RIVER TRAINING WORKS WITH SUBMERGED VANES AT DIFFERENT ANGLES

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

HYDRAULICS AND FLOOD CONTROL ENGINEERING

By

AKHIL GUPTA

Roll No. 2K12/HFE/12

Under the guidance of

MR. S. ANBU KUMAR

ASSISTANT PROFESSOR

CIVIL ENGINEERING DEPARTMENT

DELHI TECHNOLOGICAL UNIVERSITY

DELHI-110042 (INDIA)

JULY, 2014

BONAFIDE CERTIFICATE

This is to certify that the project report entitled "RIVER TRAINING WORKS WITH SUBMERGED VANES AT DIFFERENT ANGLES" is a record of the bonafide dissertation work carried out by me, AKHIL GUPTA, towards the partial fulfilment of requirements for the award of the degree of Master of Technology in Hydraulics & Flood Control Engineering.

Also, I do hereby state that I have not submitted the matter embodied in this thesis in any other University/Institute for the award of any degree as per my knowledge and belief.

AKHIL GUPTA
M. Tech (Hydraulics & Flood Control)
Roll No: 2K12/HFE/12
Delhi Technological University, Delhi

This is to certify that the above made statements made by the candidate are correct to the best of my knowledge.

MR. S. ANBU KUMAR
ASSISTANT PROFESSOR
Department of Civil Engineering
Delhi Technological University, Delhi

ACKNOWLEDGEMENT

I feel privileged in extending my earnest obligation, deep sense of gratitude, appreciation and honor to my advisor, Mr. S. Anbu Kumar, Assistant Professor, Department of Civil Engineering, Delhi Technological University, Delhi, whose benevolent guidance, apt suggestions, unstinted help and constructive criticism have inspired me in successful completion of making of this dissertation report.

I choose this opportunity to express my earnest thanks and indebtedness towards the faculties of the department of Civil Engineering, DTU, Delhi for their support and imparting knowledge with great love and care. I express my sincere gratitude to Dr. A. Trivedi, Professor and Head of the Department of Civil Engineering, DTU-Delhi for the facilities extended. A special thanks to Prof. R.K Arya, Professor of Civil Engineering Department, DTU-Delhi for clarifying my doubts and providing suggestion during the early phase of my work.

Special thanks to Prof Nayan Sharma Sir for providing me valuable suggestions and allowing me to perform experiments in IIT Roorkee labs under his guidance and Lab Assistant Beer Singh Chauhan Sir for guiding me during the experiments during the experiments for the preparation of this thesis.

Special and sincerest thanks to my Mother Usha Gupta, Father Rajesh Gupta, my Sister Swati Gupta for their persistent support, encouragement and prayers throughout the duration of my study at Civil Engineering Department, Delhi Technological University , Delhi.

Ultimately I would like to thank Almighty God for giving me the chance to study in this prestigious institute.

Date: July ,2014 Akhil Gupta

Place: Delhi Roll No. 2K12/HFE/12

ABSTRACT

Scour is the main damage cause of abutments, piers, spur dykes and the hydraulic structure in the river bed .Change in flow characteristics lead to changes in sediment transport capacity, and hence to a local disequilibrium between actual sediment load and the capacity of the flow to transport sediment. At times it is required to provide greater channel depth for the purposes of Navigation as the depth available is less than the required depth.

The technique of Submerged Vanes helps in performing both the works simultaneously. The technique of submerged vanes is a new, cost-effective and efficient sediment management method in rivers. This method has positive environmental effects. The performance and efficiency of a submerged vane is related to its shape.

In this dissertation, Submerged Vanes performance analysis is done with different attacking angle in order to study the effect of scouring and deposition occurring due to different attacking angles and thus developing their Bed Profile and Developing their Speed Profile in the flume at various points.

Contents

List of Tables

List of Images

List of Figures

CHAPTER 1

INTRODUCTION

1.1 Submerged Vanes

Submerged Vanes is the latest technique which reduces the severity of floods. These can be small, double, rectangular, curved, patented structures for sediment management in rivers for better River Training works. They are designed for the protection of the river banks, maintain navigation depth and flood flow capacity in rivers and control sediment at diversions and water intakes during the severe times even. The Vanes are small, submerged (to a depth of one-third to one-fourth)flow training structures or foils designed to modify the near flow bed pattern and distribute sediment load and flow within the channel cross section.

They are designed for small aspect flow training structures installed on the streambed, usually oriented at 10° to 25° to the local primary flow direction. Vane height is usually 0.2 to 0.4 times the local water depth during the design flow conditions. In curves key to vane performance is horizontal force that they exert against water flow and effects on circulation induced in flow downstream from vanes and near bed flow.

1.2 River Training Work

River Training Work involves all the engineering works which are constructed in the river so as to confine and guide the flow in the river channel, and to control bed configuration thus ensuring safe and effective disposal of floods and sediment loads.

In a river at times it is required to provide greater depth than what is available for the purpose of Navigation and whatever the Sediments get eroded from the banks of the river needs to be addressed.

The technique of Submerged Vanes solves our both the above problem simultaneously as it scours the bed where channel depth is to be increased and it deposits the sediments where erosion on the banks occur.

In this dissertation we will be working Submerged Vanes for angles 10^0 and 15^0 and the Vane height is .33 times the local water depth. With the course of this study we will be studying the effect on the bed profile during the experiment and how much deposition and scouring occurs due to Submerged Vanes. Also the Speed profile of the channel will also be studied and assessed with the help of the instrument named Acoustic Doppler Velocimetry.

CHAPTER 2

Literature Review

2.1 Sediment management with Submerged Vanes

Sediment control in rivers may be required for greater channel depth for maintaining a certain optimum flow depth so that navigation can be made possiable, prevent bed and bank erosion due to action of water, improve non regime channel or divert flow from one channel to another, or to a water intake. Many different techniques are available for that. They range from construction of wing dams, jetties, dykes, and revetments to dredging. All these techniques lacks of analytical tools for predicting their effectiveness and impact on the channel and to what extent they simplify our problem which is quite important factor for the study and analysis of any structure

Submerged Vanes is the new eco-friendly technique which helps not only providing greater depth but also deposits the sediments where scouring is to be prevented by the process of deposition. Submerged vanes can be made from plastic, concrete, wooden planks, wooden piles, sheet piles etc.

Submerged vanes(by controlling the sediments) can be used for stream bank protection, increasing channel capacity, maintaining a certain flow depth, realigning of stream etc. which in turn can be effectively used in flood management.

2.2 Working of Submerged Vanes

The vane generates secondary air circulation in the direction of flow. The circulation alters magnitude and direction of the shear bed stress and causes a change in the distribution of speed, depth and sediment transport in the area influenced by the vanes. As a result, the riverbed aggrades in one portion of the channel cross section and degrades from another thus thereby providing erosion of the bed as well as deposition wherever it is required. The control of the sediment load movement, scouring and deposition is one of the most difficult problems faced by river engineers. Bed scours along the bank of the river curves frequently causing undermining of bank and losses of soil which leads to subsequent flooding and bank breach in the marginal area.

By directing the near bed current towards the outer bank, the submerged vanes counter the centrifugal induced secondary current and, hence inhibit bank erosion. The vanes stabilize the toe of the bank.

The vanes are laid out to make the water and sediment move through the river curve as if it is straight. These vanes can be arranged in various combinations as per required by the designers. Regardless of size small submerged vanes can also produce significant changes in the distribution of velocity and depth in the river channel. By introducing relatively small changes in the bed shear stresses, arrays of vanes can generate local changes in the bed elevation of the order of vane height.

These vane changes the bed profile of the channel accordingly on the magnitude of the flow and in the direction of Submerged Vanes being laid for the purpose of requirement.

2.3 Dimension and Shape of Submerged Vane for Sediment Management

The performance of the submerged vane is also related to its dimensions and shape. The effectiveness of the Submerged Vanes varies from shape to shape and size to size .In curved structure the changes are gradual whereas in Rectangular structures the variation in the bed profile are quite abrupt.

Variation of Submerged Vanes for different requirements various accordingly

(1) Rectangular plates with various lengths and heights.

(2) Tapered plates with linear increasing or decreasing in length from the base to the top

(3) Plates of parallelogram or other shape with the top of the plates swept backward or forward.

Various model tests have been conducted for the calculation of transverse bed profile in the cross section of a straight alluvial channel induced by a single submerged vane is induced. The model is utilized to investigate the performances for three types of vanes

2.4 Effect of Angle Of Submerged Vanes

Investigation on scouring, deposition of the sediment load and determination of hole of scouring are among the most important issues in submerged vanes designation with model submerged vanes were measured in a laboratory flume with 10° under clear water. Experiments are majorly conducted for attacking angles of attack 15, 20, 25 and 30 degree with a flow for various Froude Numbers.

The result of the model study had indicated that the maximum value of scour and deposition of bed load is highly depended on experimental duration. It was observed that, suitable control at scour hole associated with angle 15 degree submerged vane. With increasing Froude number the maximum scour hole increases.

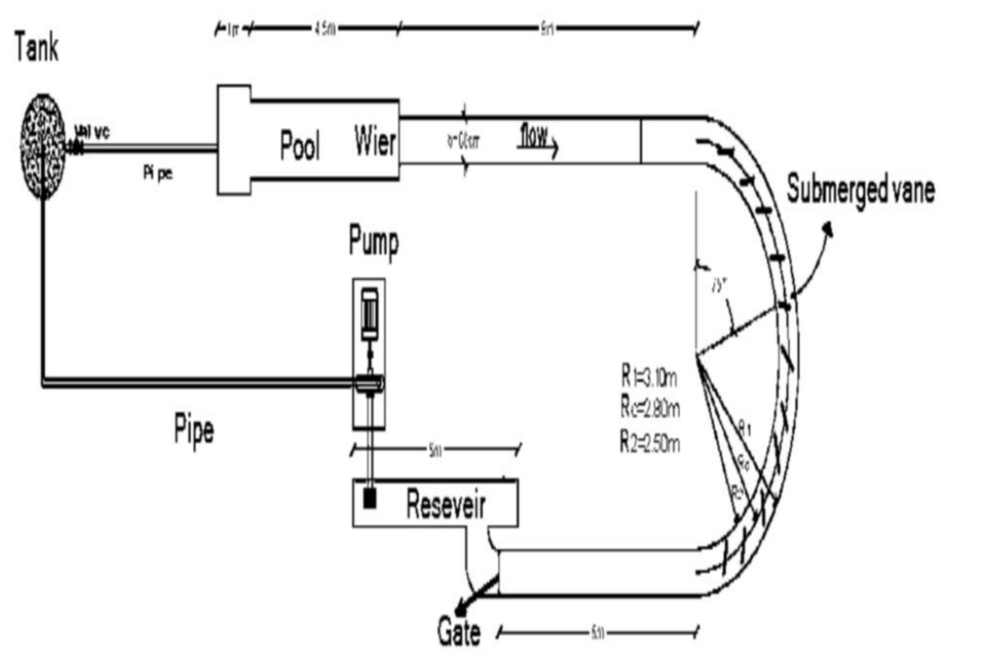


Fig. 3: The experimental setup (Plan)

Fig 2.1 Experimental Setup

The experiments were conducted on four different Froude's Number.

- 0.286
- 0.269
- 0.252
- 0.236

The scour occurring at a submerged vane is divided into three categories:

- General Scour
- Constriction Scour
- Local Scour

Local Scour results directly from the impact of submerged vanes on the local flow pattern.

Fig. 4: A submerged vane and scour hole (Plan)

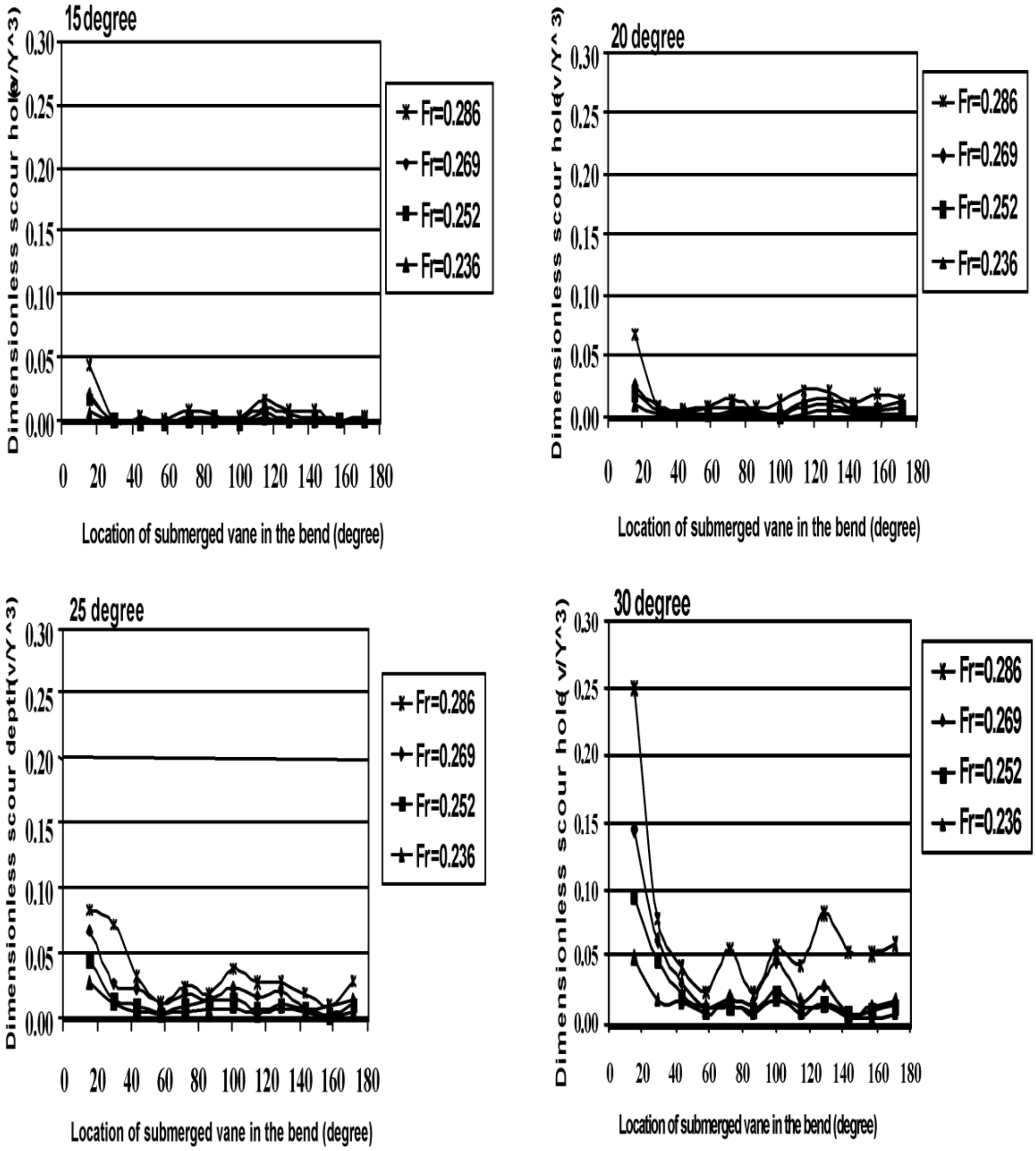


Fig 2.2 Graph-1

Fig. 5: Scour hole for different Froude number

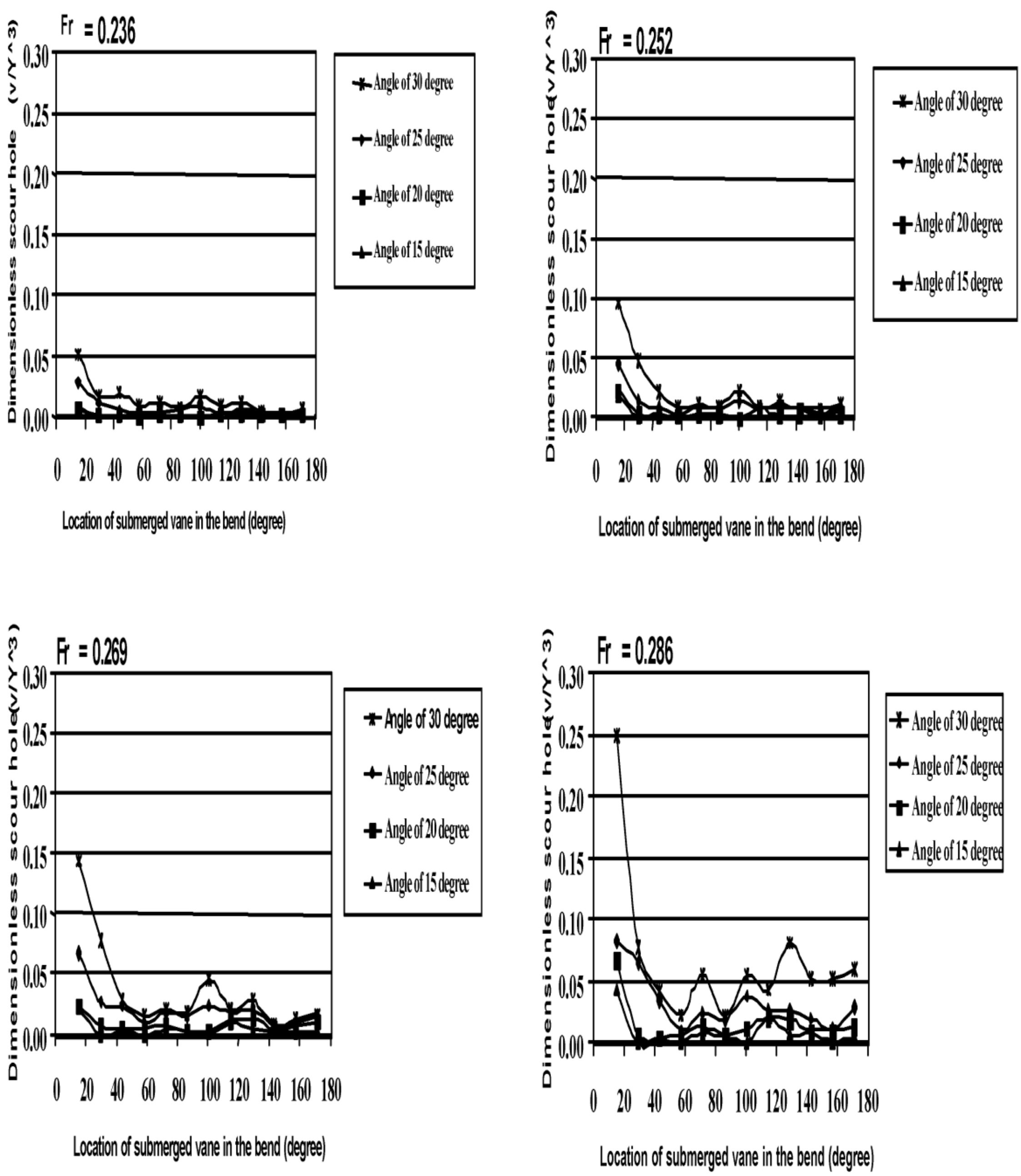


Fig. 6: Scour hole for different angle

Fig 2.3 Graph-2

2.5 Bank Attached Vanes for Bank Erosion Control and Restoration of River Meanders

Spurs or Groynes for bank protection have few limitations that a considerable part of the width of the channel is blocked. Large reverse eddies are formed behind these structures creating embayment or causing excessive siltation which can adversely affect instream biodiversity .Prescribing the optimum angles, relative to the tangent at the bank, and the location for such spurs on the outer bank of an eroding bend are major challenges. Similar problems also exist in case of submerged vanes due to the variation of angle of attack of the flow as stage levels change. In rivers with finer bed materials, scour around the base of individual vanes can affect their structural integrity (Odgaard and Spoljaric).The bank-attached vane, on the other hand, is a spur-type instream structure. They have been advocated for bank protection and habitat improvement. Vanes have also been proposed for reducing Local Scouring near bridge abutments. However, the flow patterns induced by these vanes and their working principle, needs further clarification.

CHAPTER 3

Submerged Vanes

It is a hydraulic structure which is built across the river so that the severity due to floods can be minimized. These vanes works by producing secondary air circulation which tends to distribute the flow and the bed stresses of the river as per the requirement. Due to generation of reverse eddies in the flow the river beds gets aggraded from one side and degrades from another.

Submerged Vanes is a new technique which helps us in keeping check on river bank erosion as well as providing channel depth for navigation purposes simultaneously thus two problems are solved by Submerged Vanes.

Depending on the requirements these vanes can be arranged in various shapes or order. For example Four Vanes can be arranged in a horizontal line or the same Four Vanes can be arranged in a zig-zag manner or any other pattern such that the requirements are full filled. These vanes are laid to certain angles to the direction of flow .These angles can vary from 10^0 to 30^0 which are assessed as per the designer. Generally it is observed that for attacking angle of 15^0 the best results are attained. The performance of these vanes is independent of its size. These vanes introduce small-small changes to the river bed conditions. These vane changes the bed profile of the channel accordingly on the magnitude of the flow and in the direction of the Vanes are laid.

These vanes can be very easily be made up of from various sources like from Plastics, Wood (bamboo), Concrete, Sheet Piles etc. although for quick installation and working Bamboos are preferred cause they could be directly embedded into the river bed without any extra requirements.

These vanes are embedded to a depth of One-Third to One-Fourth of its height and the flow of water maintained in the river is three times its depth in water such that the secondary currents can be generated.

Due to all these various benefits and its eco-friendly aspect Submerged Vanes are fast developing its name in the field of Hydraulic Structure as it very convenient to install and use with good performance. Various projects regarding Submerged Vanes are initiated in India and are in progress.

CHAPTER 4

River Training Works

It is a wider aspect which deals with the Engineering works which are constructed on a river so as to safely allow the passage of the water in the river without changing the bed condition such that the flow direction and the Shear Bed Stress does not affect.

4.1 Importance of River Training Works

River Training works guides and ensures the flow in the river channel and to control and regulate the river bed condition such that scouring in the bed or at the banks is minimised if not stopped. Thus outflanking is avoided with the help of them they also ensure safe disposal of the sediment bed load thus ensuring unnecessary deposition or scouring. They also provide navigational depth. Its chief aim is to provide ultimate stability to the river with its help and measures.

4.2 Objectives of River Training Works

- Prevent rivers from changing their direction of flow thus avoiding the outflanking of structures.
- To provide flooding of surrounding area by providing a safe passage for the flow without overtopping.
- To protect the banks by deflecting the river away from the banks.
- To effectively dispose of sediment load.
- To provide sufficient depth for Navigation purposes.

4.3 Methods Adopted for River Training

- Levees
- Guide Banks
- Submerged Vanes
- Groynes or Spurs
- Artificial Cut Off
- Pitched Islands
- Bandalling
- Pitching of banks and provision of Launching aprons.
- Miscellaneous Methods

4.4 Classification of River Training

Depending on the nature of the River Training Work, these are classified into following categories :

1. High Water Training or Training for Discharge
2. Low Water Training or Training for Depth
3. Mean Water Training or Training for sediment

4.4.1 High Water Training

This type of training work primarily works on the purpose of flood control. Thus it aims at providing minimum river cross-section for the passage of Maximum River Flood & is concerned with making the adjoining place flood-proof by construction of levees or dykes etc.

4.4.2 Low Water Training

This type of training work primarily works on the purpose of providing minimum depth in the channels during low water periods. It is attained by concentrating and improving the flow in the channel by closing other rivers.

4.4.3 Mean Water Training

This type of training work primarily works on the purpose of providing at efficient disposal of bed load and sediment load and thus preserves the channel in good shape. The maximum accretion of a river occurs near the dominant or water discharge.

Thus the changes in the bed are tried as per the stage of the flood flow. This type of training work is one of the most important of all and also forms the basis on which the earlier two are planned.

CHAPTER 5

Acoustic Doppler Velocimetry

Acoustic Doppler Velocimetry is an instrument which measures instantaneous velocity in all the direction for a point with a relatively high frequency. This technique is based upon the Doppler Shift Effect.

5.1 PROBE & TIP

The probe consists of one transmitter and three receivers which are placed at an equal distance with each other so that when the particle crosses between any two receivers the velocity of the particles can be measured.

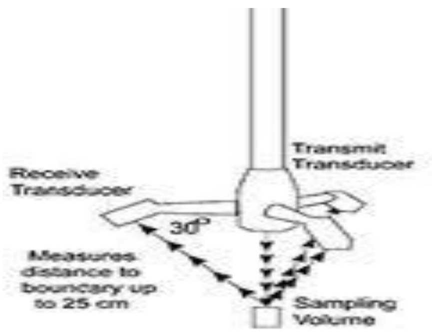


Fig 5.1 : Acoustic Doppler Velocimetry

The velocity measured can be either positive or negative depending on the direction of the probe. The ADV signals also compute the noises generated by machines, turbulent shear and other nearby noises. These data has to be eliminated so that a better data can be analysed. These variations are called Spikes and are removed by various techniques.

The height between the Sample Volume and the Probe tip is generally maintained around 5 cm and if the difference varies from this range then the position of the Probe is slightly changed so that the correct difference can be attained.

The Probe Number used in the experiment of Submerged Vanes is A1047.

This ADV instrument is connected to a computer system from where the data regarding the velocity is collected and converted to MS-Excel sheets.

These sheets are developed after completing the run fully for 6-8 hours, so that the velocity profile around the Submerged Vane can be developed.

Image 5.1 Showing ADV Probe and Tip while taking a reading

CHAPTER 6

Experiment Procedure

The experiments were conducted for 10^0 and 15^0 attacking angles of Submerged Vanes, in which they were placed at an angle of 10^0 and 15^0 to the direction of flow of water. The starting point of the vane was placed at the centre of the flume which is 3m X 0.5m at an angle of 10^0 and was embedded into the bed to a height of 3cm such that 4cm height of the vane is above the bed of the flume.

Image 6.1 Showing collection of readings during the experiment

Water was allowed to run in the flume and a constant depth of 12cm was maintained throughout the experiment. The bed profile was viewed regularly at constant interval of time period and after Six hours of Duration the Velocity Profile of the channel was developed with the help of Acoustic Doppler Velocimetry.

The ADV was placed at 5cm upstream side of the Vane and was moved laterally in three different positions and at each position three readings were taken by changing the depth of the reading gauge.

For ex

Reading 1: 5cm Upstream at a distance of 3.25cm in lateral direction at a depth of 77cm.

Reading 4: 5cm Upstream at a distance of 0 cm in lateral direction at a depth of 77cm.

After completing 9 readings for 5cm Upstream the ADV was shifted to 3cm Upstream of the Vane and 9 more readings were collected in a similar manner.

The Velocity Profile of the channel was generated with the help of ADV which was connected to a system and the profile was developed in MS-Excel Sheets.

After developing Velocity profile of the Channel with the help of ADV the bed profile was developed after emptying the flume and depth of the bed was taken at several location throughout the surrounding area of the vanes and the graph was developed

Image 6.2 Showing flowing of the water in the flume

Then the Submerged Vane was again set up for 15^0 of attacking angle to the direction of flow of water and similarly the Vane was embedded into the bed to a depth of 3cm and 12cm depth of flow was maintained throughout the experiment.

The same procedure was followed as it was done during 10^0 of attacking angle and the bed profile for it was generated.

CHAPTER 7

Experimental Work

The experiments were conducted in the River Engineering labs of IIT Roorkee under the guidance of Prof Nayan Sharma and Lab in Charge Beer Singh Chauhan Sir.

The water was allowed to run through the Flume and the Submerged Vane made of plastic was placed at the middle of the flume at different angles to the flowing water.

The Bed Profile for two different attacking angles was studied near the Vane at different time intervals and velocity profile was also studied with the help of Acoustic Doppler Velocimetry.

Flume Dimensions = 3m X .5m

Vane Dimensions = 7cm X 14cm

Positioning of the Vane = 1.5 m upstream

Vane bedded to a Depth of = 3cm

Depth of Water maintained in the Flume = 12cm

Discharge Maintained = 10 litres/sec

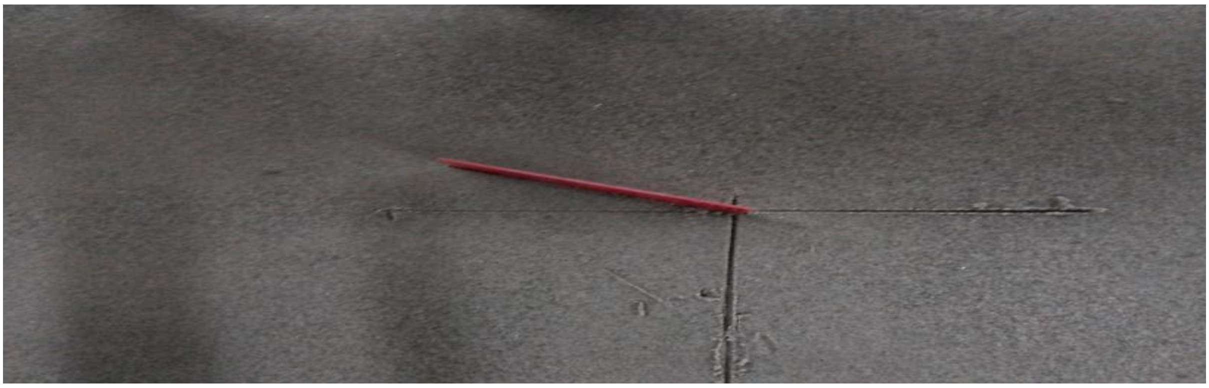


Image 7.1 Plane Bed Profile Initially

7.1 Deflecting Angle 10°

Bed Level at 1m Upstream = 50.47cm

Bed Level at 2.9m Upstream = 49.55cm

Slope of the Bed = $(50.47 - 49.55)/190$

= 0.00484

= 1 in 206

Discharge = 0.01m^3/sec

7.1.1 Bed Profile

Head of the Submerged Vane is considered to be the origin and all the values are taken accordingly

Table 7.1 : Bed Profile Values for 10°

Cms	-13.5	-10.5	0	3	4
-2	0.40	-0.46	-1.06	-0.13	0.05
-1	0.52	0.78	-1.09	-0.13	0.04
0	0.62	0.84	-1.23	-0.14	0.02
1	0.41	0.44	-1.20	-0.15	0.05
2	0.19	0.28	-1.10	-0.14	0.07

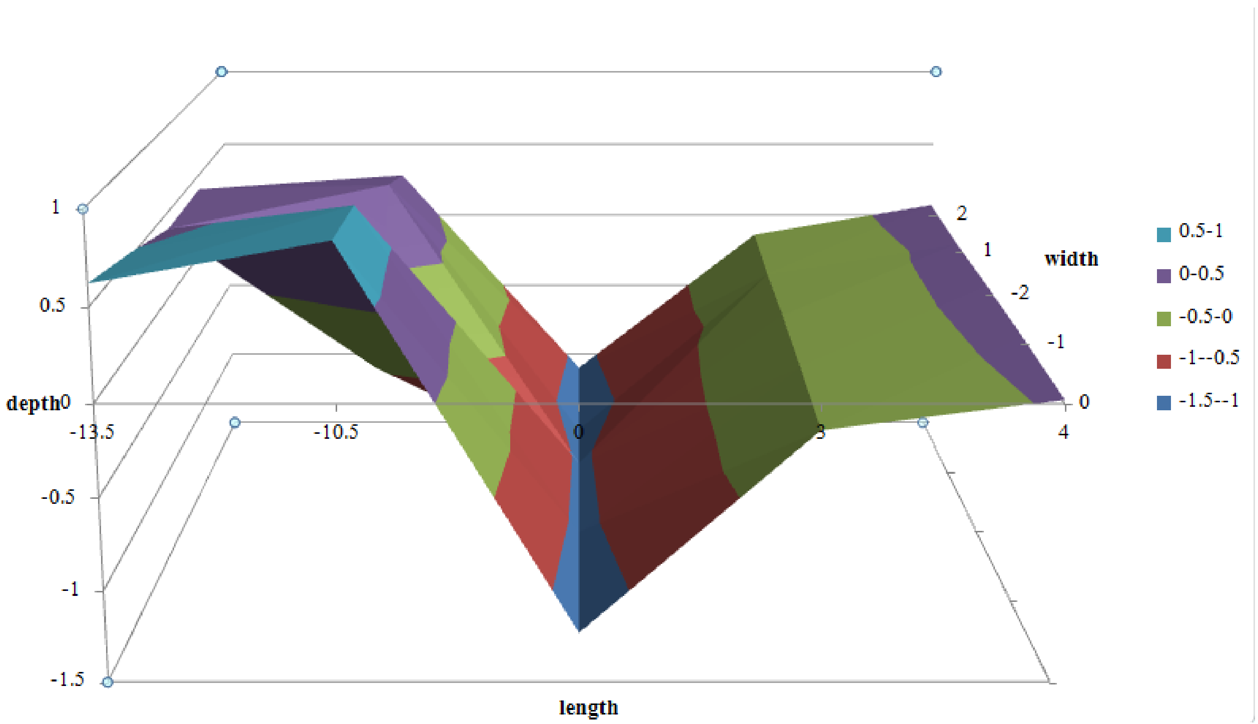


Fig 7.1 : Showing Bed Profile for 10° Angle

7.1.2 Speed Distribution

7.1.2.1 Speed Distribution from 5 cm upstream of the Submerged Vane

Table 7.2 : Showing Mean Speed at 5cm Upstream

Depth of Water in cm ↓ / Lateral Distance from the Vane(cm) →	3.25	0	-3.25
77	7.5814	6.1062	6.3700
76	8.3811	3.2851	6.7471
75.5	4.6974	7.8982	7.1790

7.1.2.2 Velocity Variation at 5 cm Upstream and 3.25 cm away from the Vane

Run 2

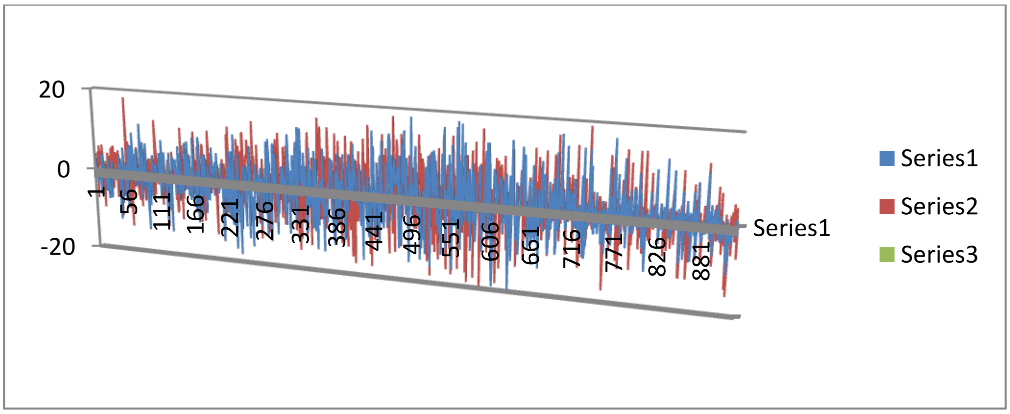


Fig 7.2 : For 77 cm depth

Run 3:

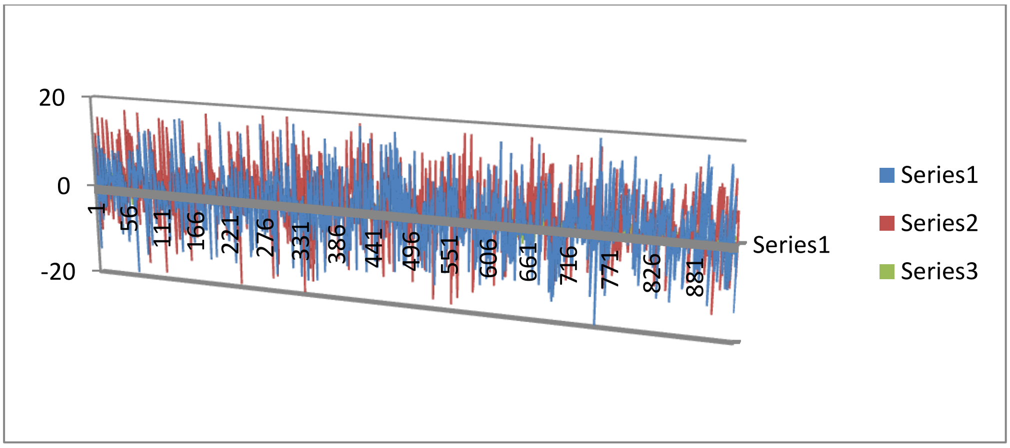


Fig 7.3 : For 76 cm depth

Run 4

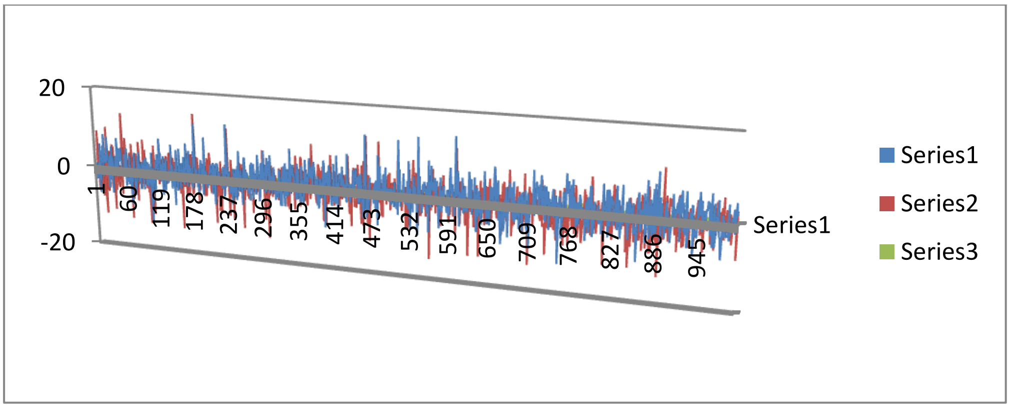


Fig 7.4: For 75.5 cm depth

7.1.2.3 Velocity Variation at 5cm Upstream and 0 cm away from the Vane

Run 5

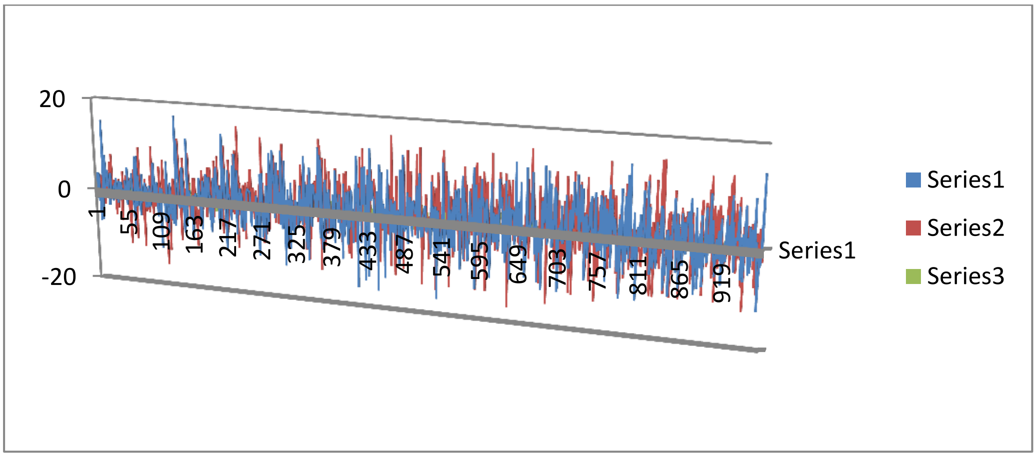


Fig 7.5 : For depth 77cm

Run 6

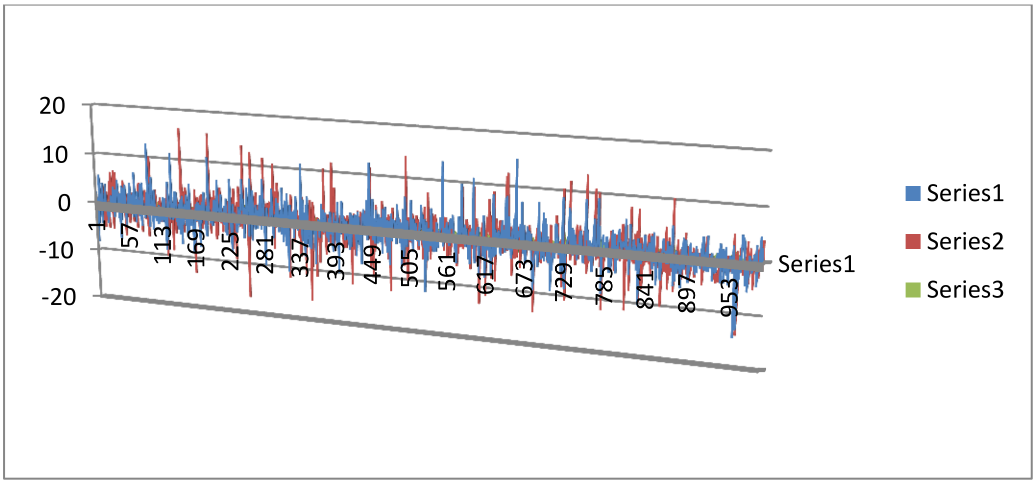


Fig 7.6 : For depth 76cm

Run 7

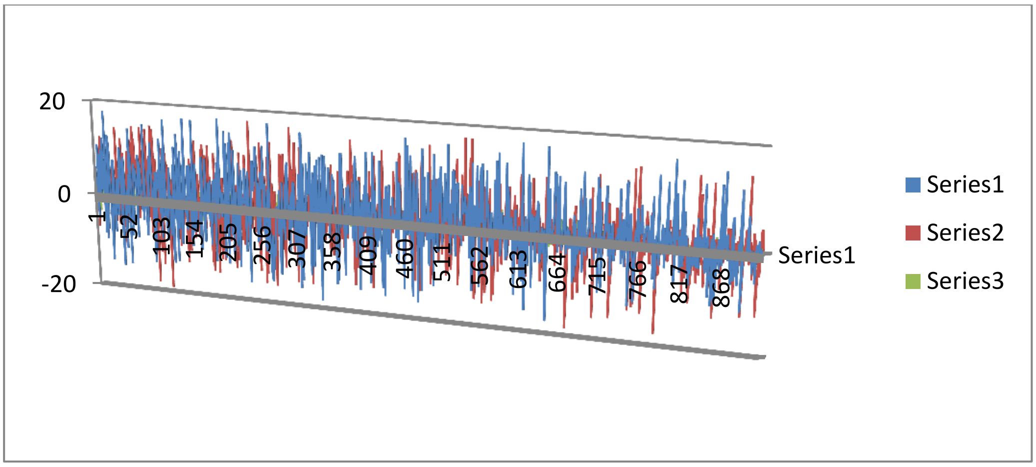


Fig 7.7 : For depth 75.5 cm

7.1.2.4 Velocity Variation at 5cm Upstream and -3.25 cm away from the Vane

Run 8

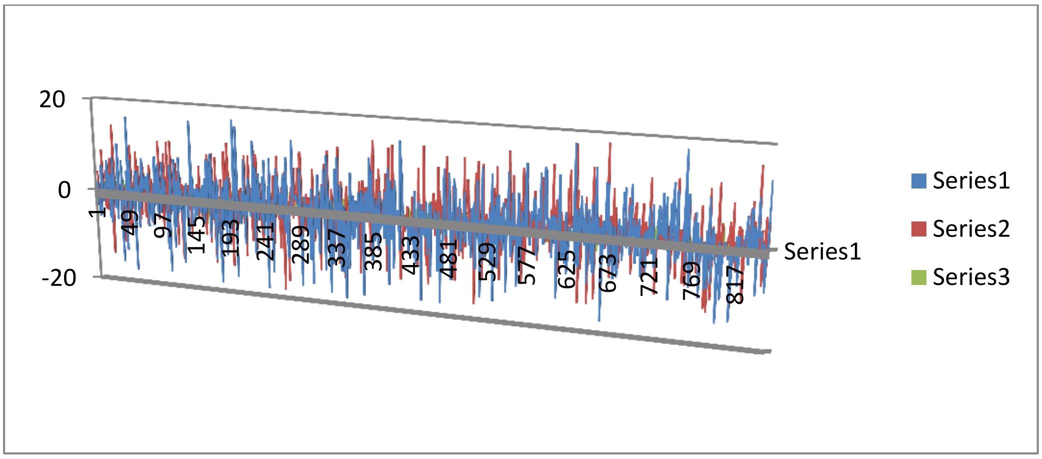


Fig 7.8 : For 77cm depth

Run 9

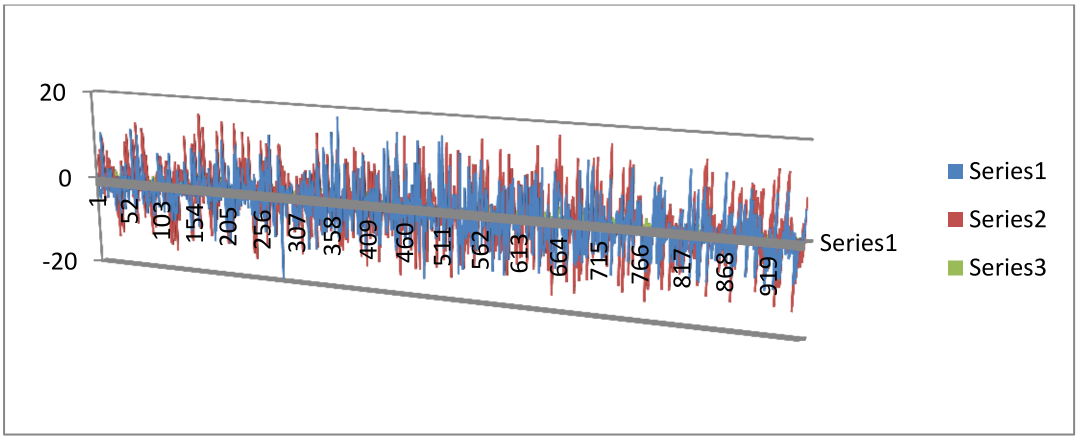


Fig 7.9 : For 76 cm depth

Run 10

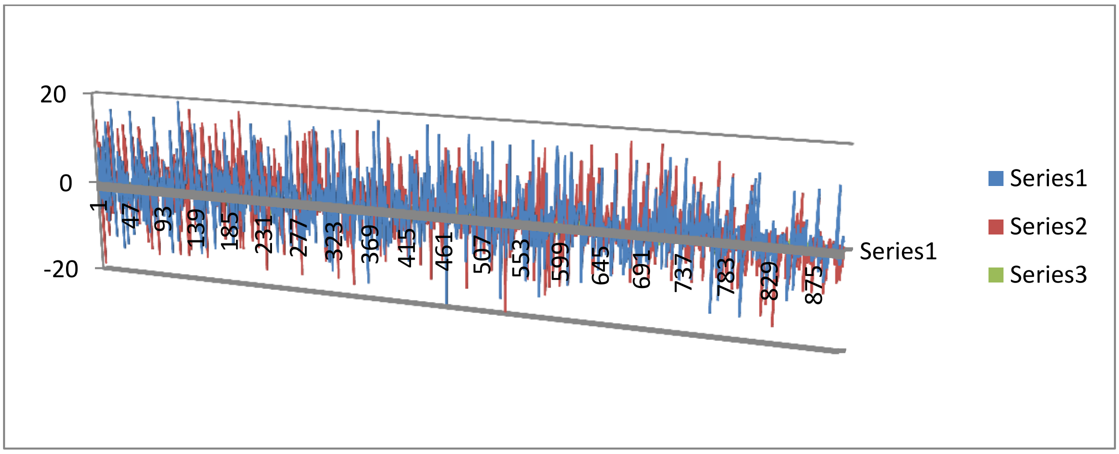


Fig 7.10 : For 75.5 cm depth

7.1.2.5 Speed Distribution from 3 cm upstream of the Submerged Vane

Table 7.3 :Showing mean speeds at 3 cm Upstream

Depth of Water in cm ↓ / Lateral Distance from the Vane(cm) →	-3.25	0	3.25
77	7.3389	3.2558	5.0149
76	5.2886	6.2747	8.1889
75.5	11.1790	5.4614	5.2068

7.1.2.6 Velocity Variation at 3cm Upstream and 3.25 cm away from the Vane

Run 11

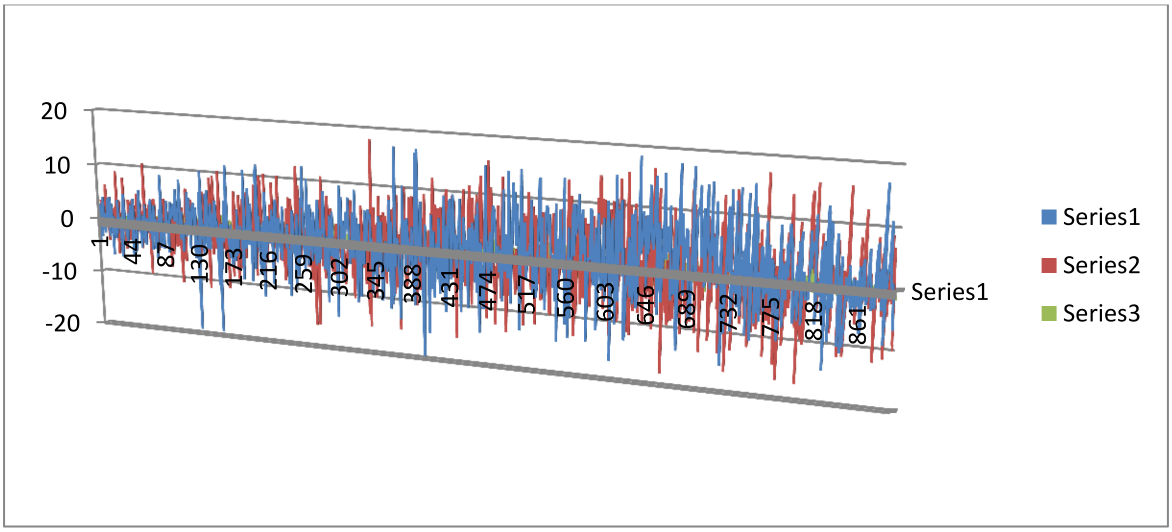


Fig 7.11 : For 77 cm depth

Run 12

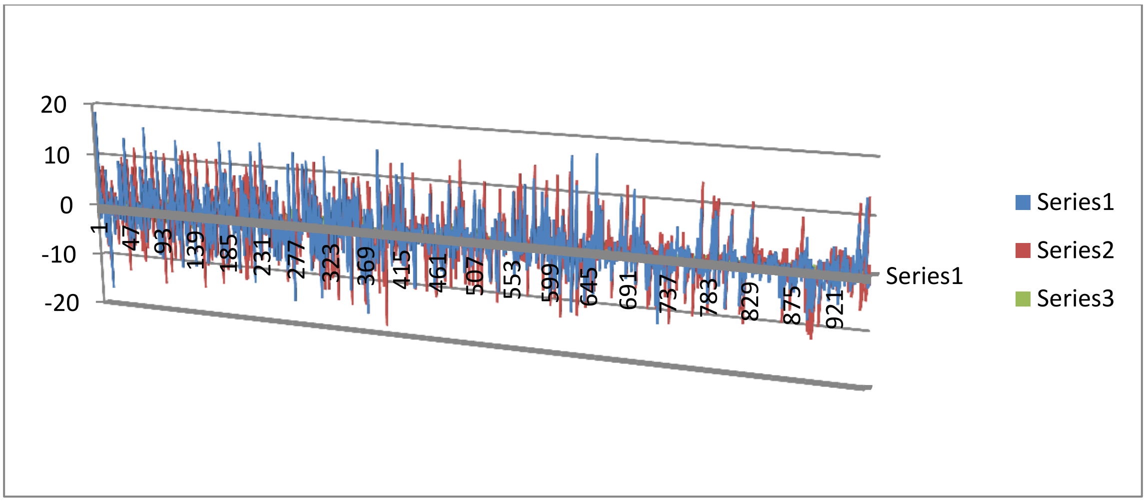


Fig 7.12 : For 76 cm depth

Run 13

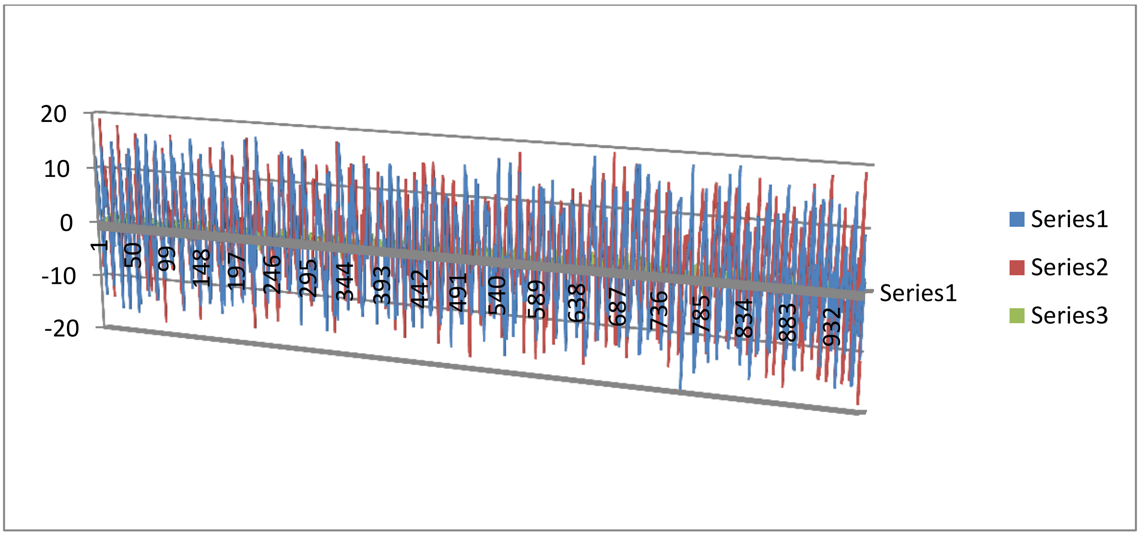


Fig 7.13 : For 75.5 cm depth

7.1.2.7 Velocity Variation at 3cm Upstream and 0 cm away from the Vane

Run 14

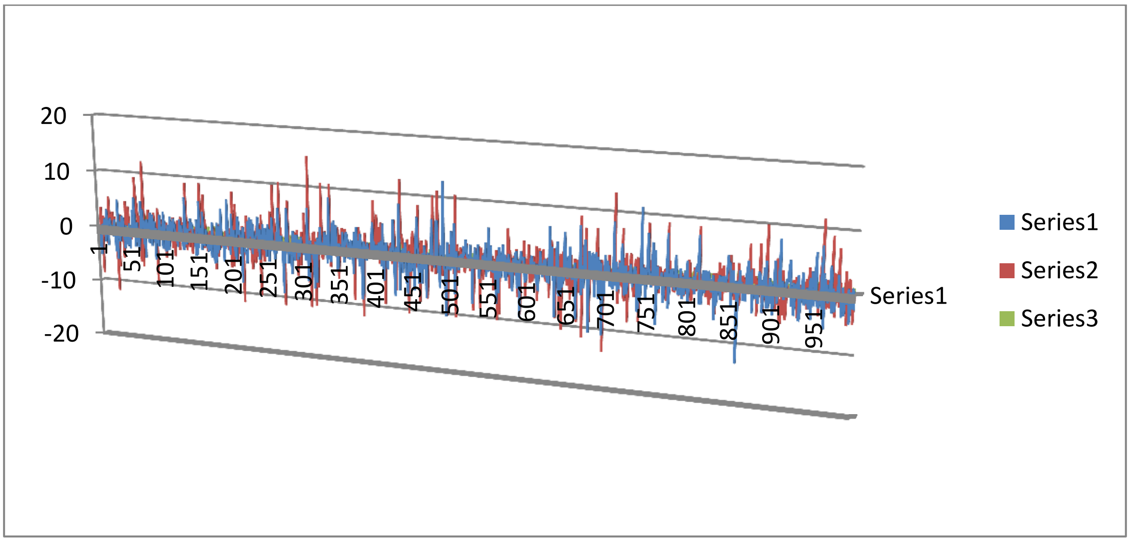


Fig 7.14 : For 77 cm depth

Run 15

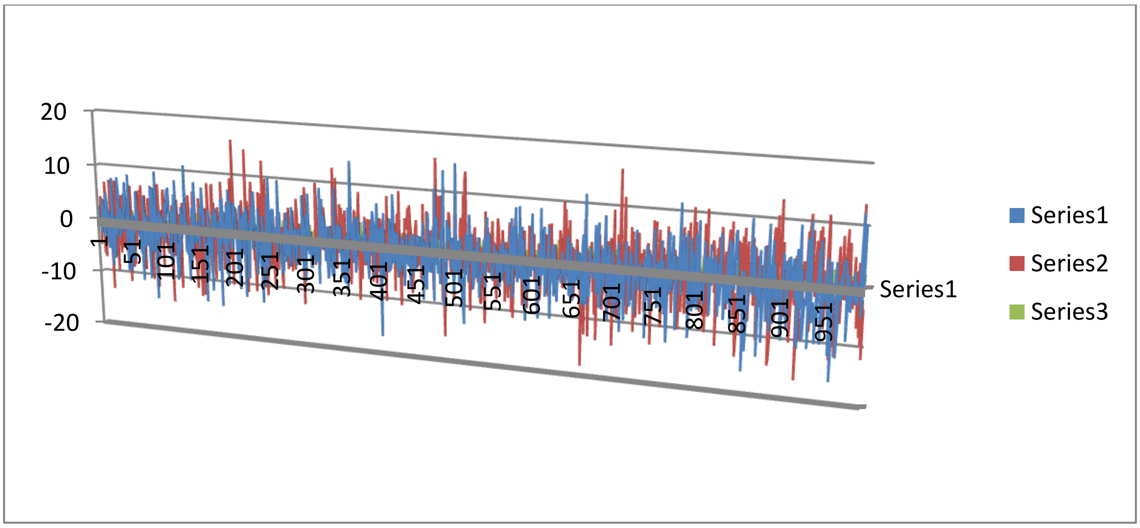


Fig 7.15 : For 76 cm depth

Run 16

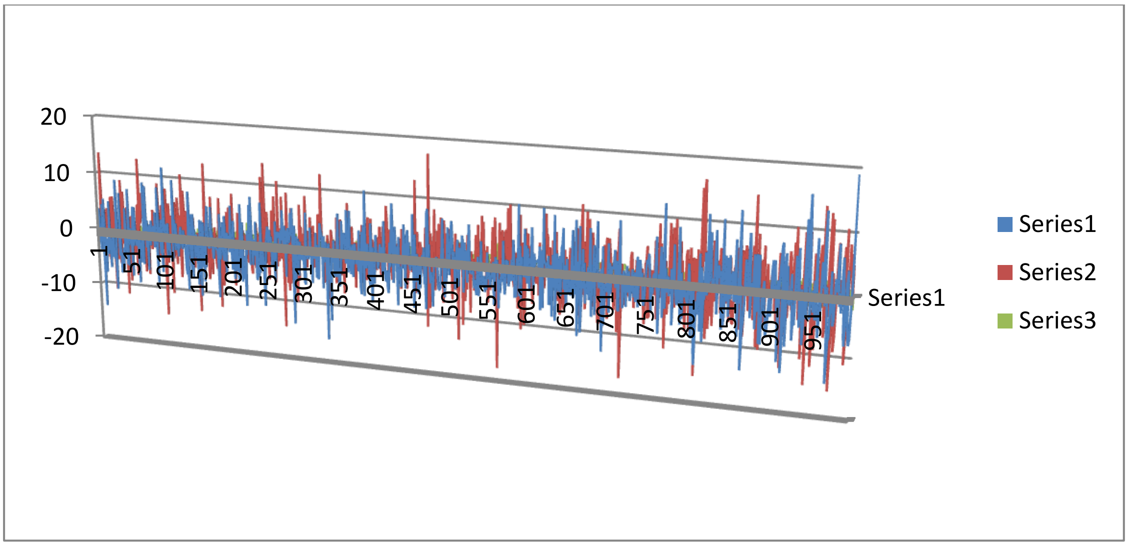


Fig 7.16 : For 75.5 cm depth

7.1.2.8 Velocity Variation at 3cm Upstream and -3.25 cm away from the Vane

Run 17

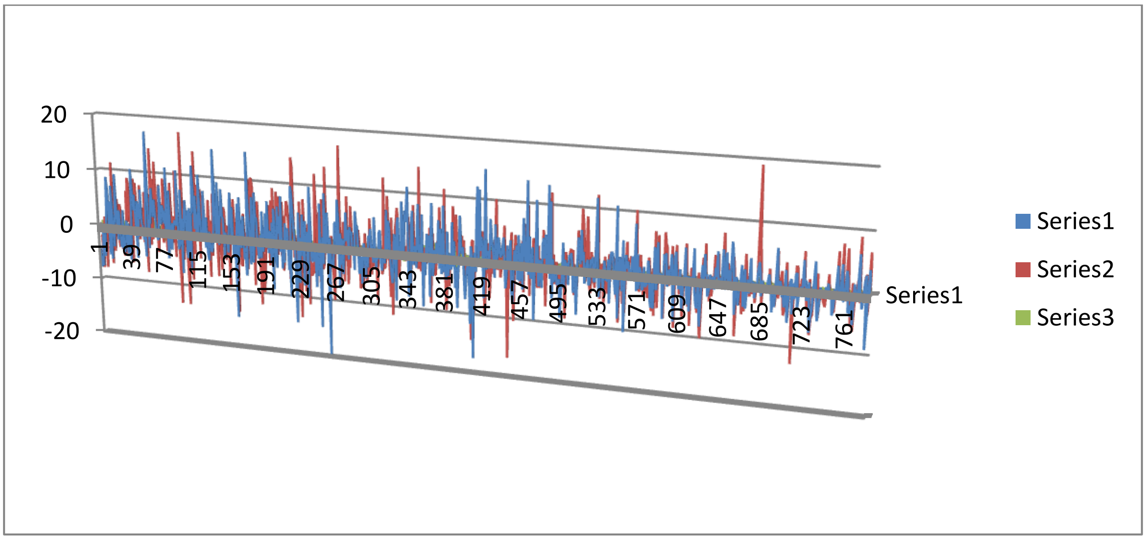


Fig 7.17 : For 77 cm depth

Run 18

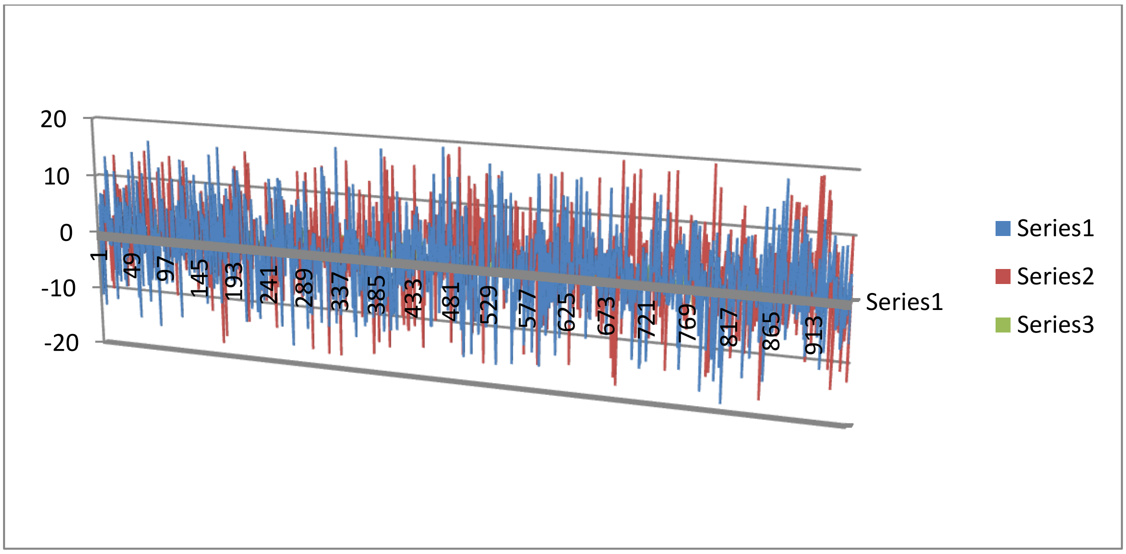


Fig 7.18 : For 76 cm depth

Run 19

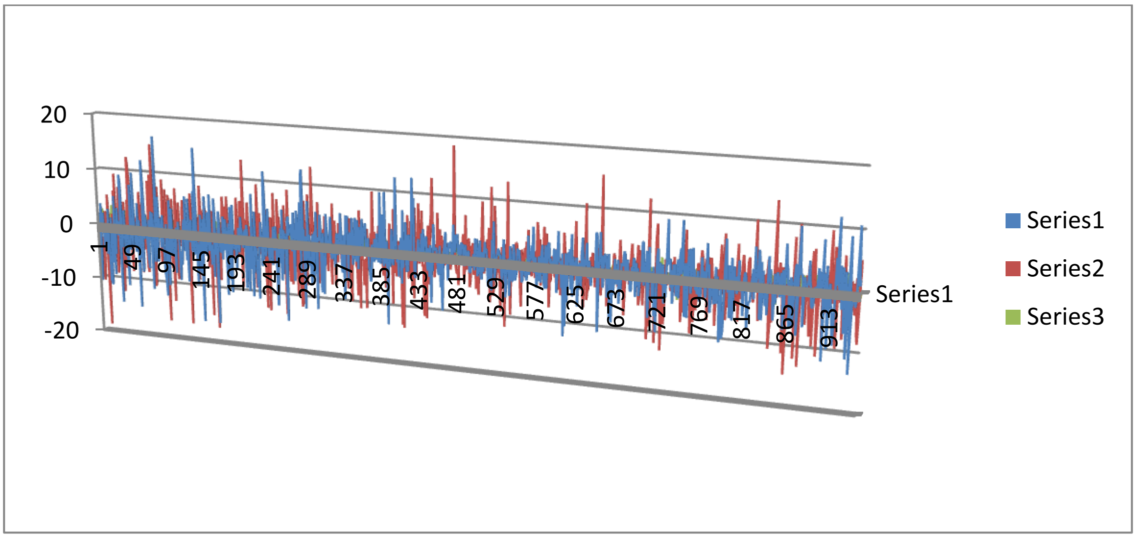


Fig 7.19 : For 75.5 cm depth

Different Images of Bed Profile for 10⁰ Attacking Angle

Image 7.2

Image 7.3

Image 7.4

7.2 Deflecting Angle 15°

Bed Level at 2m Upstream = 50.34cm

Bed Level at 1m Upstream = 49.95cm

Slope of the Bed = $(50.34 - 49.85)/100$

= 0.00490

= 1 in 204

Discharge = 0.01m^3/sec

7.2.1 Bed Profile

Head of the Submerged Vane is considered to be the origin and all the values are taken accordingly

Table 7.4 : Bed Profile Values for 15°

cms	-13.5	-10.5	0	3	4
-2	0.44	0.9	-1.17	-0.13	0.05
-1	0.57	0.96	-1.24	-0.14	0.06
0	0.72	0.91	-1.33	-0.16	0.07
1	0.51	0.73	-1.26	-0.15	0.05
2	0.33	0.49	-1.22	-0.14	0.04

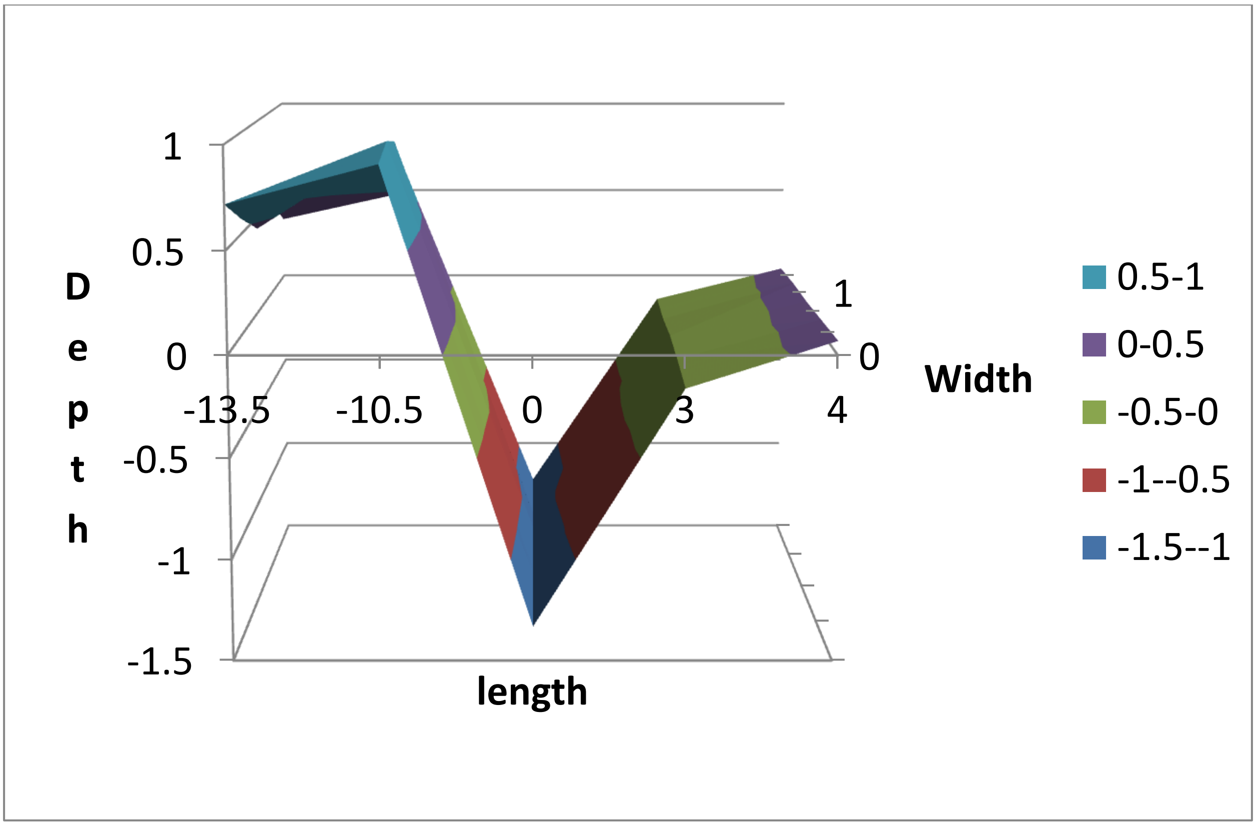


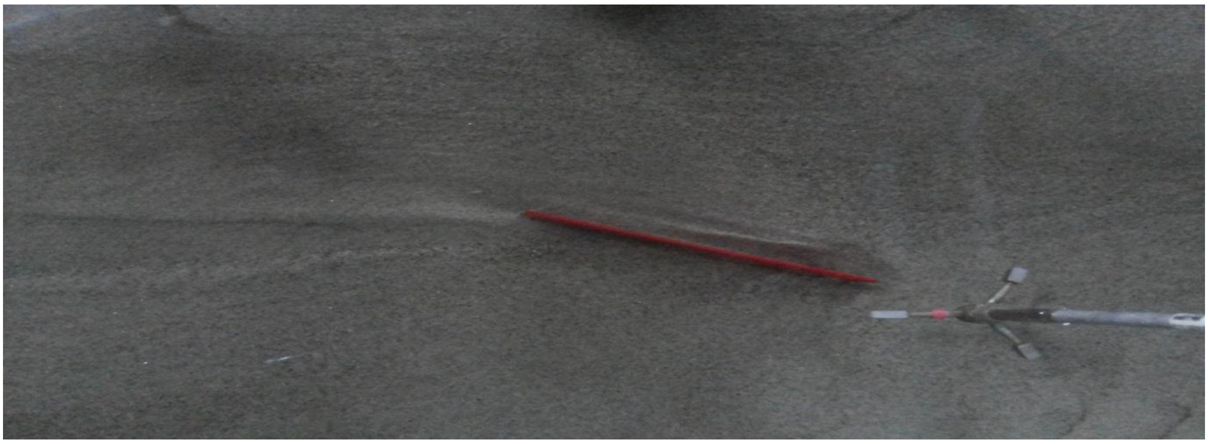
Fig 7.20 : Showing Bed Profile for 15° Angle

Different Images of Bed Profile for 15^0 Angle

Image 7.5

Image 7.6

Image 7.7



CHAPTER 8

RESULT & CONCLUSION

The bed profile for two angles that are 10^0 and 15^0 is generated with the help of MS-Excel and is observed that in the case of both the angles near the Starting of the Submerged Vanes the soil bed gets eroded and near the far end of the Vane the soil gets deposited along the Vanes, Furthermore it was observed that the degree of bed erosion and deposition is more prominent in the case of 15^0 Angle.

The Speed profile of 10^0 Angle is generated with the help of Acoustic Doppler Velocimetry.

The bed profile changes in the both the angles which were visualized at various interval of time and it was observed that the bed profile changes starts at a good speed in the beginning but gradually it starts decreasing and then after 3-4 hours the bed profile changes becomes constant or it does not change at all although the experiments is supposed to run for Six Hours.

The Speed profile which is developed with the help of Acoustic Doppler Velocimetry consists of various noises generated from turbines, machines etc. thus they are removed in the MS-Excel sheet and the Speed Profile is developed of the reduced number of particles. A lower and a higher value was set up of the velocities of the particles and only the desired values were computed for generating the Speed of the flume at various location at the upstream side of the Submerged Vanes.

The graph for the individual location was generated by depicting the velocities in three different directions with Series-1 indicating velocity in x-direction, Series-2 indicating velocity in y-direction and Series-3 indicating speed in z-direction

CHAPTER 9

REFERENCES

1)American Society of Civil Engineers (ASCE). (1975). *Sedimentation engineering*, ASCE Manuals and Reports on Engineering Practice No. 54, ASCE, New York, N.Y.

2) Barkdoll, B. D., Ettema, R., and Odgaard, A. J. (1999). "Sediment control at lateral diversions:Limits and enhancements to vane use," *J. Hydraul. Eng.*, 125(8), 862–870.

3) Biedenham, D. S., Elliot, C. M., and Watson, C. C. (1997). "The WES stream investigation and streambank stabilization handbook," U.S. Army Corps of Engineers, Vicksburg,Miss.

4) Bledsoe, B. P., and Watson, C. C. (2001). "Logistic analysis of channel pattern thresholds:Meandering, braiding, and incising," *Geomorphology*, 38, 281–300.

5) Doyle, M. W., Shields, D., Boyd, K. F., Skidmore, P. B., and DeWitt, D. (2007). "Channelforming discharge selection in river restoration design," *J. Hydraul. Eng.*, 133(7),831–837.

6) Ettema, R. (1990). "Bathymetric survey of the Cedar River at the Duane Arnold EnergyCenter," IIHR LD Report No. 166, The University of Iowa, Iowa City, Iowa.

7) Odgaard, A. J. (1987). "Streambank erosion along two rivers in Iowa," *Water Resour. Res.*,23(7), 1225–1236.

8) Odgaard, A. J. (1989a). “River-meander model. I: Development,” *J. Hydraul. Eng.*, 115(11),1433–1450.

9) Odgaard, A. J. (1989b). “River-meander model. II: Applications,” *J. Hydraul. Eng.*, 115(11),1451–1464.

10) Odgaard, A. J. (2008). “Stability analysis in stream restoration,” *World Environmental and Water Resources Congress 2008 Ahupua’a*, ASCE/EWRI, Honolulu, Hawaii, May 12–16.

11) Odgaard, A. J., and Abad, J. D. (2007). “River meandering and channel stability.” *Sedimentation engineering: Processes, measurements, modeling, and practice*,” M. Garcia, ed.,

ASCE Manuals and Reports on Engineering Practice No. 110, ASCE, Reston, Va.

12) Odgaard, A. J., and DeWitt, R. J. (1989). “Sediment control by submerged vanes,” *Proc., 20th Annual Conf., Intl. Erosion Control Assoc.*, Vancouver, British Columbia, Canada.

13) Odgaard, A. J., and Kennedy, J. F. (1983). “River-bend bank protection by submerged vanes,” *J. Hydraul. Eng.*, 109(8), 1161–1173.

14) Odgaard, A. J., and Lee, H. Y. E. (1984). “Submerged vanes for flow control and bank protection in streams,” IIHR Report No. 279, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

15) Odgaard, A. J., and Mosconi, C. E. (1987). “Streambank protection by submerged vanes,”*J. Hydraul. Eng.*, 113(4), 520–536.

16) Odgaard, A. J., and Spoljaric, A. (1986). “Sediment control by submerged vanes,” *J. Hydraul.Eng.*, 112(12), 1164–1181.

17) Odgaard, A. J., and Spoljaric, A. (1989). “Sediment control by submerged vanes. Design basis,”in “River meandering,” S. Ikeda and G. Parker, eds., Water Resources Monograph No. 12, American Geophysical Union, Washington, D.C., 127–151.

18) Odgaard, A. J., and Wang, Y. (1990). “Sediment control in bridge waterways,” Report No. 336, Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

19) Odgaard, A. J., and Wang, Y. (1991). “Sediment management with submerged vanes. I: Theory,” *J. Hydraul. Eng.*, 117(3), 267–283.

20) Odgaard, A. J., and Wang, Y. (1991). “Sediment management with submerged vanes. II:Applications,” *J. Hydraul. Eng.*, 117(3), 284–302.

21) Odgaard, A. J., Wang, Y., and Neary, V. S. (1990). “Hydraulic-laboratory model study of river intake at Duane Arnold Energy Center,” IIHR Limited Distribution Report

No. 177, The University of Iowa, Iowa City, Iowa

22) Wang, Y. _1991_. “Sediment control with submerged vanes.” Ph.D. dissertation,Iowa Institute of Hydraulic Research, University of Iowa,

Iowa City, Iowa.

23) Wang, Y., and Odgaard, A. J. _1993_. "Flow control with vorticity." *J.Hydraul. Res.*, 31_4_, 549–562.

24)Wang, Y., Odgaard, A. J., Melville, B. W., and Jain, S. C. _1996_. "Sediment control at water intakes." *J. Hydraul. Eng.*, 122_6_, 353–356