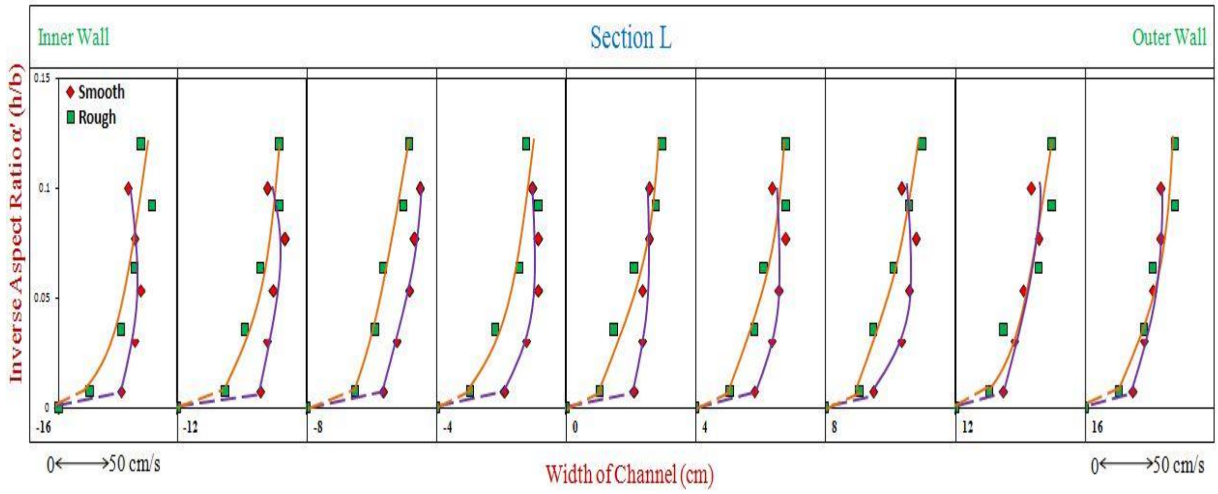


Figure 21.12

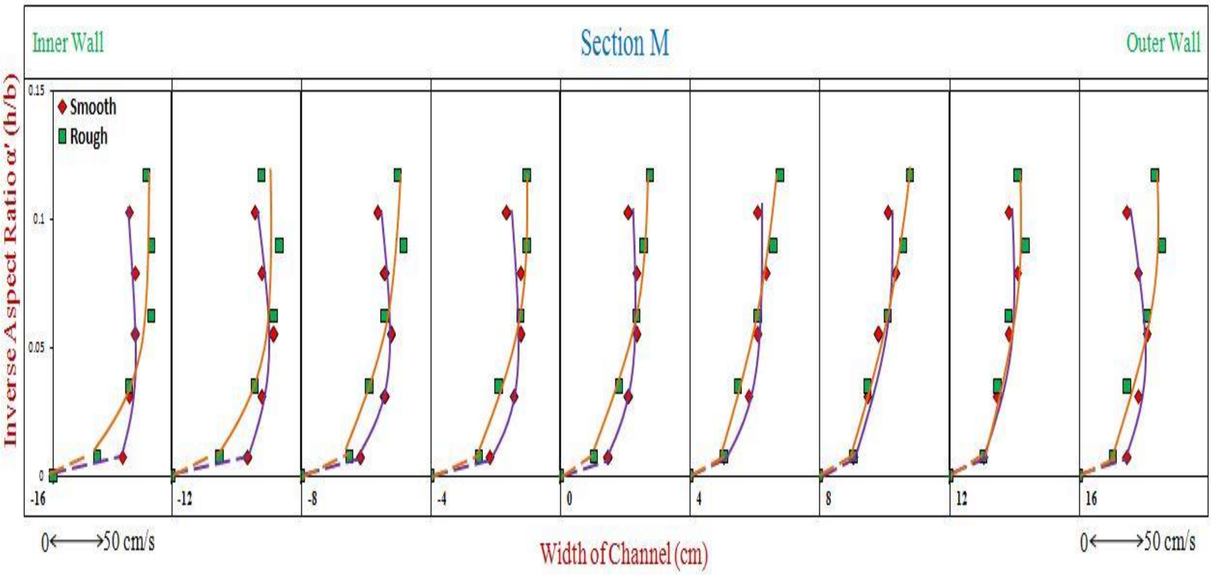


Figure 21.13

Figure 21.1-21.13: Vertical Velocity Profile comparison between Rough and Smooth Meandering Channels

5.5 SIMULATION RESULT

The simulation result part described here is divided into two segments. One segment showing the outcomes from the input of variables in the CCHE MESH window i.e. figure 22 to 31 displays the results seen in the CCHE MESH window after the user has given his respective input files.

The second segment showing the output files that were attained from the CCHE GUI window in proportion to the mesh files and with the input of some initial conditions, boundary condition and the simulation flow parameters to review the outputs. Figure 32 to 51 shows the respective outputs seen in the CCHE GUI window. The output simulation results are also well picturised in the following figures describing the stability of the numerical model with the experimental results as obtained manually in the laboratory.

5.5.1 CCHE MESH FILES

The following figures display the working area of CCHE MESH.

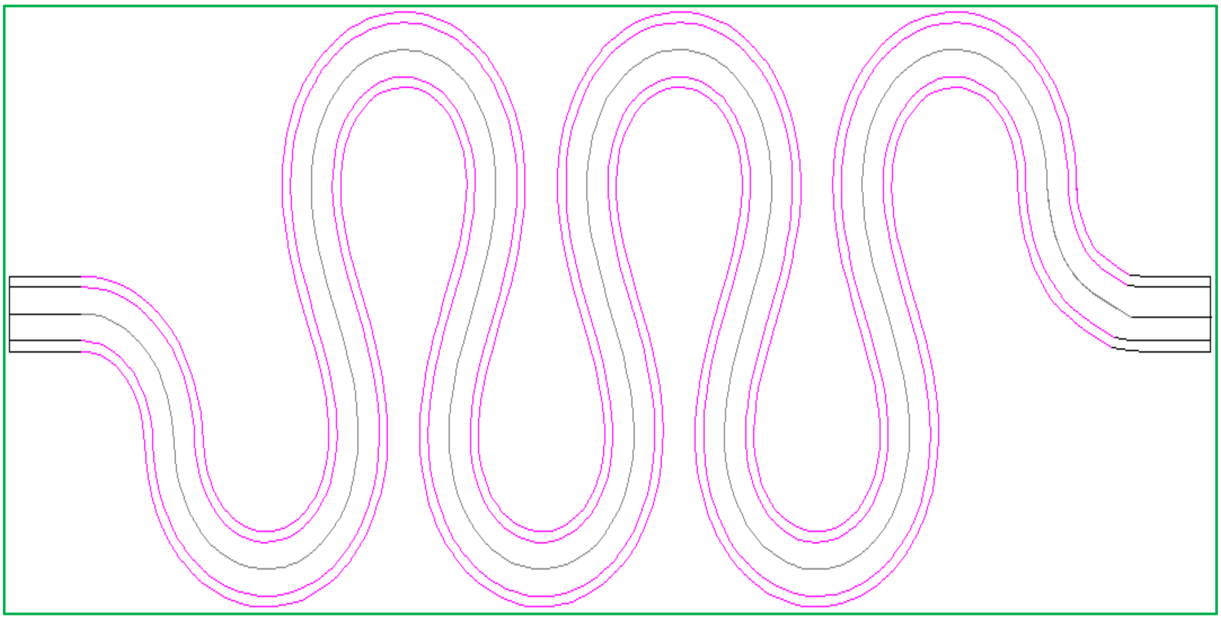


Figure 22- CAD FILE OF MEANDERING CHANNEL

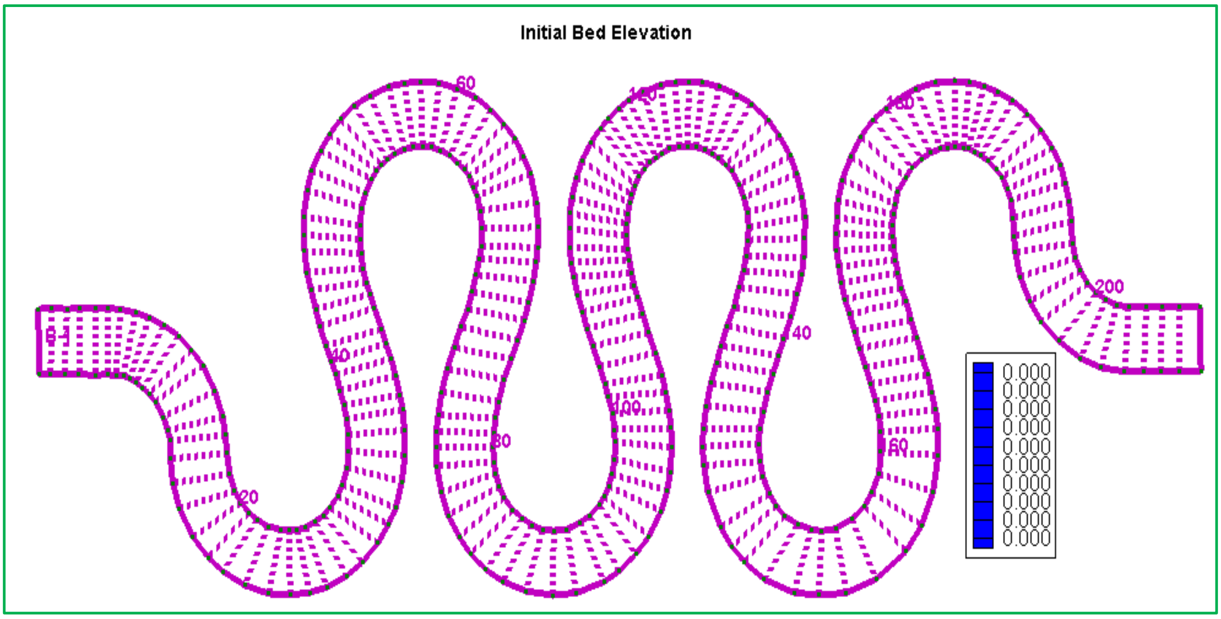


Figure 23- BOUNDARY BLOCKS IN THE NUMERICAL MODEL

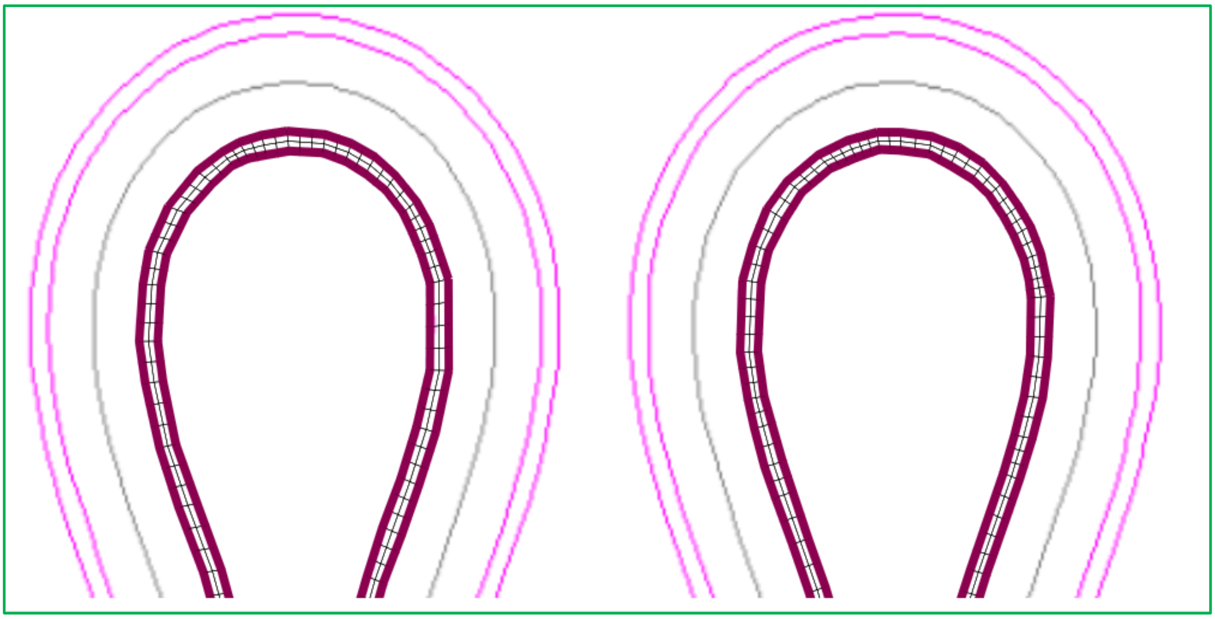


Figure 24- FIRST BLOCK ALGEBRAIC MESHING

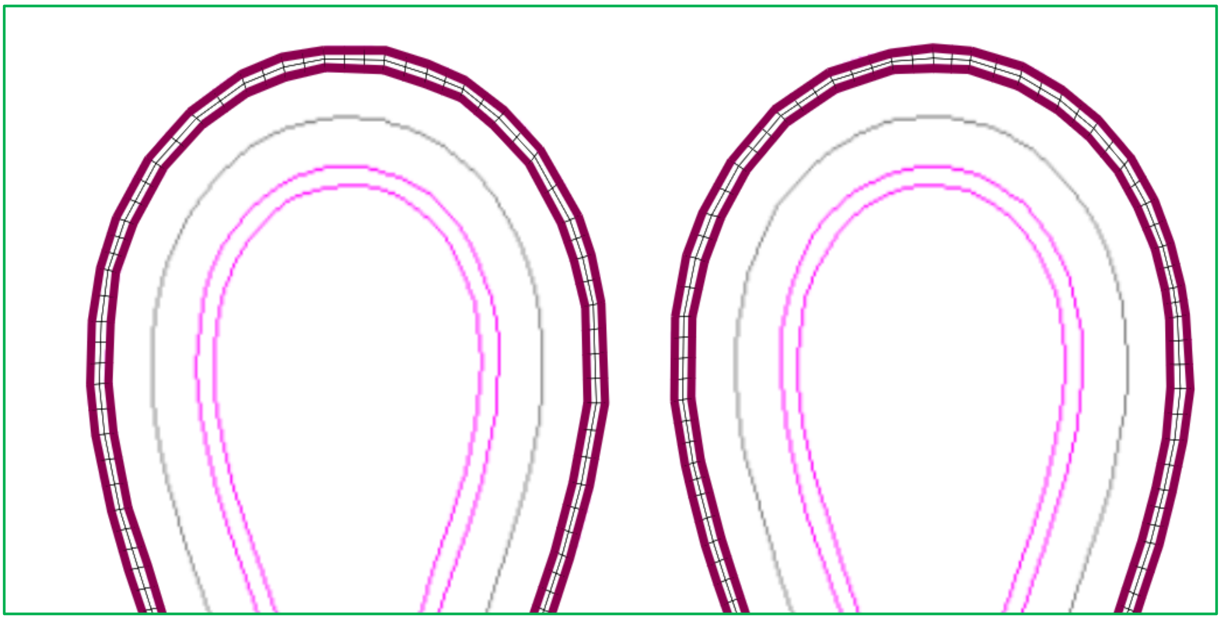


Figure 25- SECOND BLOCK ALGEBRAIC MESHING

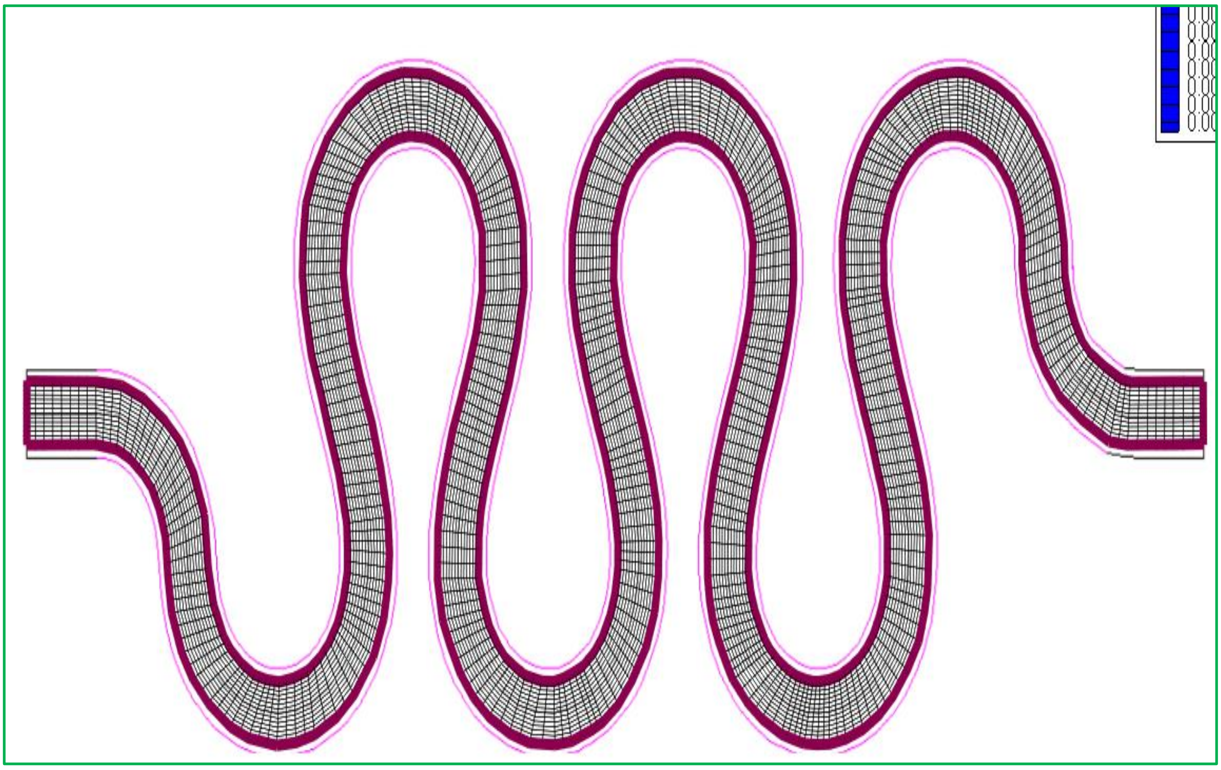
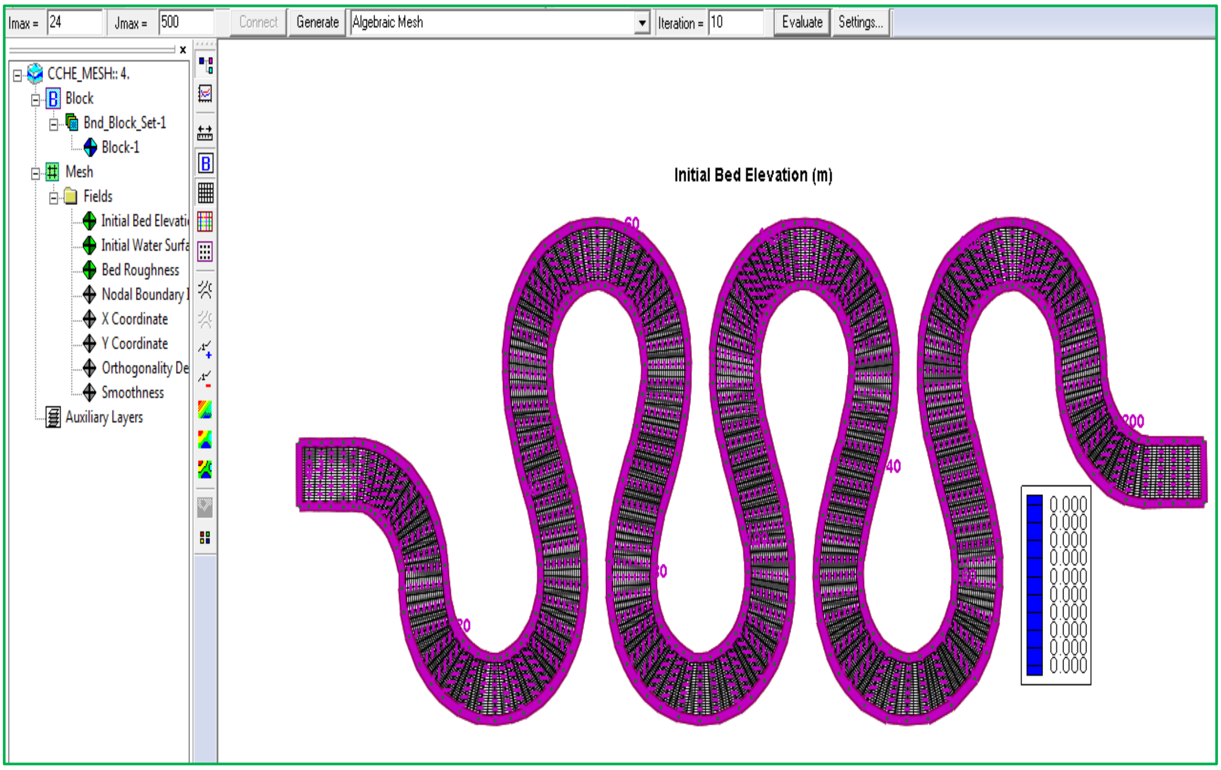


Figure 26- THIRD BLOCK ALGEBRAIC MESHING



Imax = 24 Jmax = 500

Algebraic Mesh

Iteration = 10

Figure 27- CONNECTED ALGEBRAIC MESHING

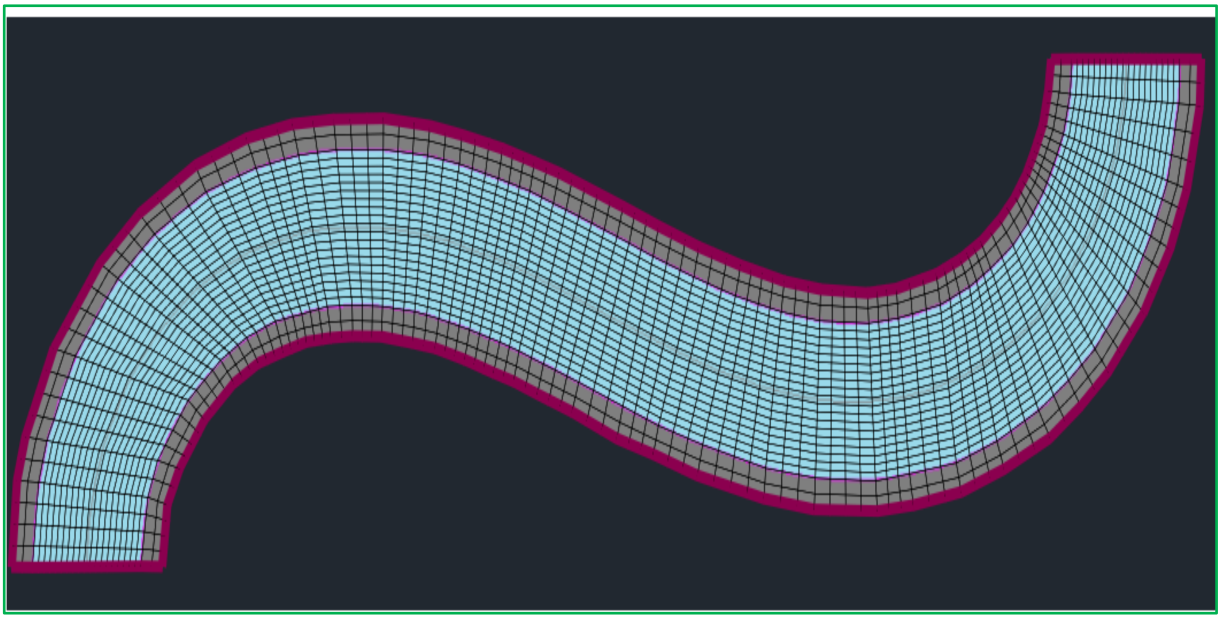
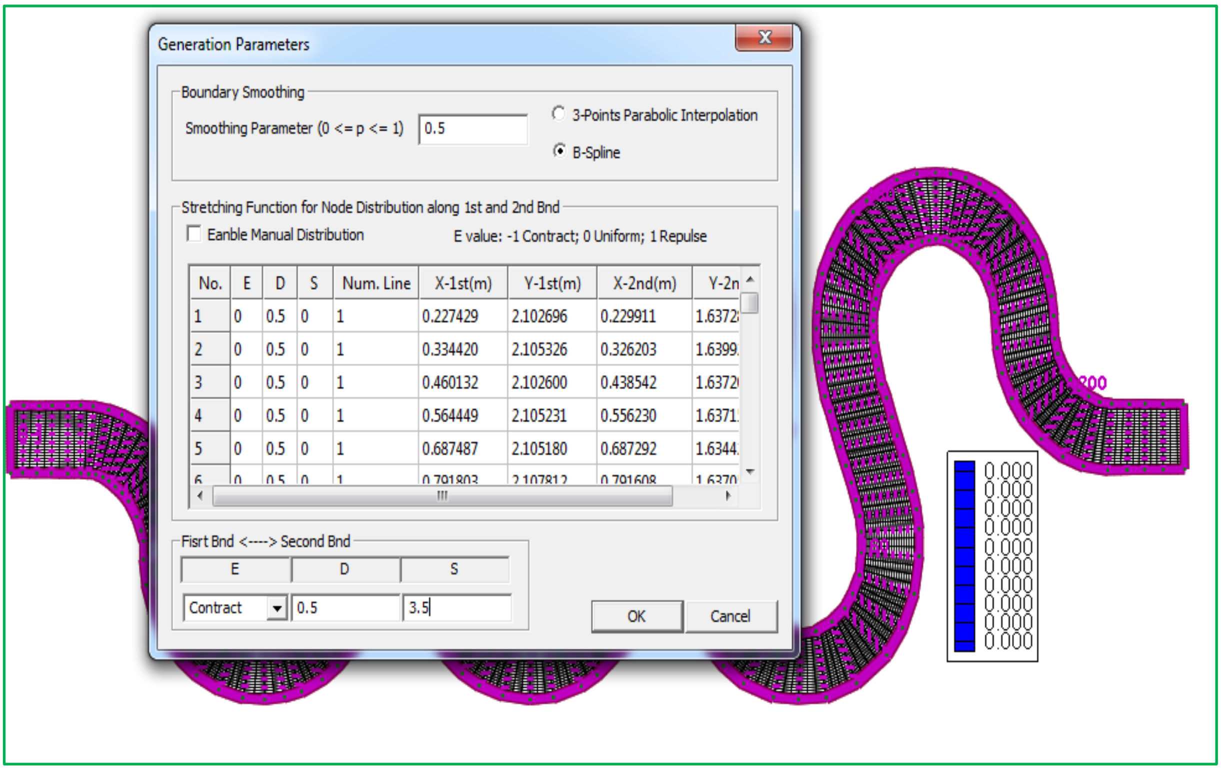


Figure 28- MAGNIFIED VIEW OF MESHING OF MEANDER PATH



Generation Parameters

Boundary Smoothing

Smoothing Parameter (0 <= p <= 1) 0.5

○ 3-Points Parabolic Interpolation

● B-Spline

Stretching Function for Node Distribution along 1st and 2nd Bnd

☐ Eanble Manual Distribution

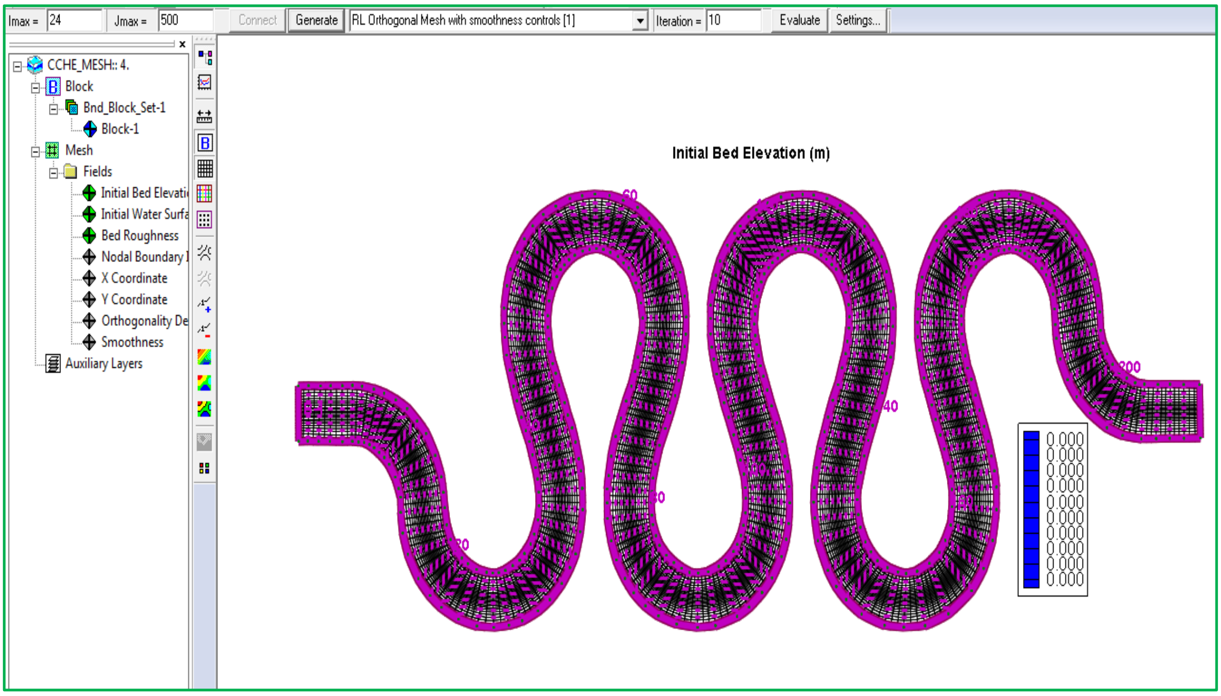
E value: -1 Contract; 0 Uniform; 1 Repulse

No.	E	D	S	Num. Line	X-1st(m)	Y-1st(m)	X-2nd(m)	Y-2n
1	0	0.5	0	1	0.227429	2.102696	0.229911	1.6372
2	0	0.5	0	1	0.334420	2.105326	0.326203	1.6399
3	0	0.5	0	1	0.460132	2.102600	0.438542	1.6372
4	0	0.5	0	1	0.564449	2.105231	0.556230	1.6371
5	0	0.5	0	1	0.687487	2.105180	0.687292	1.6344
6	0	0.5	0	1	0.791803	2.107812	0.791608	1.6370

Fisrt Bnd <----> Second Bnd

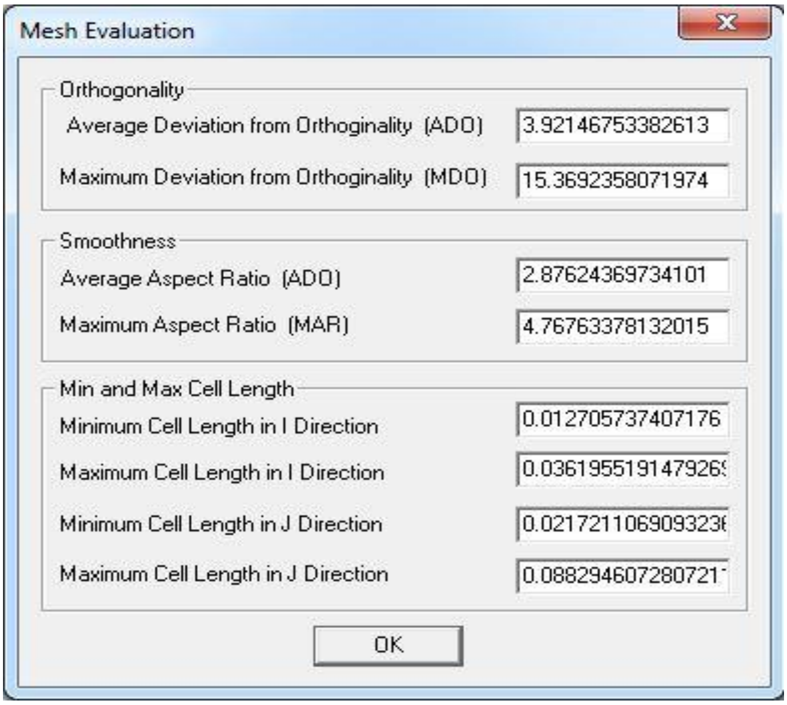
E	D	S
Contract	0.5	3.5

Figure 29- GENERATION PARAMETERS EDS



Imax = 24
Jmax = 500
RL Orthogonal Mesh with smoothness controls [1]
Iteration = 10

Figure 30- NUMERICAL MESH GENERATION



Mesh Evaluation

Orthogonality

Average Deviation from Orthoginality (ADO) 3.92146753382613

Maximum Deviation from Orthoginality (MDO) 15.3692358071974

Smoothness

Average Aspect Ratio (ADO) 2.87624369734101

Maximum Aspect Ratio (MAR) 4.76763378132015

Min and Max Cell Length

Minimum Cell Length in I Direction 0.012705737407176

Maximum Cell Length in I Direction 0.036195519147926

Minimum Cell Length in J Direction 0.021721106909323

Maximum Cell Length in J Direction 0.088294607280721

Figure 31 MESH EVALUATION

5.5.2 CCHE GUI FILES

The following figures display the working area of CCHE GUI.

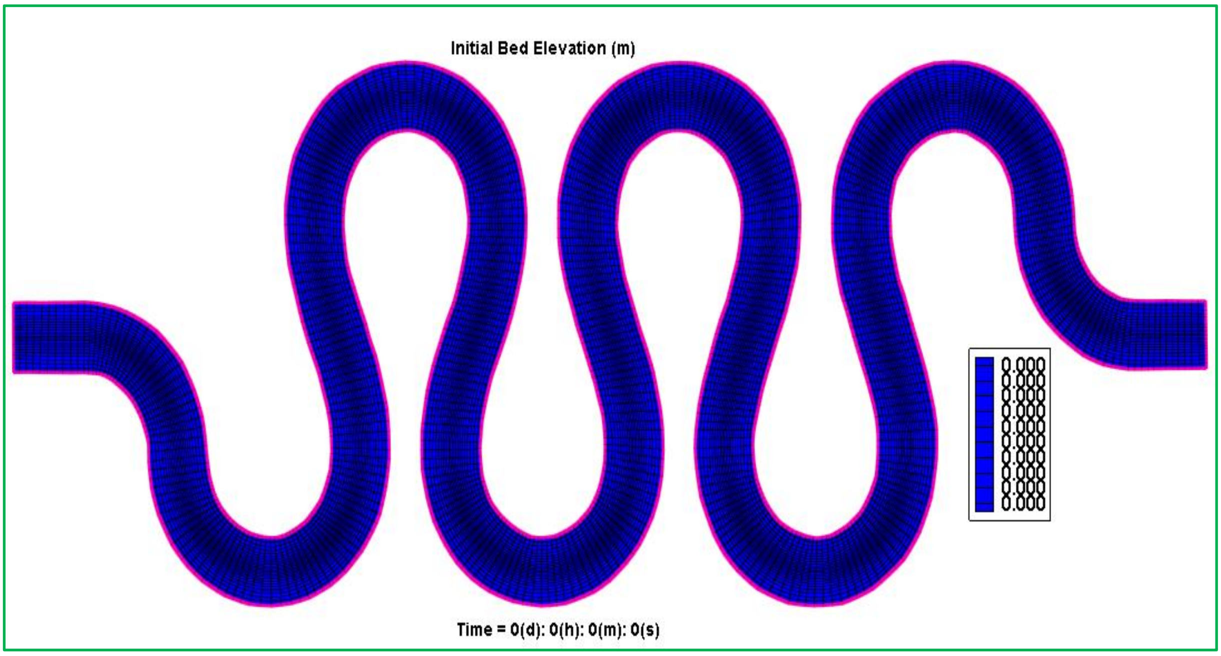


Figure 32- GEO FILE IN CCHE GUI WINDOW

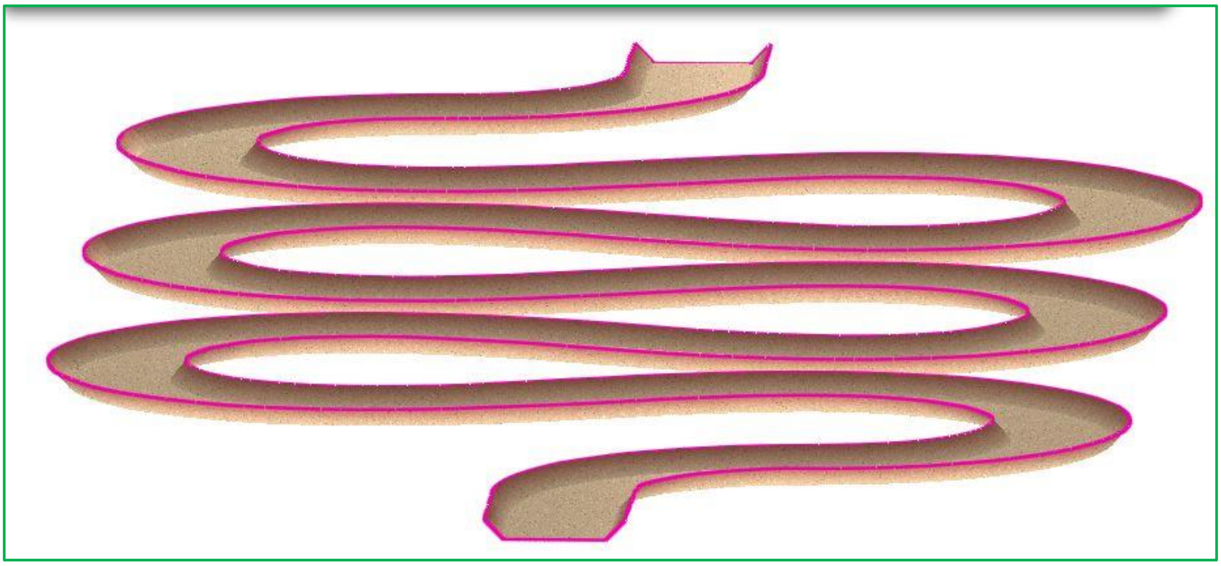


Figure 33- 3D VIEW OF THE MEANDERING CHANNEL

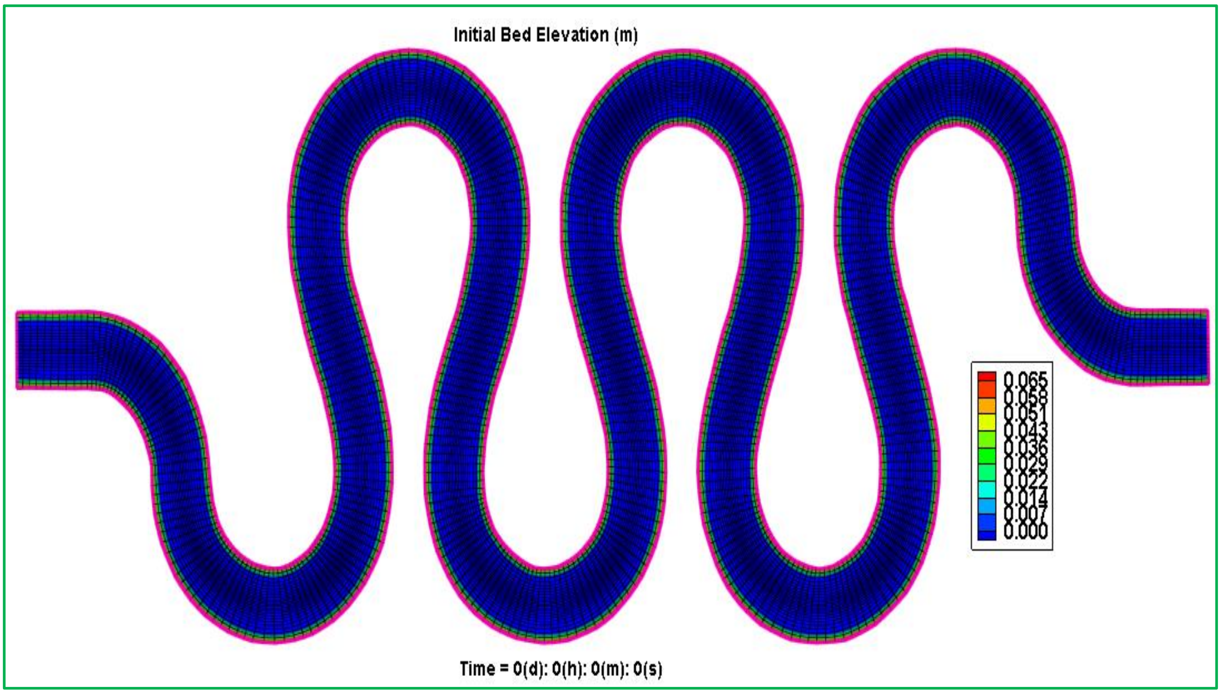


Figure 34- BED ELEVATION

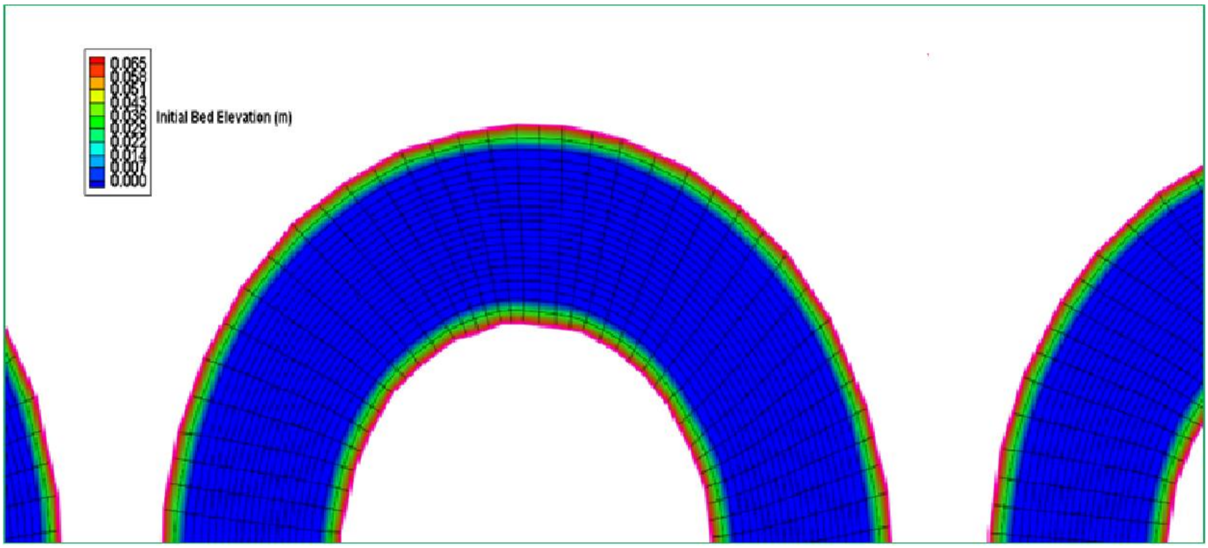


Figure 35- MAGNIFIED VIEW OF INITIAL BED ELEVATION

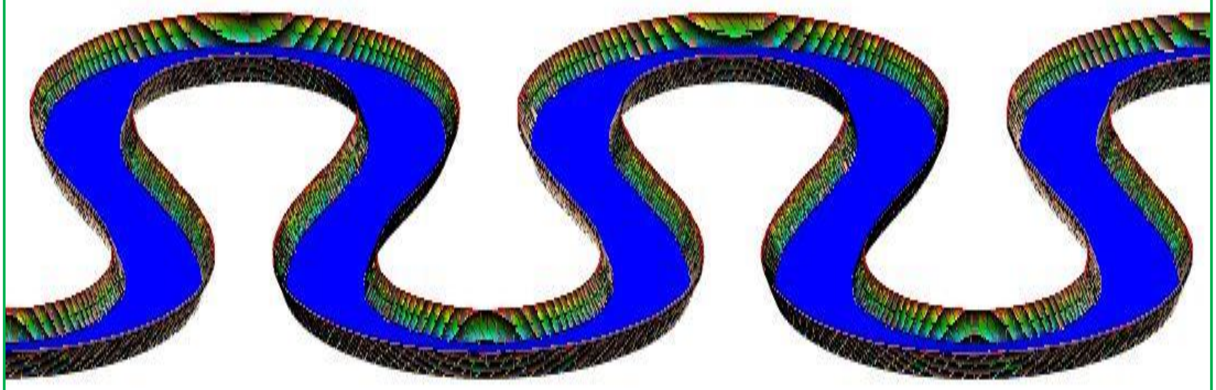
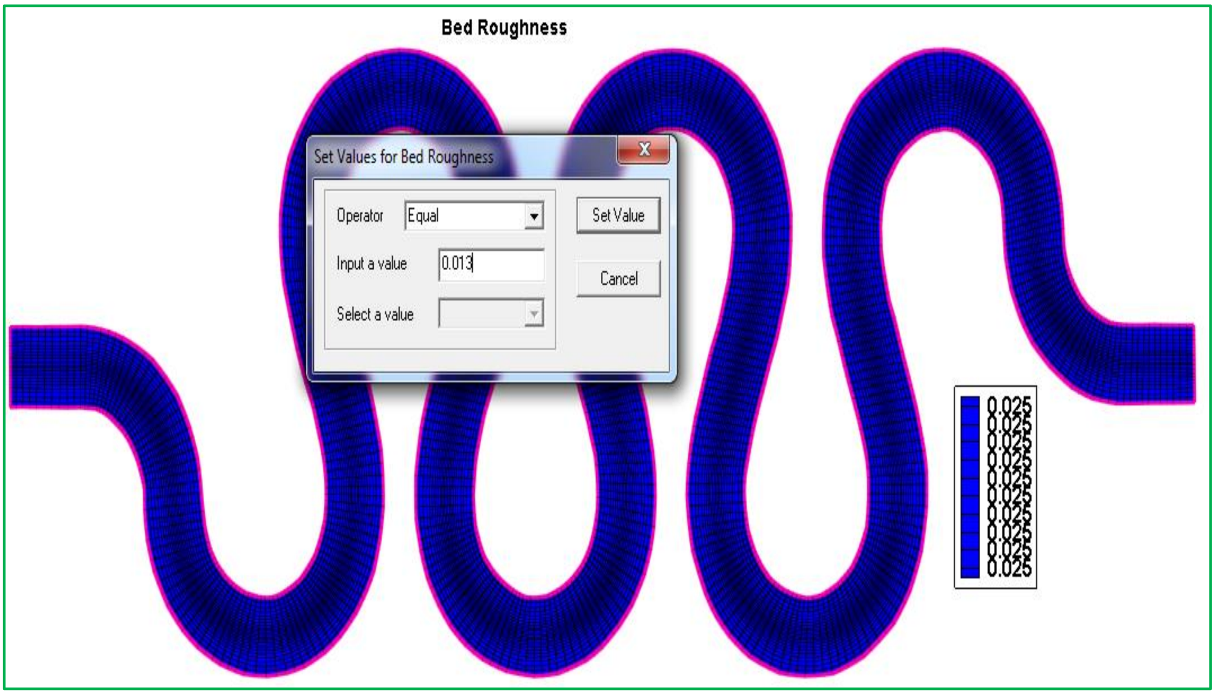


Figure 36- 3D VIEW OF THE BED ELEVATION



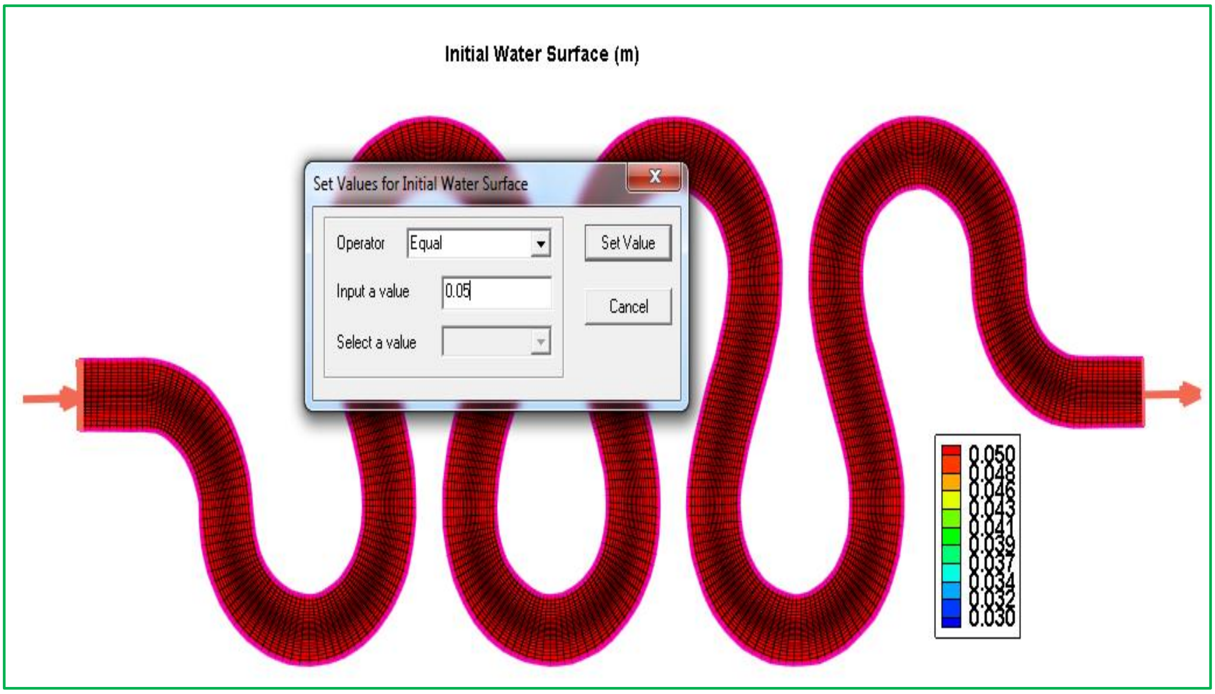
Set Values for Bed Roughness

Operator: Equal

Input a value: 0.013

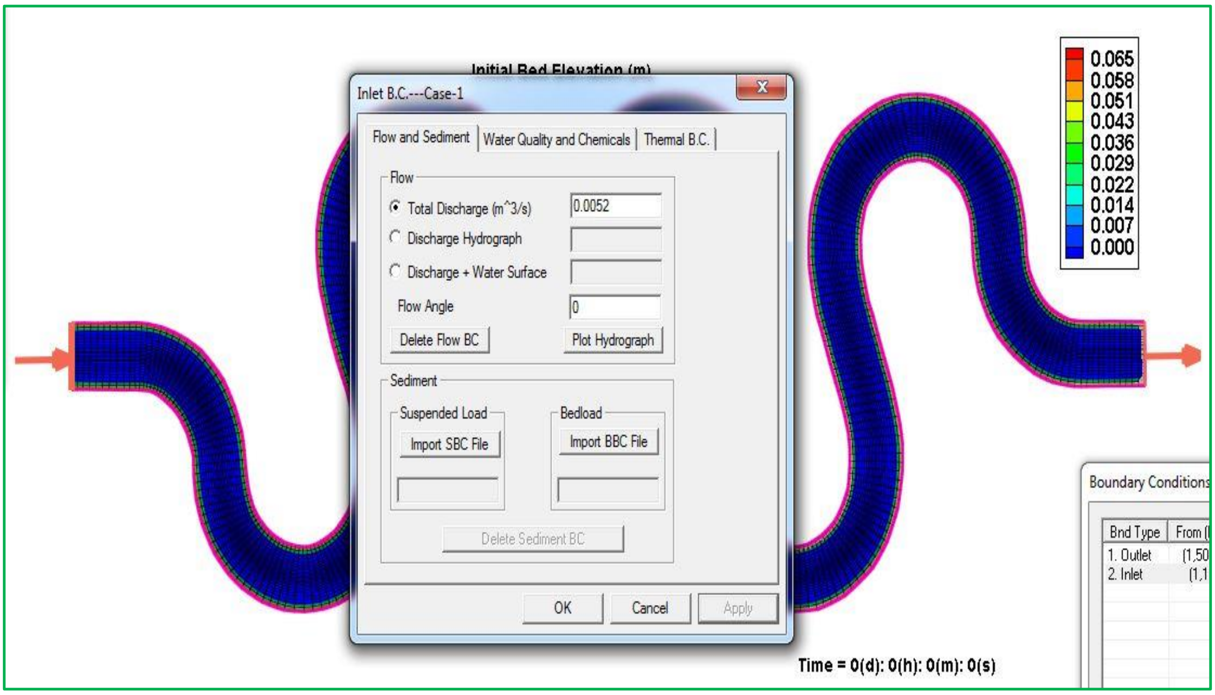
Select a value:

Figure 37- BED ROUGHNESS VALUE



Operator: Equal
Input a value: 0.05
Select a value:

Figure 38- INITIAL WATER SURFACE VALUE

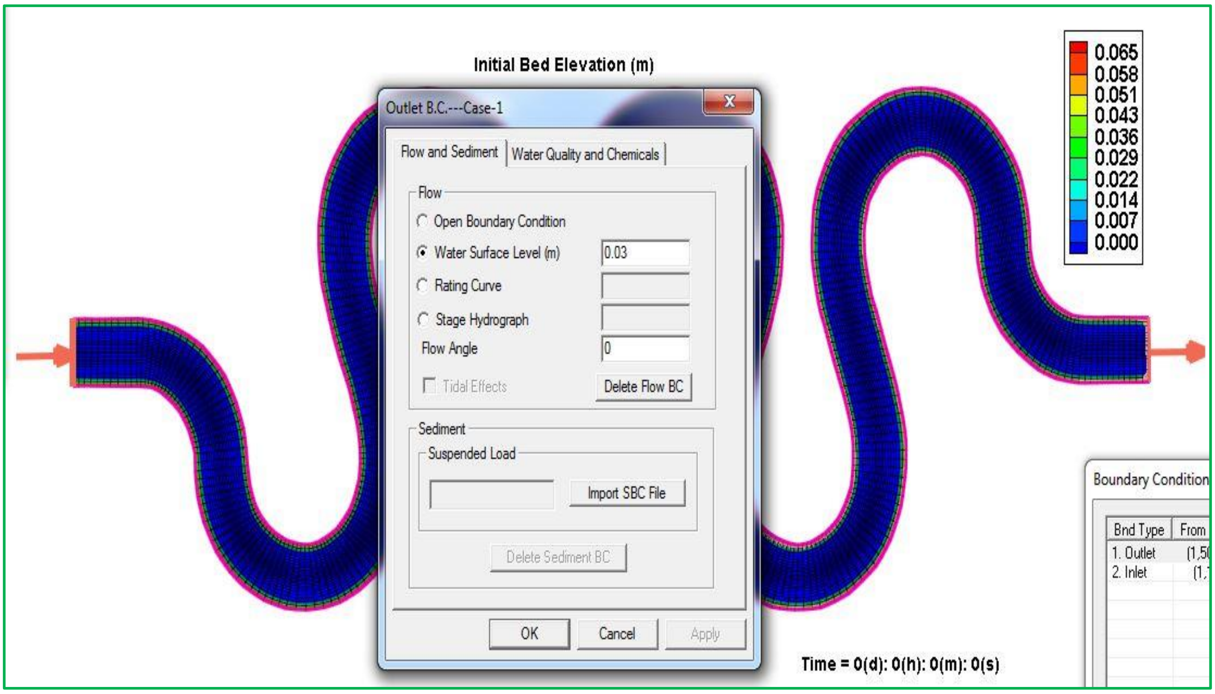


● Total Discharge (m^3/s): 0.0052
○ Discharge Hydrograph:
○ Discharge + Water Surface:
Flow Angle: 0

Bnd Type	From (
1. Outlet	(1,50
2. Inlet	(1,1

Time = 0(d): 0(h): 0(m): 0(s)

Figure 39- INLET BOUNDARY CONDITION



○ Open Boundary Condition
● Water Surface Level (m) 0.03
○ Rating Curve
○ Stage Hydrograph
Flow Angle 0
☐ Tidal Effects

Figure 40- OUTLET BOUNDARY CONDITION

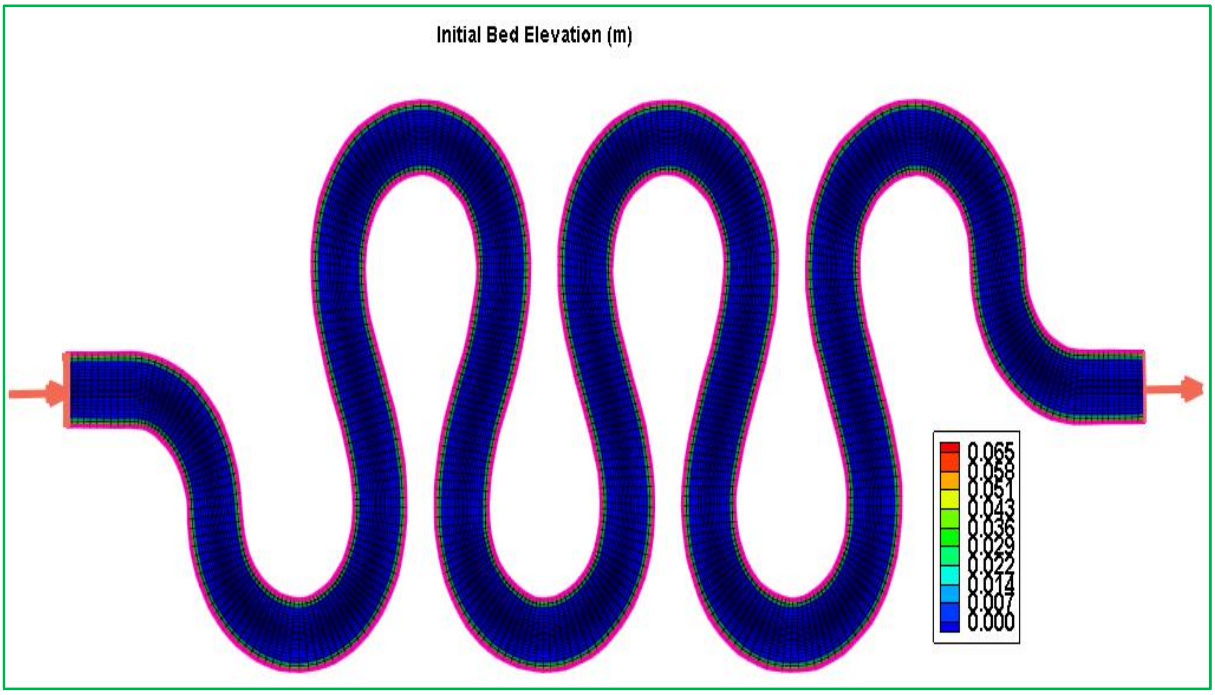
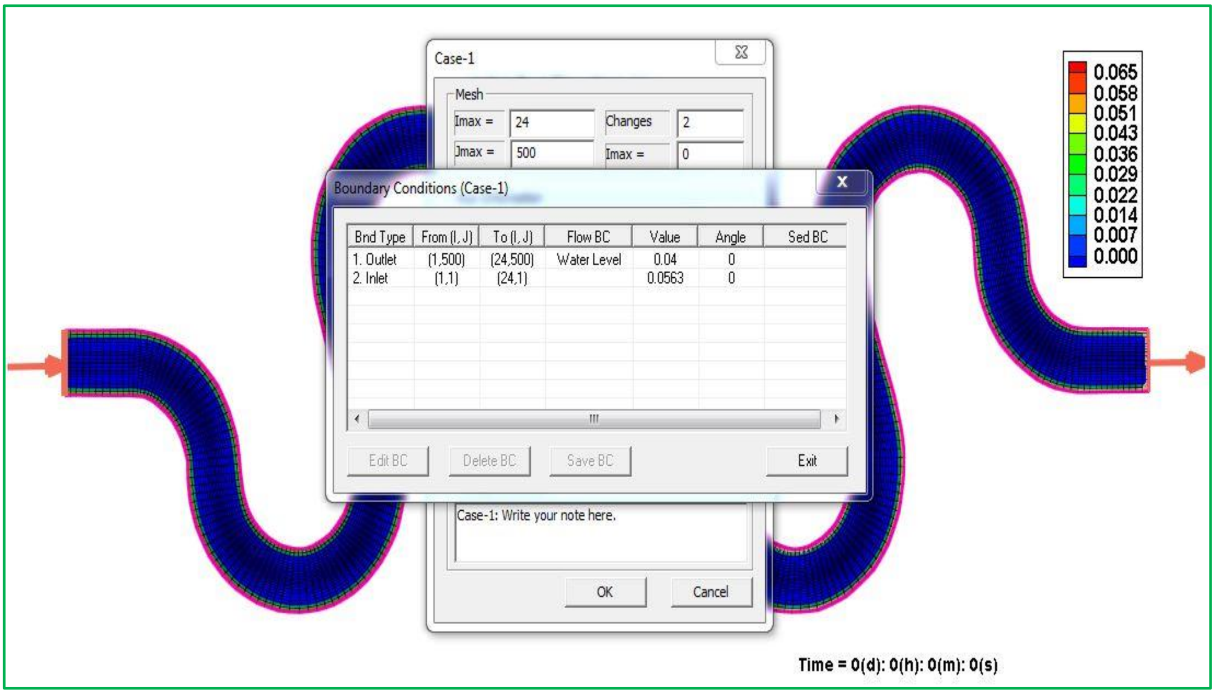


Figure 41- INLET-OUTLET DIRECTIONAL VIEW



Case-1

Mesh

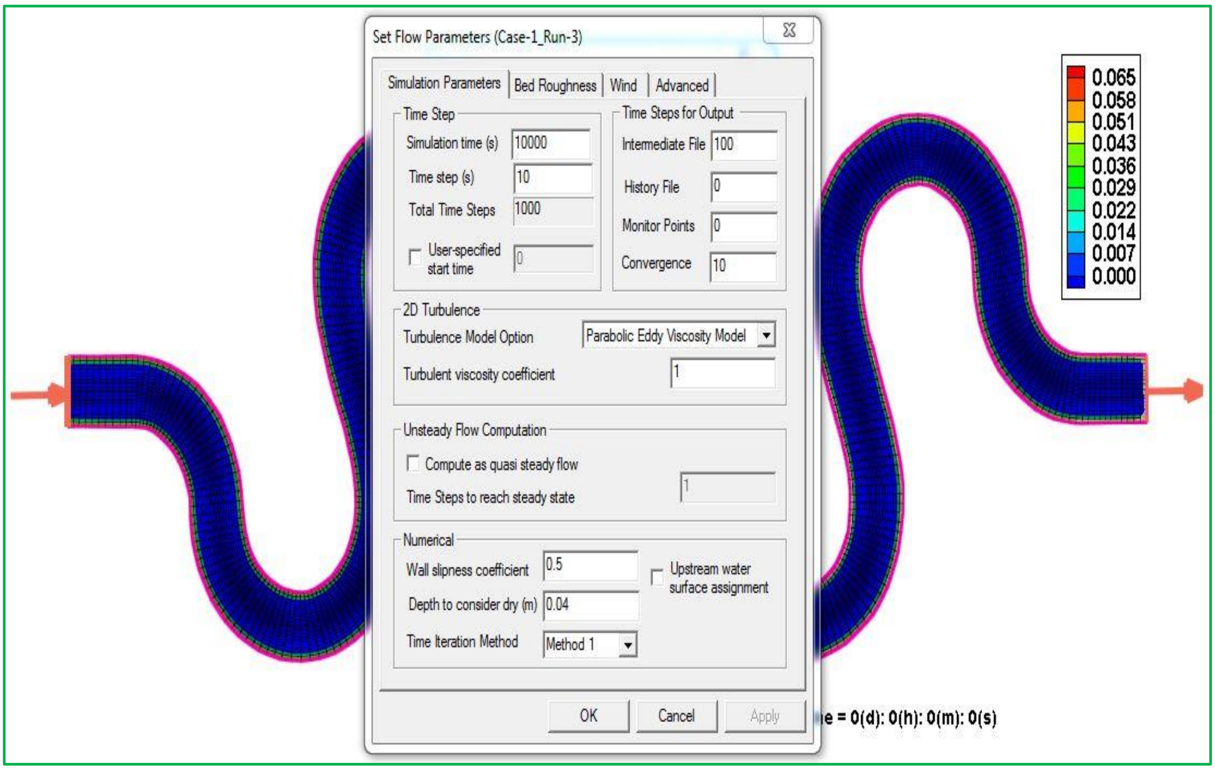
Imax = 24
Jmax = 500
Changes 2
Imax = 0

Boundary Conditions (Case-1)

Bnd Type	From (I, J)	To (I, J)	Flow BC	Value	Angle	Sed BC
1. Outlet	(1,500)	(24,500)	Water Level	0.04	0	
2. Inlet	(1,1)	(24,1)		0.0563	0	

Case-1: Write your note here.

Figure 42- BOUNDARY CONDITION



Set Flow Parameters (Case-1_Run-3)

Time Step

Simulation time (s) 10000
Time step (s) 10
Total Time Steps 1000
☐ User-specified start time 0

Time Steps for Output

Intermediate File 100
History File 0
Monitor Points 0
Convergence 10

2D Turbulence

Turbulence Model Option: Parabolic Eddy Viscosity Model
Turbulent viscosity coefficient 1

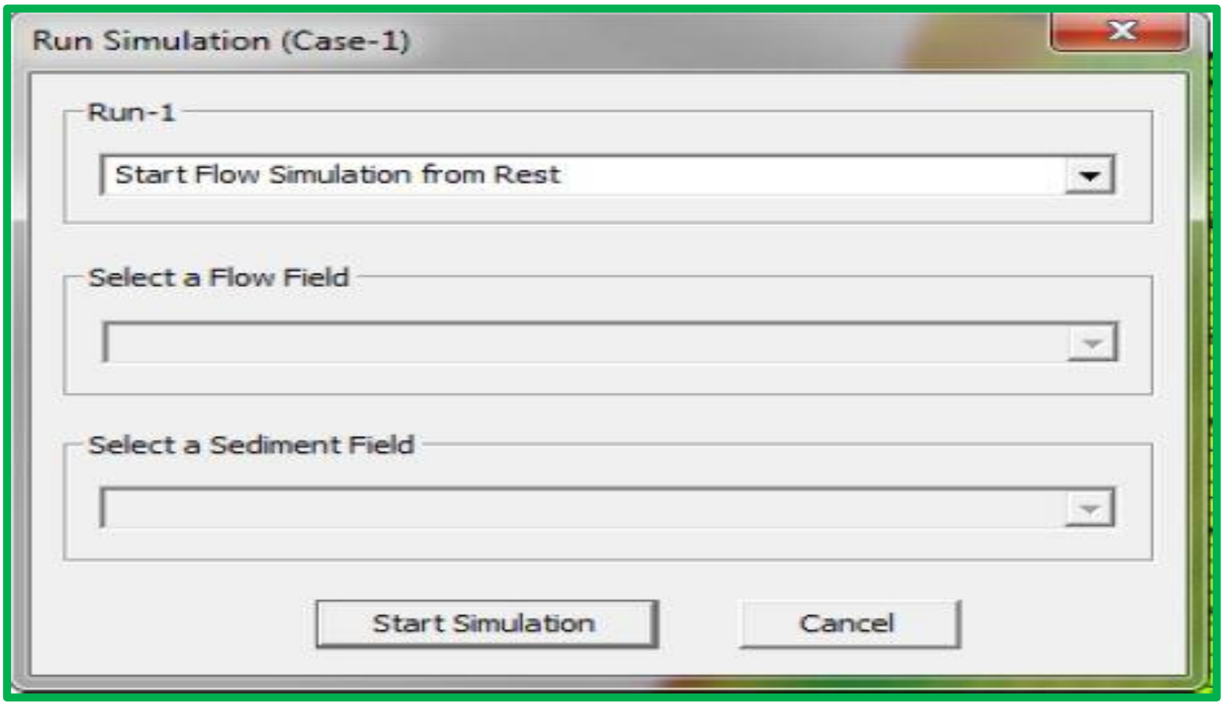
Unsteady Flow Computation

☐ Compute as quasi steady flow
Time Steps to reach steady state 1

Numerical

Wall slipness coefficient 0.5
Depth to consider dry (m) 0.04
Time Iteration Method: Method 1
☐ Upstream water surface assignment

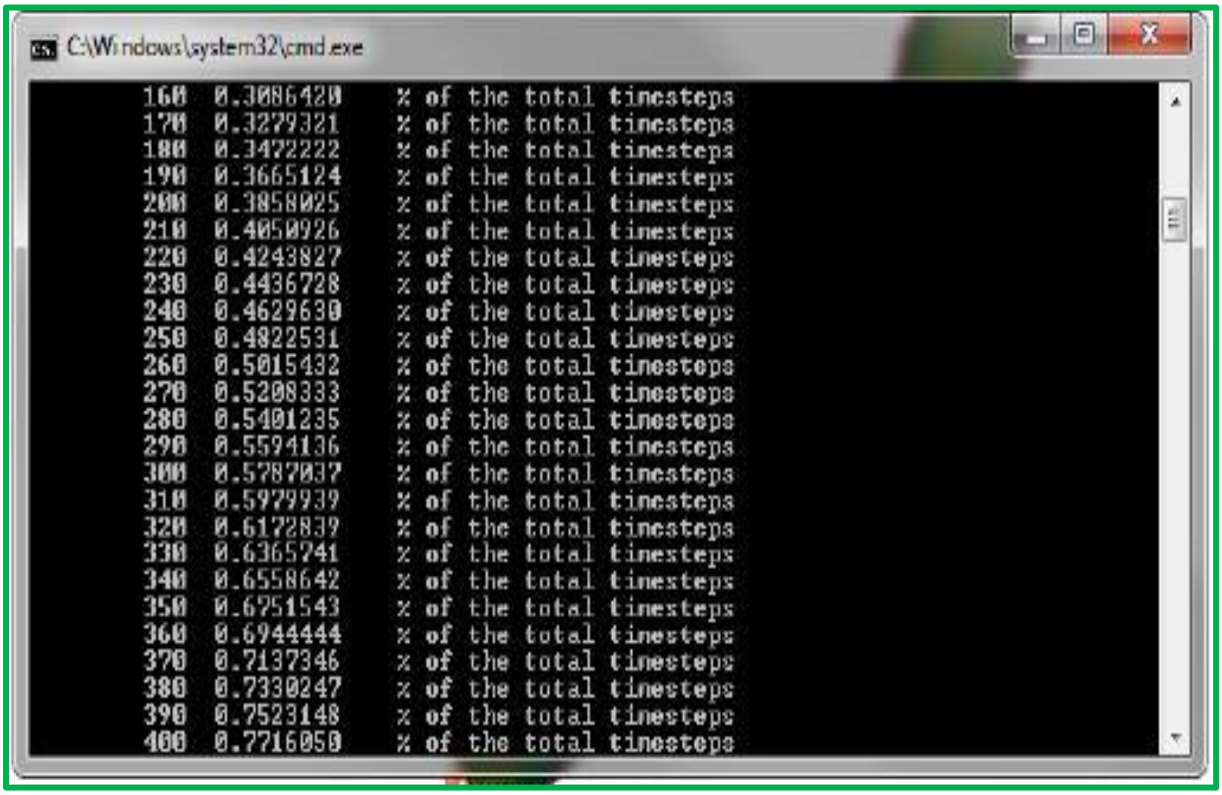
Figure 43- FLOW PARAMETERS SETTING



Run Simulation (Case-1)

Run-1: Start Flow Simulation from Rest

Figure 44- SIMULATION WINDOW



C:\Windows\system32\cmd.exe

```
        160  0.3086420    % of the total timesteps
        170  0.3279321    % of the total timesteps
        180  0.3472222    % of the total timesteps
        190  0.3665124    % of the total timesteps
        200  0.3858025    % of the total timesteps
        210  0.4050926    % of the total timesteps
        220  0.4243827    % of the total timesteps
        230  0.4436728    % of the total timesteps
        240  0.4629630    % of the total timesteps
        250  0.4822531    % of the total timesteps
        260  0.5015432    % of the total timesteps
        270  0.5208333    % of the total timesteps
        280  0.5401235    % of the total timesteps
        290  0.5594136    % of the total timesteps
        300  0.5787037    % of the total timesteps
        310  0.5979939    % of the total timesteps
        320  0.6172839    % of the total timesteps
        330  0.6365741    % of the total timesteps
        340  0.6558642    % of the total timesteps
        350  0.6751543    % of the total timesteps
        360  0.6944444    % of the total timesteps
        370  0.7137346    % of the total timesteps
        380  0.7330247    % of the total timesteps
        390  0.7523148    % of the total timesteps
        400  0.7716050    % of the total timesteps
```

Figure 45- SIMULATION COMMAND PROMPT WINDOW

5.5.3 FINAL RESULTS

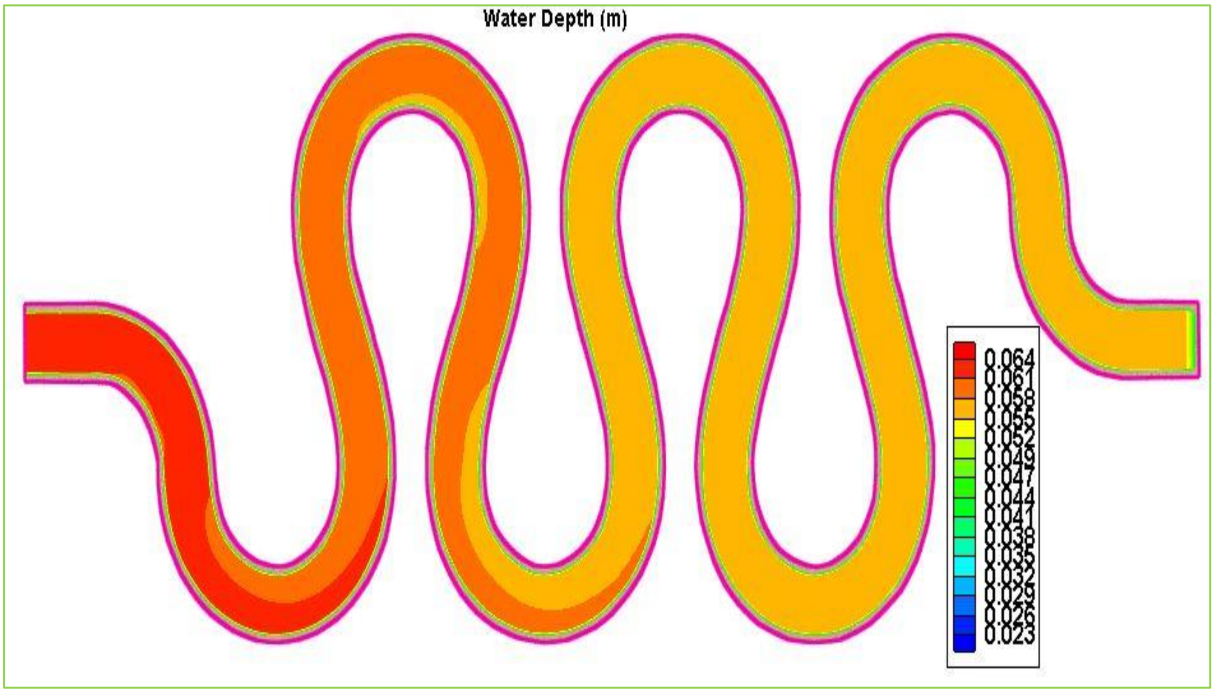


Figure 46- WATER DEPTH

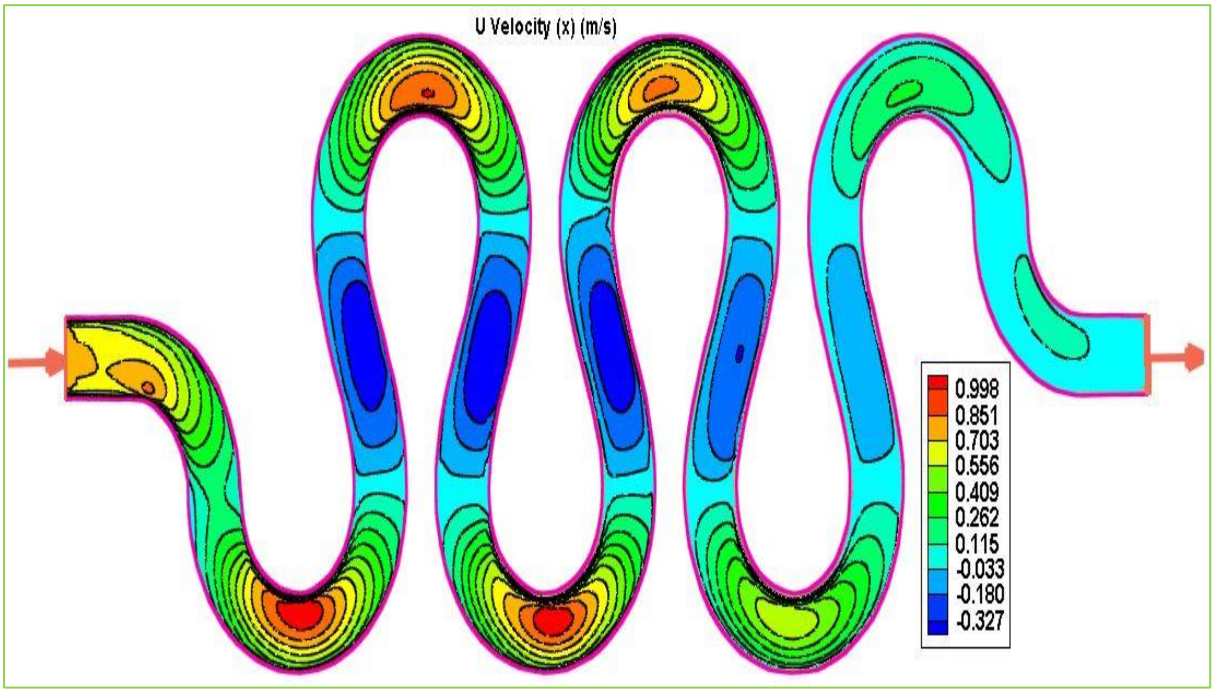


Figure 47-U VELOCITY

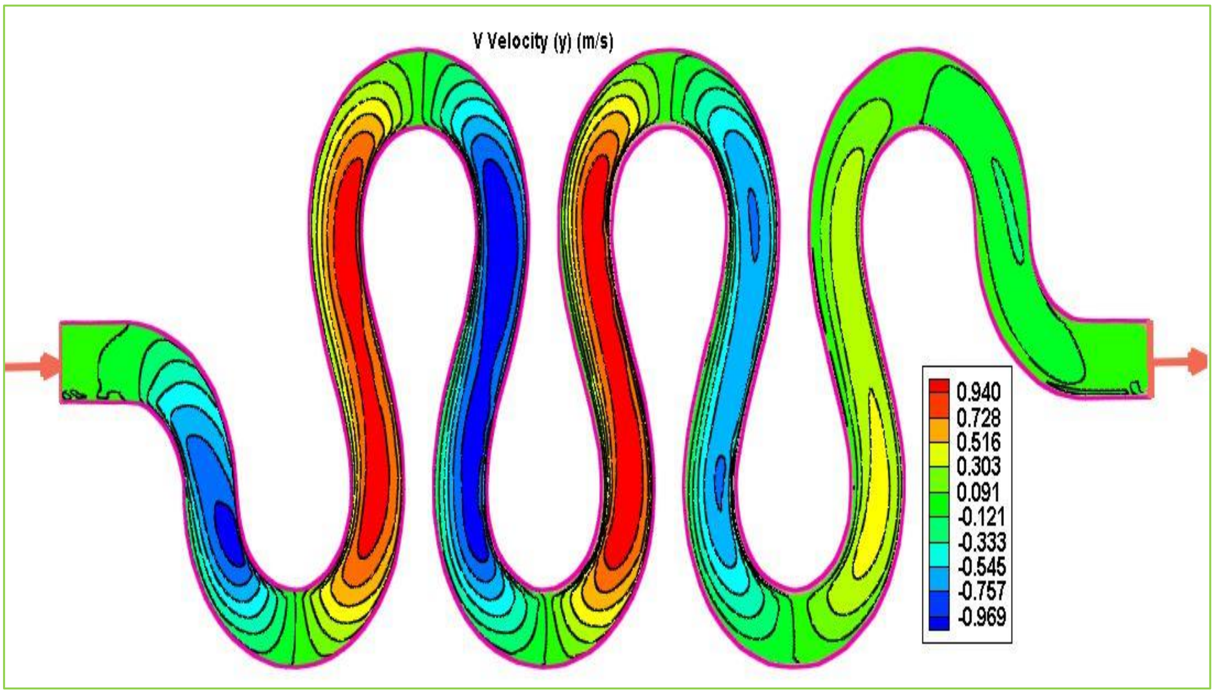


Figure 48- V VELOCITY

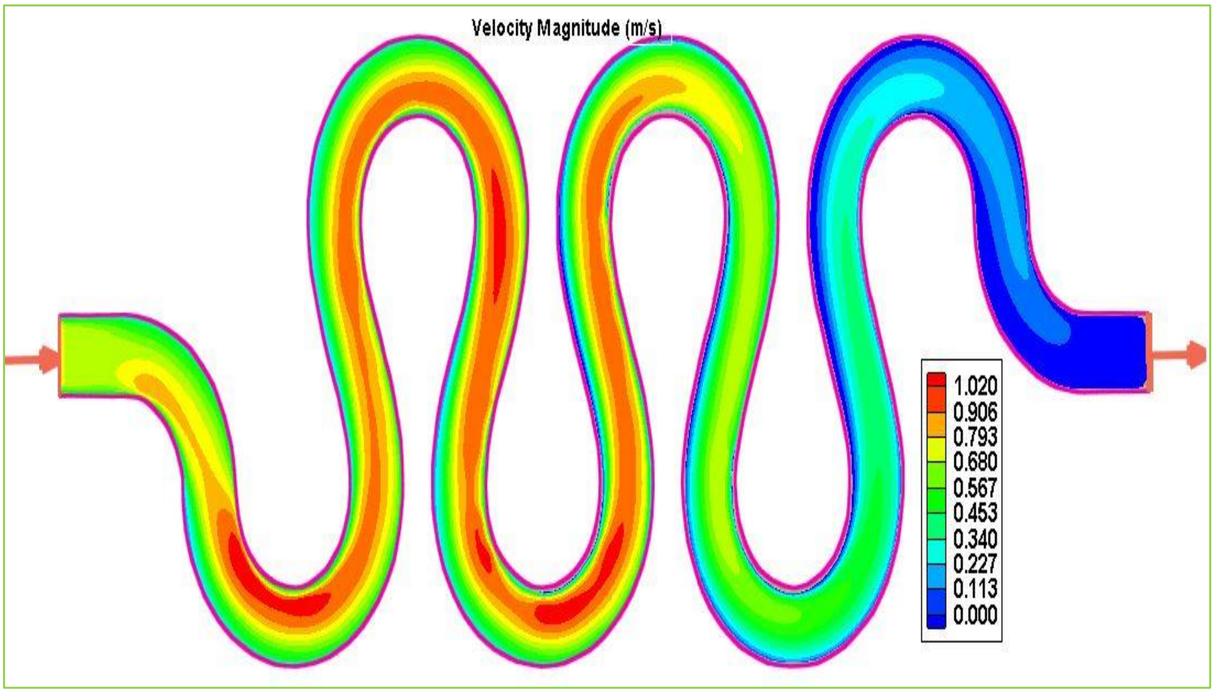


Figure 49- VELOCITY MAGNITUDE

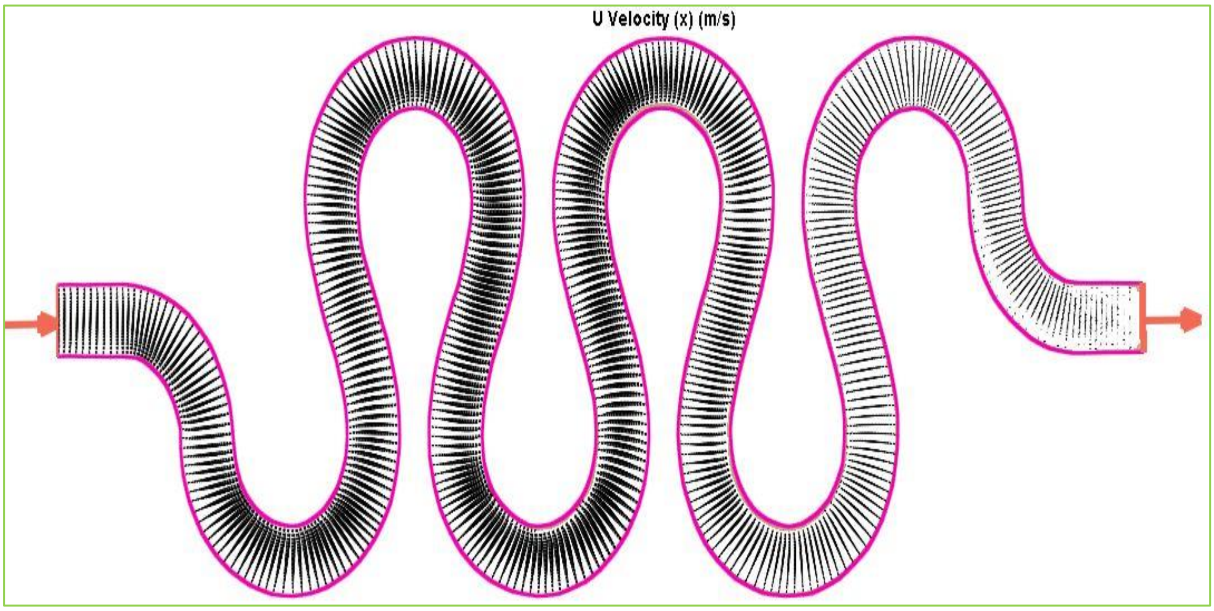


Figure 50- VELOCITY VECTORS

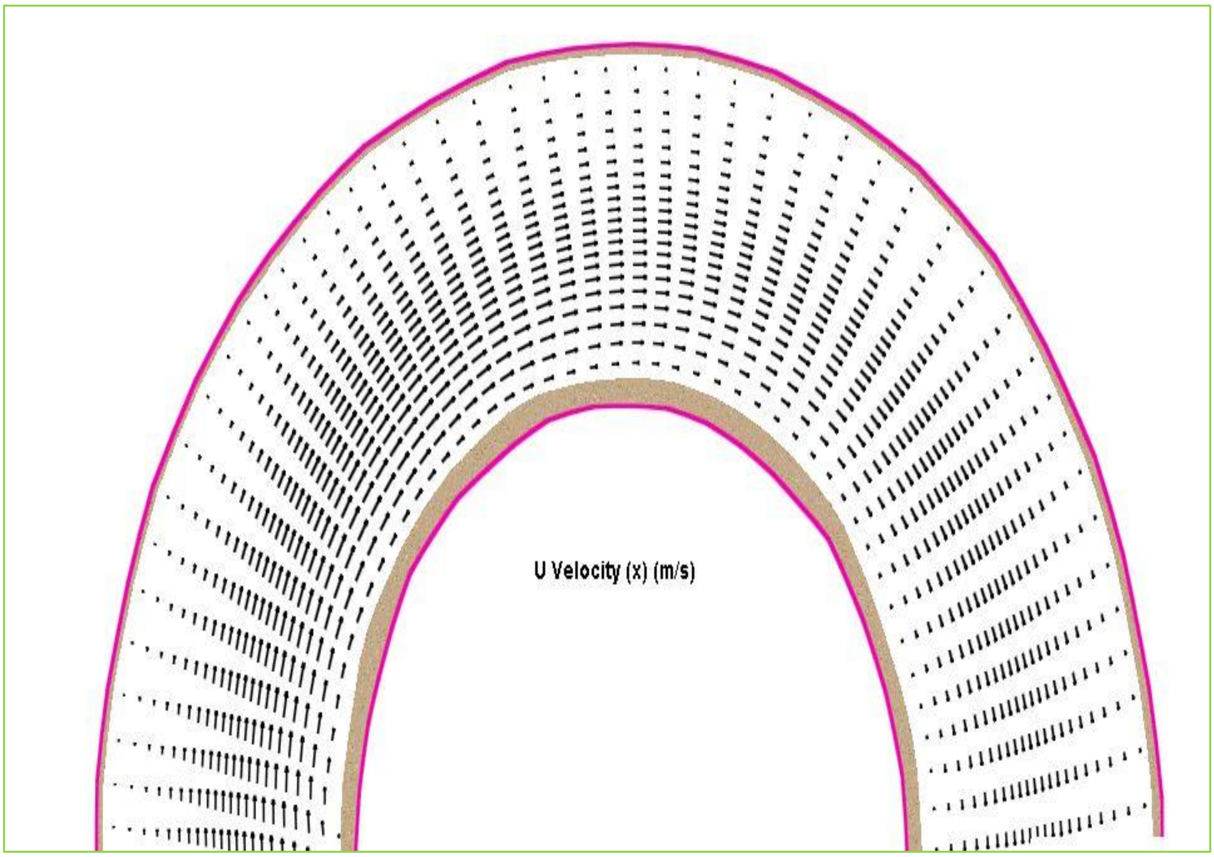


Figure 51- MAGNIFIED VIEW OF VECTOR LINES

CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS

The present theoretical investigation supported by experimental observation is made for a rough simple meandering channel. The results for new experimental analysis done in a rough meandering channel have been reported in this thesis. The tests were conducted under quasi uniform flow and sub-critical flow condition. The longitudinal velocity along the meander path selected was measured for thee highly sinuous channel under various in-bank flow conditions. A 2D hydrodynamic model (CCHE2D) was applied to the flume experimental analysis. On thebasis of the investigations concerning flow, longitudinal velocity distribution, a well-organized comparison between smooth and rough bed and application of numerical tool in roughmeandering channel, the following conclusions are drawn.

1) It is concluded with a observation of vertical velocity profile remaining higher at the inner wall as compared to the outer wall in a highly sinuous channel.
2) At the bed of the cross-over section, the local maximum velocity is found to move towards the center of the section, with gradual variations towards the inner and outer walls.
3) Longitudinal velocity at the cross-over section are found to occur at the center of the channel section the highest value of which is positioned 0.6Habove the bed.
4) The maximum velocity in longitudinal direction is seen to be moving from the inner side of bend apex section to the centre region. It is seen moving closer to the surface but further it moves towards the bed.
5) Sections C and K (intermediate sections) have the highest maximum velocity throughout the meander path as seen in the longitudinal velocity contour plots for the entire path. Such observations are due to the curvature of the meander path moving towards the cross-over.

6) In the comparisons at the bend apex the velocity in the vertical direction for rough meandering channel is found to be less as compared to smooth channel. This happen up to mid depth after the vertical profile reverses.
7) At the inner middle section the point velocities of the rough channels are always seen to be less in the comparative analysis.
8) In the comparative analysis coming from outer to inner wall deviation is more at inner wall.
9) In every case the vertical velocity profile are found to be power function with vertical distance. This may be due to higher sinuosity of the channel.

6.2 SCOPE FOR FUTURE RESEARCH

The currentinvestigation gives awideopportunity for upcoming investigators to explore new ideas on other phases of ameandering channel. The currentstudy is restricted to a single discharge flow examination of the meandering path. The research can be continued for different discharges to get a completeillustration about the flow attributes.The future scope of the present research can be summarized as:

1. The flow analysis can be carried out at different discharges, giving the variation in surface profile and velocity profiles.
2. The work can be extended for meander paths with different roughness surfaces.
3. Experimentation can be carried out for mobile bed meandering channels.
4. Experimental findings can be compared with data of other sinuous channels to carry out numerical modelling.
5. Mathematical modelling and numerical modelling can be carried out to predict the water surface profile, velocity profile and boundary shear stress distributions.
6. Experimental work on 3D velocity readings can be carried out to have the turbulence and flow structure study.

REFERENCES

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Publications from the Research

A: Journal

1. **Sovan Sankalp**, Kishanjit. K. Khatua, Arpan Pradhan, "Boundary Shear Stress Analysis in Meandering Channels at the Bend Apex", Elsevier Aquatic Procedia, ICWRCOE 2015, Vol 4, pp 812-818.
2. **Sovan Sankalp**, Kishanjit. K. Khatua, Arpan Pradhan, "Variation of Flow Profile along a Highly Sinuous Meander Path", International Journal of Civil and Structural Engineering Research, ISSN 2348-7607, Vol 3 Issue 1 pp 95-99.

B: Conference

1. **Sovan Sankalp**, K. K. Khatua, Arpan Pradhan, “An investigation of velocity distribution in a rough meandering channel using hydrodynamic numerical model”*HYDRO-2015 International, 20th International Conference on Hydraulics, Water Resources and River Engineering*, Dec. 17-19,2015, IIT, Roorkee, India. (Communicated)