

AN EXPERIMENTAL STUDY ON FLOW BEHAVIOUR AROUND LAUNCHING APRON

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**DEPARTMENT OF WATER RESOURCES ENGINEERING
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA**

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Md Ehsanul Haque

A thesis submitted to the Department of Water Resources Engineering in partial
fulfillment of the requirements for the Degree of Master of Science in
Water Resources Engineering

Department of Water Resources Engineering
Bangladesh University of Engineering & Technology
Dhaka

January, 2010

CERTIFICATE OF RESEARCH

This is to certify that this thesis work has been done by me and neither this thesis nor any part thereof has been submitted elsewhere for the award of any degree or diploma.



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**“AN EXPERIMENTAL STUDY ON FLOW BEHAVIOUR AROUND
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has been accepted as satisfactory in partial fulfillment for the degree of
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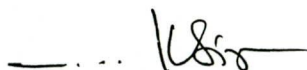
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ABSTRACT

Launching apron is widely used at the toe of all riverbank protection works. Use of launching apron around revetment is very popular for protection of structures against scour failure. A systematic experimental investigation was conducted to study the flow behaviour around launching apron in a laboratory channel situated in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering, BUET. Since launching apron is a measure to limit scour in sand bed for riverine structures, initially the investigation incorporated flow behaviour and then the scour study were observed. The extent of aerial coverage of launched apron was determined during the test runs in connection with the study.

Before the test runs, few trial runs were conducted initially to gather information on flow behaviour and scour using fixed as well as mobile bed with a view to visualizing some idea about the size of apron materials. Afterwards necessary test runs were conducted. Each test was run for 8 hours to maintain uniformity among the tests. Sixty test runs were conducted in total of which 24 test runs were conducted using fixed bed and 36 test runs were conducted using mobile bed. For fixed bed bank slopes of 1:1.25, 1:1.5 and 1:2 were used. For mobile bed also the same three bank slopes were utilized. Three discharges of 40 l/s, 50 l/s and 60 l/s were used for test runs. The apron materials fabricated using sand-cement were of sizes 3mm, 4mm, 5mm and 6 mm. Geobags were also used as apron materials which was prepared by filling with sands inside properly sewn cloths and weighing approximately 1 gm. These materials were placed on the toe of sloping revetment. Test runs were conducted for specified conditions and measurement were taken. The study was made under clear-water condition and the channel bed formed ripples during test runs, while mobile bed test runs were conducted.

Test runs were conducted for different apron setting configuration and velocities were measured using a programmable 2-D electromagnetic liquid velocity meter. The flow behavior was analyzed critically by examining the measured data on velocity. The flow field analyses were conducted by examining the variation of stream wise velocity and changes along vertical direction. The study showed that presence of apron at the toe of revetment caused a change in the velocity distribution near bed. In

most of the cases, shifting away of maximum velocity was observed that caused shifting of maximum discharge flux away from the revetment. Analysis of velocity contour also revealed this trend of shifting maximum velocity away from the revetment.

It was found that, when apron material was laid around a structure, the apron behaved like a submerged extension of the revetment. It was also observed that, launching apron was protecting the revetment structure in two ways – one was by forming a protective layer on the sloping face of the developed scour hole and the other was by forcing the scour hole to be formed away from the structure for mobile bed tests. Scour depth was found to vary with velocity variation of flow and an increasing tendency of scour depth has been observed with increasing flow intensity. It was found that placing of apron in different arrangement not only reduced the maximum scour depth but also had changed the deposition pattern around revetment.

Attempts were made to establish non-dimensional relationship between relative scour depths with projected area of apron provided. Using data obtained for different test arrangements regression analyses were performed to derive expressions. These expressions are expected to be useful for practical applications.

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NOTATIONS

A	Cross sectional area of channel
B	Width of channel
B_s	Width of scour hole
b	Flow restriction width
b_0	Width of sloping abutment at water level
C	Constant
D	Maximum scour depth
D_s	Scour depth
D_e	Equivalent spherical diameter of stone
D_{50}	Diameter size for which 50% of the materials are finer by weight
D_{90}	Diameter size for which 90% of the materials are finer by weight
d	Sediment diameter
f	Silt factor
g	Acceleration due to gravity
H_L	Head loss
h	Water depth
h_s	Water depth at downstream section
K	Multiplication factor
k_s	equivalent roughness height
m, n	Constants
n	Manning's roughness coefficient
Q	Discharge
Q_1, Q_2	Upstream and downstream discharge defined by fig
Q_{21}	Flow passing through area out of scour hole
Q_{22}	Flow passing through scour hole region
ΔQ_{12}	Difference between Q_1 and Q_2
Q_n	Discharge through non-scour region
q	Discharge per unit width
q_1	Approach discharge per unit width
q_{av}	Average discharge per unit width
R	Lacey's regime depth

r	Empirical constant
S	Longitudinal slope of channel
S_s	Specific gravity of stone
S_c	Specific gravity of cube
T	Thickness of rip-rap stone at bed level
T_1	Design thickness of launched apron
t	Time, thickness of stone pitching
t_e	Time at which equilibrium is reached
U, u	Approach flow velocity
U_s, u_s	flow velocity at downstream section
u_a	Mean velocity through scour hole width for flat bed
u_c	Critical velocity for sediment movement
u^*	Bed shear velocity
u_c^*	Critical bed shear velocity
V	Velocity
X	Longitudinal coordinate of channel from upstream reference point
Y	Lateral coordinate of channel from left bank
Z	Depth measured from initial bed level
α	Angle of dike made with bank
β	Constant
ϕ	Angle of repose of bed material
θ	Slope angle of structure made with horizontal
ρ	Water density
τ^*	Bed shear stress
τ_c^*	Critical bed shear stress

ABBREVIATION

ADCP	Acoustic Doppler Current Profiler
BWDB	Bangladesh Water Development Board
CS	cross section
DS	Downstream
DWL	Design Water Level
FAP	Flood Action Plan
JMREMP	Jamuna-Meghna River Erosion Mitigation Project
PWD	Public Works Department
REM	River Erosion Management
U/S	Upstream
W.L.	Water level
DWRE	Department Of Water Resources Engineering
CEGIS	Center for Environmental and Geographic Information Services
RCC	Reinforced Cement Concrete
O & M	Operation and Maintenance.
BRE	Brahmaputra Right Embankment
BRTC	Bureau of Research Testing and Consultancy

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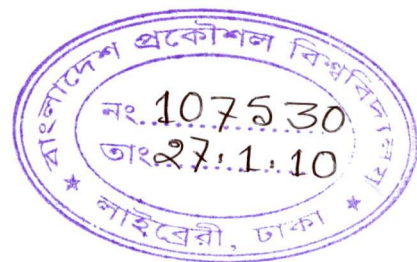
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CHAPTER ONE

INTRODUCTION



1.1 BACKGROUND

Riverbank protection is a perennial problem in Bangladesh. The increasing population density, standing at 1000 persons per square kilometre at present and expected to reach 1500 persons per square kilometre by 2050, together with the permanent widening tendency of major rivers such as the Brahmaputra and Ganges, requires the stabilization of river banks to protect flood plain lands.

The design of riverbank protection depends fundamentally on the knowledge of the river response to protective works. Perceptions about development of river depth in front of protection are of special importance to provide sufficient protection, avoiding undermining and eventually failure of the work. The maximum depth of scour is the present available design figure provided by empirical formulas, mathematical models or physical models. Strategically stockpiling processes of protective material for emergency protection, systematic monitoring during and after the implementation process and possibly required maintenance work are providing safety factors for the stability of the structure. In addition to the maximum possible scour depth, information about the scour development and its dependences are required to optimize these processes. Basically, four methods may be used to prevent the scouring process. First is to excavate and continue the slope revetment down to below the expected scour level. Second is to drive a 'cut-off wall' of sheet piling from the toe of the revetment down to non-erodible material or to below the expected scour level. Third is to lay a flexible 'falling apron' horizontally on the bed at the foot of the revetment, so that when scour occurs the materials will settle and cover the scour hole on a natural slope. Fourth is to pave the entire bed across the revetment of the waterway.

Use of launching apron or falling apron at the toe of revetment is a popular method for riverbank protection in this subcontinent including Bangladesh. Launching apron may be defined as rip-rap material placed horizontally at the foot of foundation of riverfront structures. Constructing vertical-wall structures, up to a level below the

maximum predicted scour depth, normally protects them. Aprons are also suitable for vertical structures. Inadequate protection against undermining is a frequent cause of structure failure. Some protection structures are subject to risk of failure from earth pressure on the bank side after scour occurs on the channel side, and tend to cause deeper scour. As mentioned earlier that laying of flexible 'launching apron' horizontally on the bed at the foot of the revetment, allows the materials to settle and cover the side of the scour hole on a natural slope with the progress of scour development. This method is recommended for cohesionless channel beds where deep scour is expected. A flexible toe protection in the form of a Launching Apron (Fig 1.1) is a major application for mitigating bank erosion in Bangladesh. Mainly four different materials are used for the protective layer of the launching Apron. These are boulders, quarried rocks, CC-Blocks and geobags.

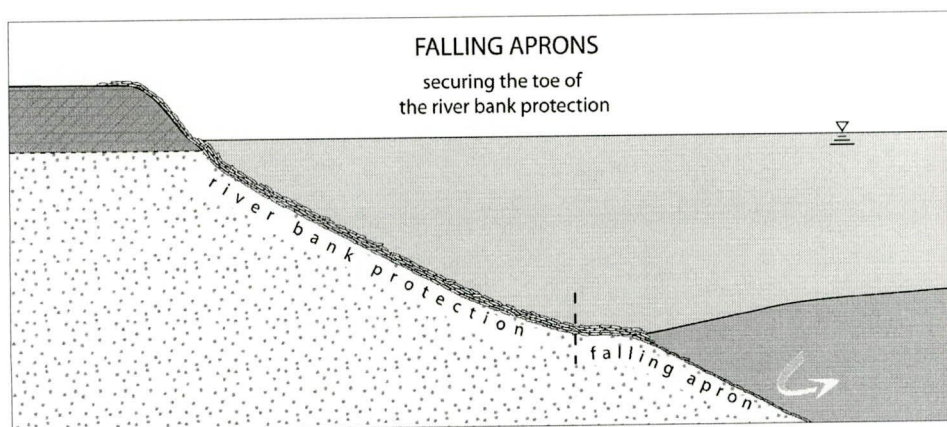


Figure 1.1: Launching Apron (Source: BRTC 2008)

Launching Apron can be applied along revetments, at the head of a groyne or along a guide bank. In common designs the slope angle after the launching of the Launching Apron is assumed to be 1:2 (Joglekhar, 1971, Inglis, 1949 and FAP 21/22, 1993).

1.2 MASS FAILURE OF BANKS

Mass failure of river banks is also very common in Bangladesh. Mass failure may occur by slip failures and block failures. The actual failing of a river bank may not follow immediately after an impact and may take several days. On the other hand, a failure may occur suddenly when active surface erosion and toe scouring is prevalent or an additional (surcharge) load is applied to the bank. The risk of mass failure is

increased during heavy rain and during quick fall of river stages after flood. Typical bank failure of major rivers in Bangladesh is shown in Figure 1.2.

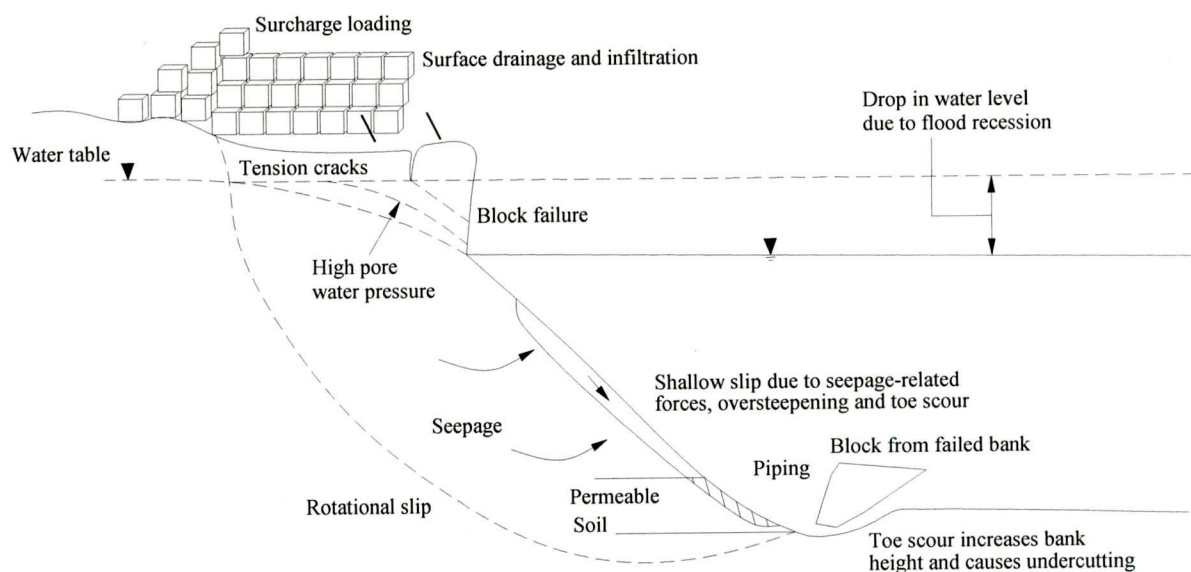


Figure 1.2 Processes responsible for failure of a river bank(Source: BRTC 2008)

1.3 REVETMENTS

Revetment is artificial strengthening of the bank slope with erosion-resistant materials. A revetment mainly consists of a cover layer, and a filter layer. Toe protection is provided as an integral part at the foot of the bank to prevent undercutting caused by scour. The protection can be termed as launching apron, which can be constructed with different materials, e.g., CC blocks and geobags. Fig.1.3 below shows a typical revetment and their different components.

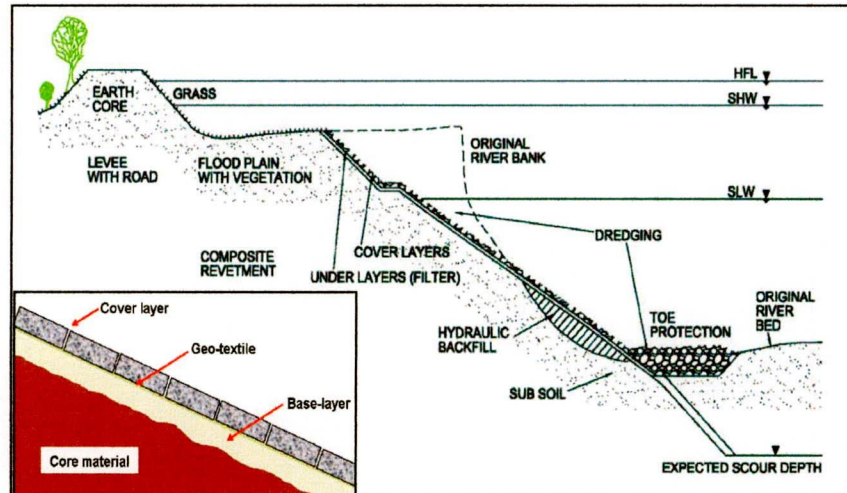


Figure 1.3 Components of a revetment on riverbank(Source: BRTC 2008)

Revetment must have the following qualities and characteristics:

- Sufficient weight to keep the subsoil stable against uplift forces;
- Sufficient permeability to prevent uplift forces;
- Sufficient thickness with appropriate permeability at transition to reduce the rate of change of excess pore water pressure;
- Filter layer to prevent migration of soil;
- Flexibility to accommodate movement within subsoil without loss of strength, and
- Stability to withstand slipping on any construction plane.

1.3.1 Types Of Revetment

Based on construction materials, revetment may be of different types: rock riprap, rubble riprap, wire enclosed rocks, pre-formed blocks, grouted rocks or paved lining etc and can be grouped as:

- Self-adjusting structures- Includes all kinds of rip-rap protection using stones, concrete blocks, hand-laid bricks and concrete block layers without interlocking, slurry-filled bags, sand-filled geotextile bags etc.

- Flexible structures- Includes articulated blocks and slabs, wire mesh netting and other forms of mattresses, tubes, gabions and interlocking block layers.
- Rigid structures- Includes asphalt and concrete paving, concrete filled pillows, grouted mattress, grouted rip-raps, soil stabilization etc.

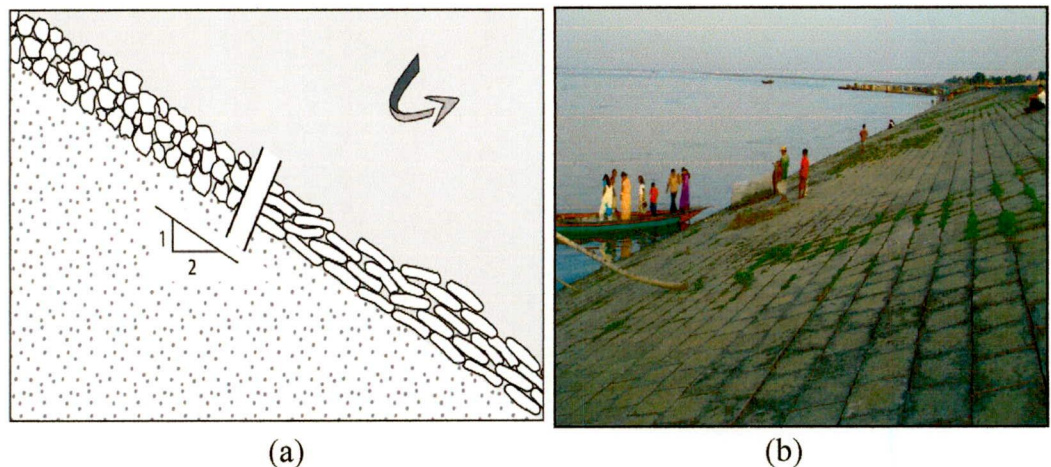


Figure 1.4 (a) Self-adjusting revetment: multi-layer riprap and geo-bags and (b) loose cement concrete blocks.

1.4 LAUNCHING APRON

A distinction is made between launching apron and falling apron. Launching apron consists of interconnected elements that are placed horizontally on the floodplain and normally anchored at the toe of the embankment. The interconnected elements are not allowed to rearrange their positions freely during scouring but launch down the slope as a flexible unit. The falling apron, on the other hand, consists of loose elements (e.g., CC blocks, geobags, stones) placed at outer end of the structure. When scour hole approaches the apron, the elements can adjust their position freely and fall down the scouring slope to protect it. Many authors have also used the launching apron and falling apron for the same purpose. In this study both terms are used as the same apron materials.

Recently sand-filled geotextile bags (geobags) have been used in Bangladesh. In this approach, the slope below low water level is protected with geobags. The slope above LWL is protected with cement concrete blocks mainly to resist wave action and current. The geotextile bags normally used are filled with sand (FM > 1.0) and weigh 78 kg, 126 kg or 176 kg. The advantages of this method are low cost and possibility of rapid deployment especially for structures with a limited design life. No additional filter layer is required as geobags have filter characteristics and retain the fine underlying subsoil. Various components of a revetment using geobag is shown in figure 1.5.

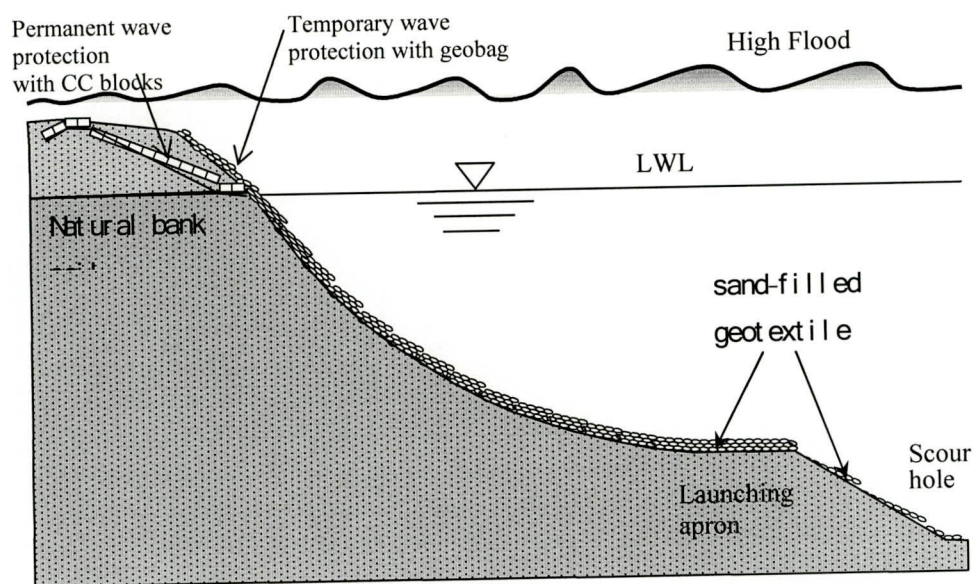


Figure 1.5 Components of a revetment(Source BRTC 2008)

The launching apron is toe protections of revetments that can adjust to scour and follow any bed erosion downwards, thus continuing to protect the toe of the bank protection. The idea is to store protective material (e.g. boulders or quarried rocks) at the toe of the revetment during construction. Scour will cause the stones to roll down, preventing or mitigating erosion. The loose elements are assumed to cover the slope.

The first Launching Apron was installed at the beginning of the last century (Joglekhar 1971). The knowledge for dredging was not then known, therefore it was the easiest way to heap the protective material at the edge of the revetment and let it launch after scouring occurs. Today the economical point of view is the important factor. Dredging the slope to dig in the revetment would be possible. But it is still an

expensive and uncertain work. That's why the concept of the Launching Apron is used commonly as an effective approach on river training. Another reason is that administrative procedures normally take a long time and after approval is obtained the river has often shifted. Therefore the Launching Apron concept as emergency measure is used as a flexible approach for it can be installed quickly and easily (Oberhagemann et al., 2006). Another advantage of a Launching Apron is that it responds immediately and precisely where the protection is needed consequently regarding the continually shifting of the erosion and changing of the attack of the flow. It is therefore very suitable for the major rivers in Bangladesh with their unpredictability and irregularity.

According to researchers the failure of various structures in Bangladesh occurred because of non performance of launching apron (Siddique 2008, Bashar 2004). Some example of failure of revetment is those of Sirajgonj in 1984, 1988, and 2001. Sirajgonj Hardpoint failed in 1998 due to nonperformance of launching apron as expected. Another example of failure of river bank protection works is Chandpur town protection works and many such examples can be cited (Ahmed, 1989). Thus it is apparent that launching apron performance plays the most vital role in any revetment or river bank protection works. Behavior of CC blocks and geobags need to be understood before using it in a better way for a certain bank protection work. It may be noted that systematic investigation on launching apron has not been done so far. Keeping this in the back of mind the present study was undertaken.

1.5 OBJECTIVES OF STUDY

The objectives selected for this study were as follows:

- (a) To investigate the flow pattern for different types of launching apron and discharge on fixed bed and mobile bed.
- (b) To investigate the scour pattern and scour protection by different types of CC blocks with different discharge.

(c) To observe launching behaviour for different sizes and types of Launching apron.

(d) To develop suitable correlation if any between hydraulic parameters and Launching apron materials.

CHAPTER TWO

LITERATURE REVIEW

2.1 GENERAL

Before delving into detail of launching behaviour of the placed materials, some discussions on scour is necessary. As such in the following section scour, factors responsible for scour/erosion, processes associated with scour and computations of various types of scour are discussed. Scouring is a natural phenomenon at the boundary of water and soil, caused by the flow of water in rivers and streams. Changes in flow characteristics (velocities and or turbulence) lead to changes in sediment transport capacity and hence to a local disequilibrium between actual sediment transport and the capacity of the flow to transport sediment. A new equilibrium may eventually be reached as hydraulic conditions are adjusted through scour. The development of river valleys reveals such activity through millennia, long before man's efforts had any appreciable impact in them. In recent times, nonetheless, the addition of many types of structures has greatly altered river regimes with significant impacts on the transport and deposition of sediment.

Scour occurs mostly in rivers with alluvial materials, but deeply weathered rock can also be vulnerable in certain circumstances. Experience has shown that scouring can progressively undermine the foundation of a structure. Due to the enormous cost, all-embracing protection against scouring is nearly impossible. The designer must seek ways to guide and control the process to minimize the risk of failure.

2.2 SCOUR/EROSION PARAMETERS

In general surface erosion of river banks or along the river bed occurs if the driving erosive forces are exceeding the resistive forces of the individual grains or of the conglomerates in case of cohesive materials. The main impacts responsible for surface erosion at river banks are as follows:

- Current induced shear stress

- Wave loads (wind, boat)
- Seepage (excessive pore pressure)
- Surface runoff
- Mechanical action (desiccation, ship impact, activities of humans and animals)
- Surcharge or stockpiling on the banks.

Shear stress induced by the current flow is the main hydraulic erosion factor. Although the secondary currents, which are mainly generated by inertia forces are smaller than the primary current (velocity component in direction of the river course), they are the key factor for the asymmetric cross sectional profiles as shown in figure 2.1.

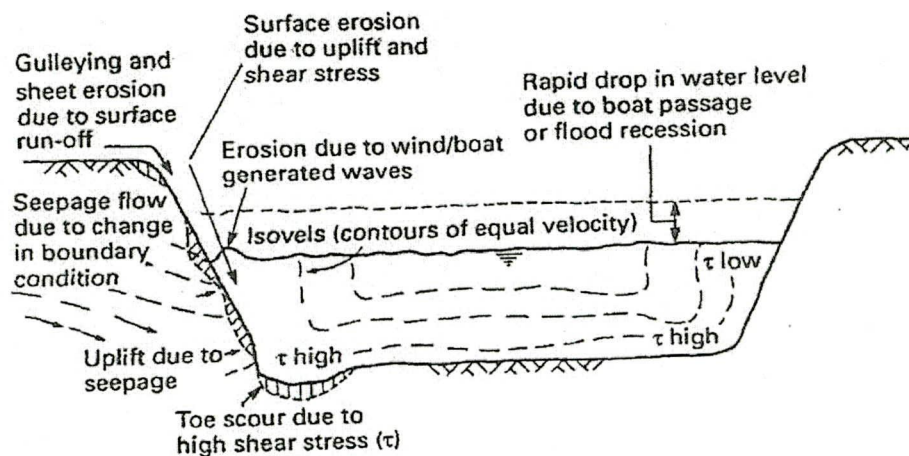


Figure 2.1 Process of surface erosion [Hemphill and Bramley, 1989]

However, due to the velocity gradient in the primary current secondary flows also exist in straight river sections, but with minor value. Moreover, in turbulent flows three-dimensionality of the current distribution is amplified by irregularities in the cross-sectional shape of the channel or by changes in the roughness of the river bed. In most formulae developed for computation of bed scour the secondary flow

component is not considered explicitly, but is taken into account through empirical coefficients. The velocity and shear stress distribution in a prismatic channel is shown in figure 2.2.

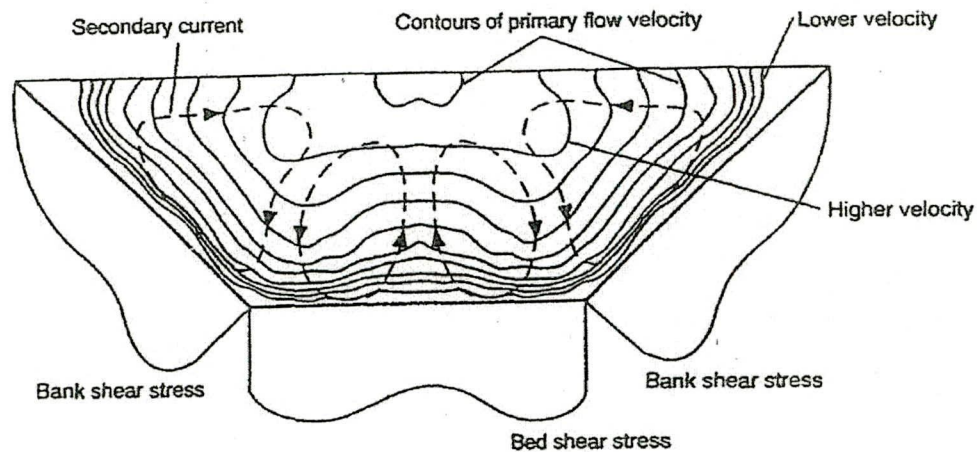


Figure 2.2 Contours of primary and secondary flows as well as the shear stress distribution in a trapezoidal channel [Hemphill and Bramley, 1989]

The geo-morphological processes in natural rivers are even more complex. Obstructions to the flow as well as variations of the roughness of the river bank and/or river bed cause changes in the velocity distribution and the secondary flow patterns. As a consequence the river starts to develop bends. Once the meandering process has started, it tends to sustain itself. This development is also possible in lower river reaches, where the slopes are gentler, in particular in alluvial soils. Significant variations of the shear stress along straight and meandering sections can be observed in the following figure 2.3. Eroded material is transported as bed load and suspended load and will be deposited in areas of smaller flow velocities. Consequently, deposition of sediment occurs at the inner bank along a river bend, caused by the decrease in shear stress.

In meandering and braiding rivers with outflanking channels, erosion generally occurs at concave banks rather than at convex banks. Maximum values of the bank shear stress during high water stages (bank full discharge) are observed at the base of the

outer bank in the meander bend. At low flows, peak values occur at the meander apex. Parallel with increasing discharge, the peak values move downstream towards the inflection point. For that reason the actual location and rate of bank erosion depends on the residence time of prevailing boundary conditions, i.e. the water level stages and associated flow conditions and shear stresses. The influence of wave action is mainly important along the actual bank line, i.e. the transition between water and adjacent flood plain of a river. In this zone the wave energy is transformed to wave run-up and wave run-down, creating high velocity components normal to the river slope, thus increasing shear stress and erosion. In addition, dependent on the breaker type especially under plunging breakers, extremely high pressure heads may occur, which have considerable destructive force when hitting the bank line is shown in figure 2.3.

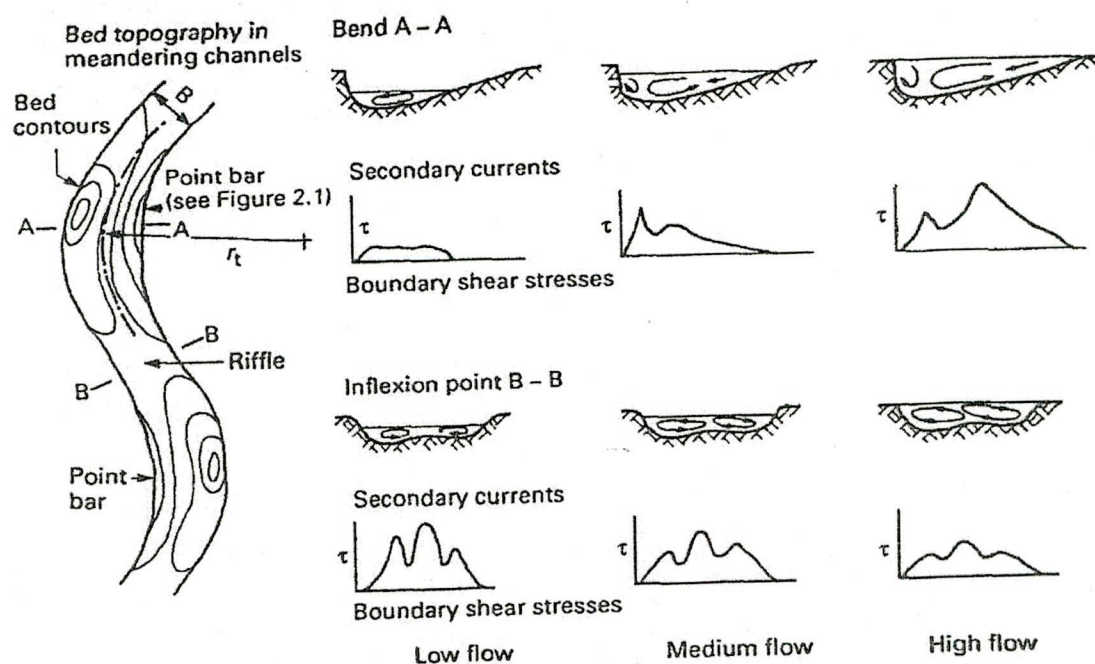


Figure 2.3 Scour and associated hydraulic factors

2.3 TYPES OF SCOUR

- **General scour**, occurs in a river or stream as the result of natural processes irrespective of whether a structure is there.
- **Constriction scour**, occurs if a structure causes the narrowing of a water course or the rechanneling of berm or flood plain flow.
- **Local scour**, results directly from the impact of the structure on the flow. This scour, which is a function of the type of structure, is superimposed on the general and constriction scour.
- **Confluence scour**, occurs, when two branches of a river meet, both the angle of confluence and water level may differ.

2.3.1 Scour in different conditions of transport

- Clear-water scour**, occurs if the bed material in the natural flow upstream of the scour area is at rest. The shear stresses on the bed some distance away from the structure are thus not greater than the critical or threshold shear stress for the initiation of particle movement.
- Live-bed scour** also referred to scour with bed material sediment transport, occurs when the flow induces a general movement of the bed material. In this situation the shear stresses on the bed are generally greater than the critical ones. Equilibrium scour depths are reached when the amount of material removed from the scour hole by flow equals the amount of material supplied to the scour hole from upstream.

2.3.2 The difference between “depth of scour and scoured depth”

The depth of scour is measured with reference to initial bed level while the scour depth refers to depth before design flood level (Fig 2.4). Since some literature and reports sometimes use different definitions, it is important to get a clear impression of

the difference between these two concepts. This report only refers to the scoured depth according to its definition as shown in figure 2.4.

The depth of scour (below initial bed) is used in some investigations, but it is a misleading parameter for rivers like the Jamuna with a width of several kilometres and varying depths, where it is not possible to determine an initial bed level at all.

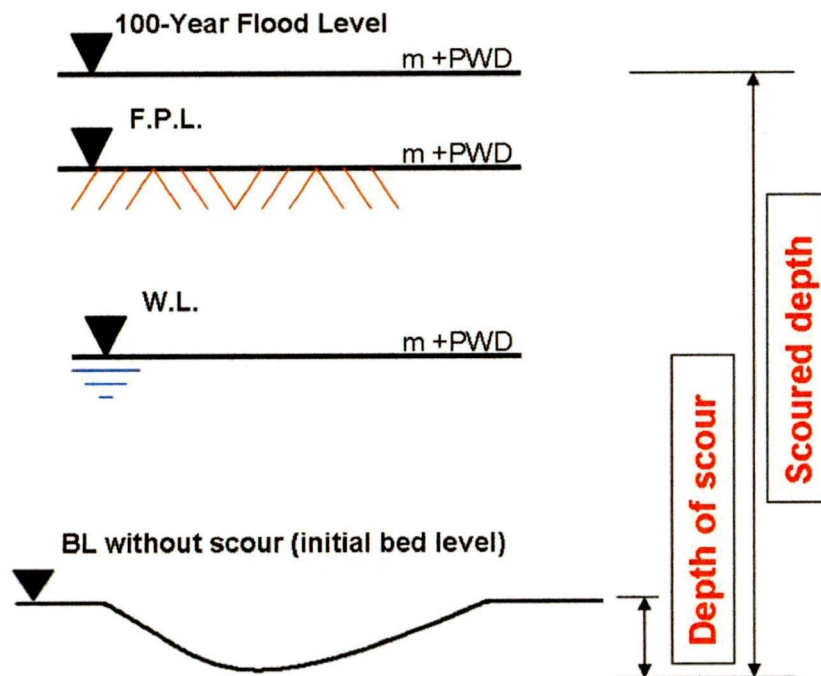


Figure 2.4 The difference between “depth of scour and scoured depth”

2.3.3 Prediction of Scour

Scour and bank erosion in any alluvial river is a perennial problem for Bangladesh. River bank erosion alone may cause loss of about 10,000 hectors of valuable lands for a land hungry country like Bangladesh. Therefore the study of scour and erosion and their forecast is very important. The following information are needed to predict scour:

- Initial geometric characteristics of the reach under consideration,
- Hydrologic regime of the river; it is often modified by man's activities and correction factors to historical data must be applied,
- Sediment inflow and outflow through the reach boundaries,
- Location and the features of the soil to be scoured.

2.3.4 Local scour depth

In recent years several summaries of local scour investigation have been published including Breusers et al. (1977), Raudkivi and Sutherland (1981), Dargahi (1982), Raudkivi (1986), Melville (1988), Breusers and Raudkivi (1991), Richardson and Davis (1995). In spite of these researches, Raudkivi [Breusers and Raudkivi (1991)] summarizes, "despite much study, the principles of analysis of scouring are not well established, and the various investigations often show differing trends." Figure 2.5 shows the variations of scour depth with mean approach velocity for clear and live bed scour. The maximum scour for clear water condition is higher than that of live bed conditions.

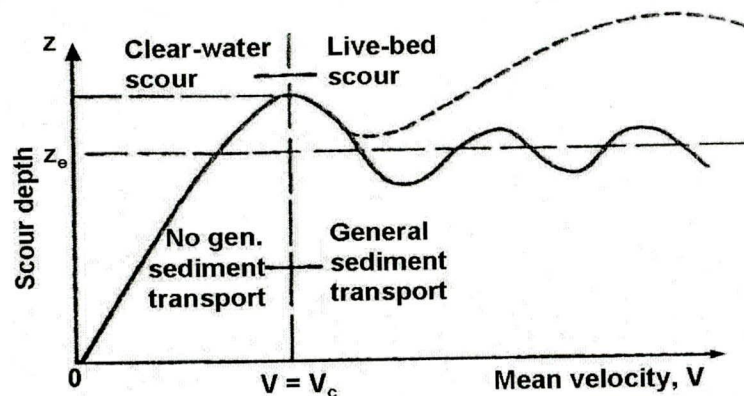


Figure 2.5 Scour depth at groyne vs mean approach velocity and time for clear and live bed scour

The figure 2.6 also shows a situation when time dependant scour for clear water condition again is seen to be higher than of live bed condition. The reason is that the

secondary current (eddy) is lesser is due to for generating the scour is lesser due to entrainment of sediments in the flow.

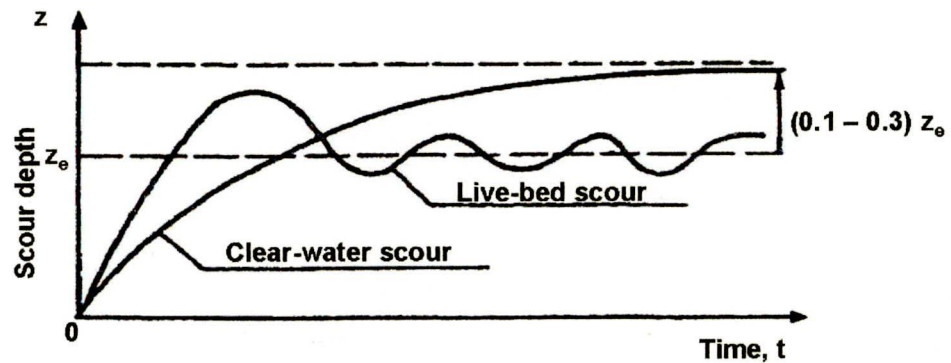


Figure 2.6 Scour depth at groyne vs. mean approach velocity and time

2.4 A CHRONOLOGICAL DEVELOPMENT OF LAUNCHING APRON

2.4.1 History of the Launching Apron

The Hardinge Bridge was built in 1912 and was the first major application in Bangladesh, which used the concept of the Launching Apron with success. Sir Robert Gales was the engineer-in-chief. His contribution to the development of the Launching Apron was very important.

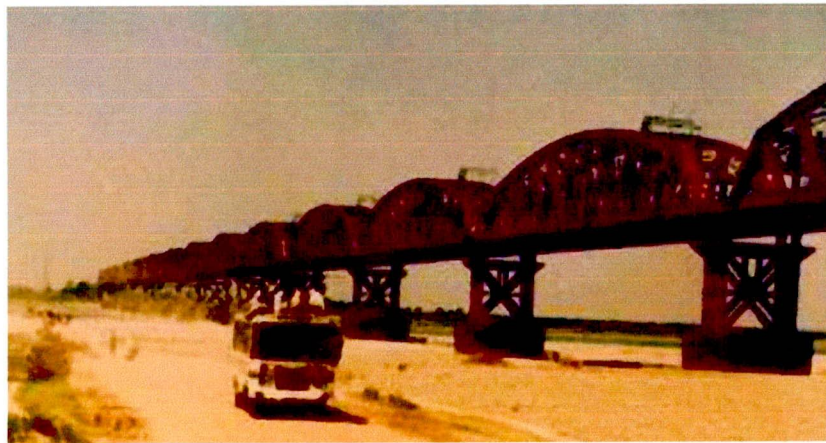


Figure 2.7 A view of Hardinge Bridge on the Ganges during lean season

His proceedings were based on observations of the river in the vicinity of the bridge and based on opinions of other engineers. The first major damages of the guide banks happened 20 years after the completion of the bridge. This is quite remarkable if considering the knowledge they had at that time and shows how well they constructed the guide banks and of course it shows how well the concept of the Launching Apron is working.

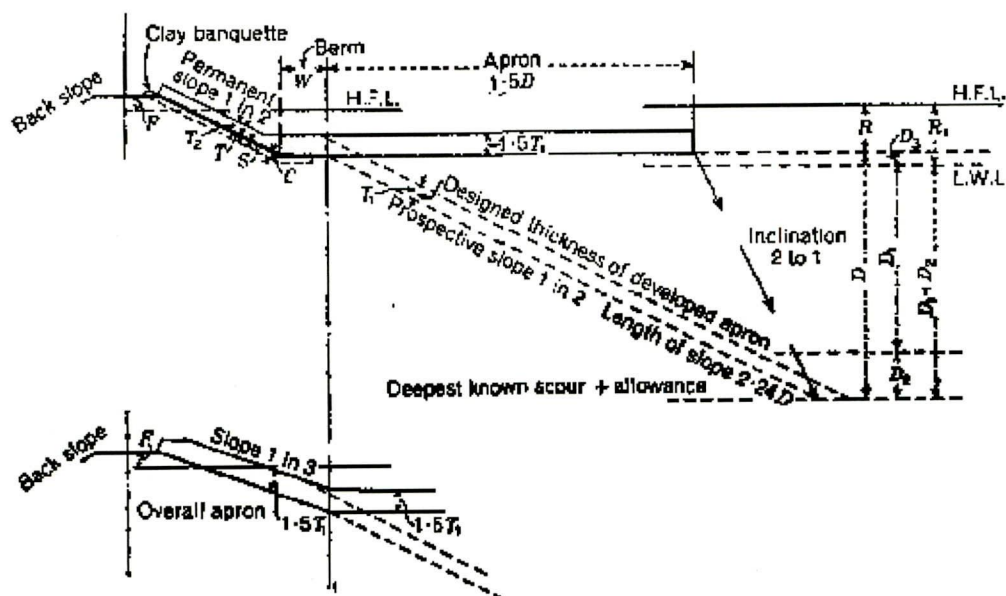


Figure 2.8 Diagram of normal apron with alternative slope covering (Gales, 1917)

The Diagram in figure 2.8 is a design consideration of Gales based on his experience he made at the Hardinge Bridge and Cruzon Bridge. His assumed slope of the Launching Apron was 1 to 2 as a result of model tests in Puna, India. They were carried out by C. Inglis (1937) in channels of various widths ($b = 1.2 - 6$ m) with discharges up to $Q = 0.68$ m³/s. The bank and bed were composed of incoherent sand of the River Ganges with a $d_m = 0.29$ mm. The protective stones which were used during the whole set of experiments were varying from 3 mm up to 152 mm.

In following figure a cross section is given, which shows the resulting inclination of the experiments with rounded stones (6 – 10 mm). The results were varying from 1:2.07 and 1:1.92 for rounded stones (boulders).

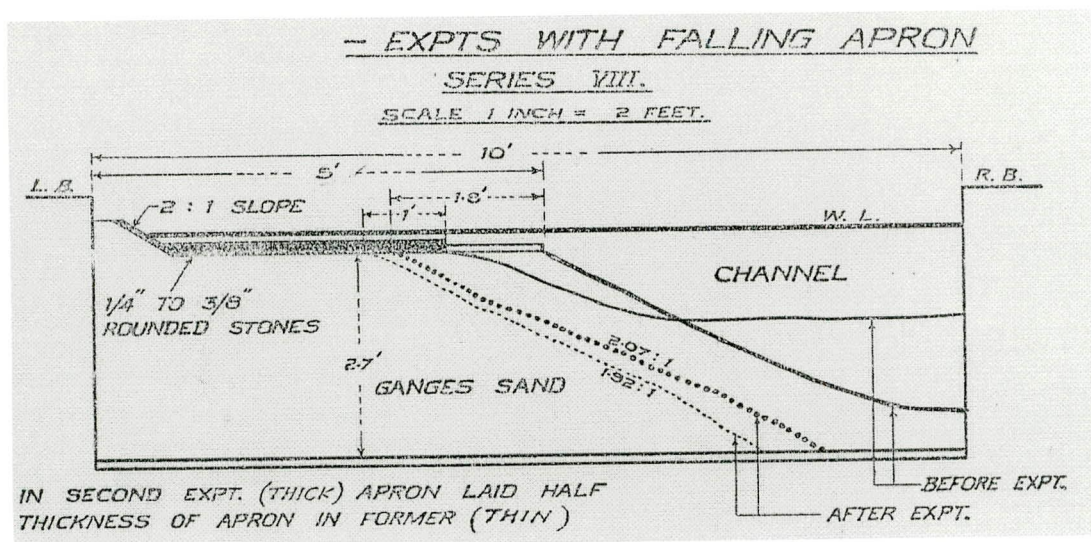


Figure 2.9 Experiments with Launching Apron, rounded stones respectively boulders (Inglis, 1937)

The computation of the thickness of the apron and the transition between the permanent and the prospective slope was geometrically. The size of the pitching stones and their mixture and set up was a result of their experiences as well. Nevertheless Gales already had a good understanding of the geotechnical aspects such as the filter problematic. That's why he proposed in many designs to try to increase the thickness of the protective slope due to lacking of a suitable filter under the Launching Apron.

It is very common in Bangladesh to design riverbank protection focusing mainly on the hydraulic loads. This is insufficient for a stable structure. It should be standard to consider the interaction of the protective elements, hydrodynamic loads and geotechnical condition. Only taking by account of all these three elements, a structure can endure its loads for a reasonable time (Pilarczyk, 2000). As a matter of fact nearly 80% of all river works in Bangladesh are failing due to neglecting the geotechnical conditions (Sokolewicz, 2006).

A characteristic design of the Jamuna Meghna River Erosion Mitigation Project (JMREMP) is shown in Figure 2.10. The Launching Apron covers a length of 15 meters with 3 layers of geobags. If it launches, it covers the slope of the scour with a single layer of geobags and withholds therefore a maximum scour of 23 meters. There are design variations depending on the construction site and the contractor.

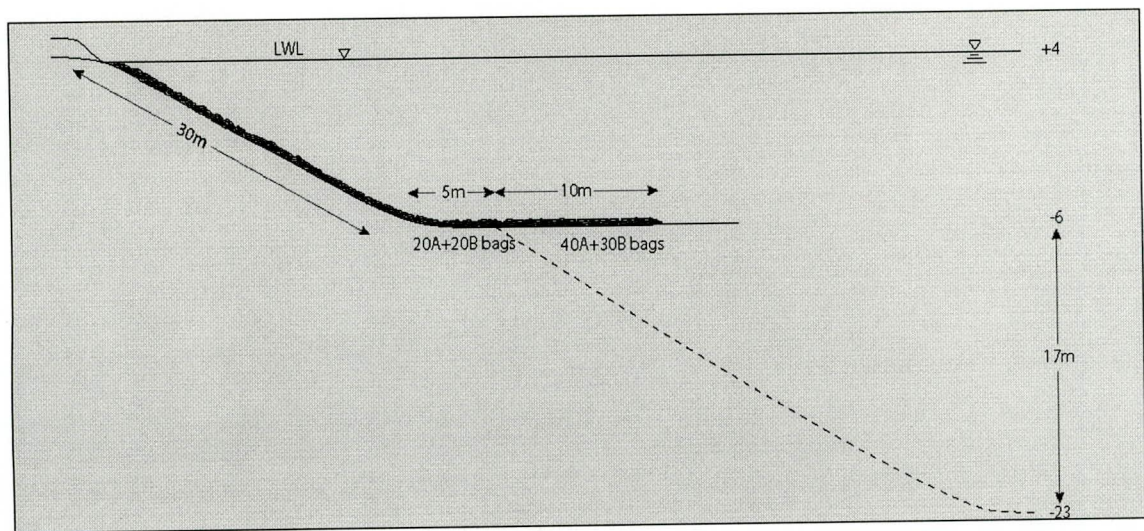


Figure 2.10 A typical design of JMREMP (Oberhagemann et al., 2007)

2.4.2 Boulders

Rounded stones or boulders are washed down some rivers from India into the Sylhet area of Bangladesh where they are collected for various engineering works (Aitken, 1992). Nevertheless the majority of the boulders are imported from India, because of absence of stones in the soil of Bangladesh. Transporting this material is difficult and expensive. This makes the protective material very valuable and increases the project costs rapidly. In addition the required sizes to match the requirements of flow velocity and filter material are not always available. For these reasons boulders and quarried rocks are not used extensively in Bangladesh.

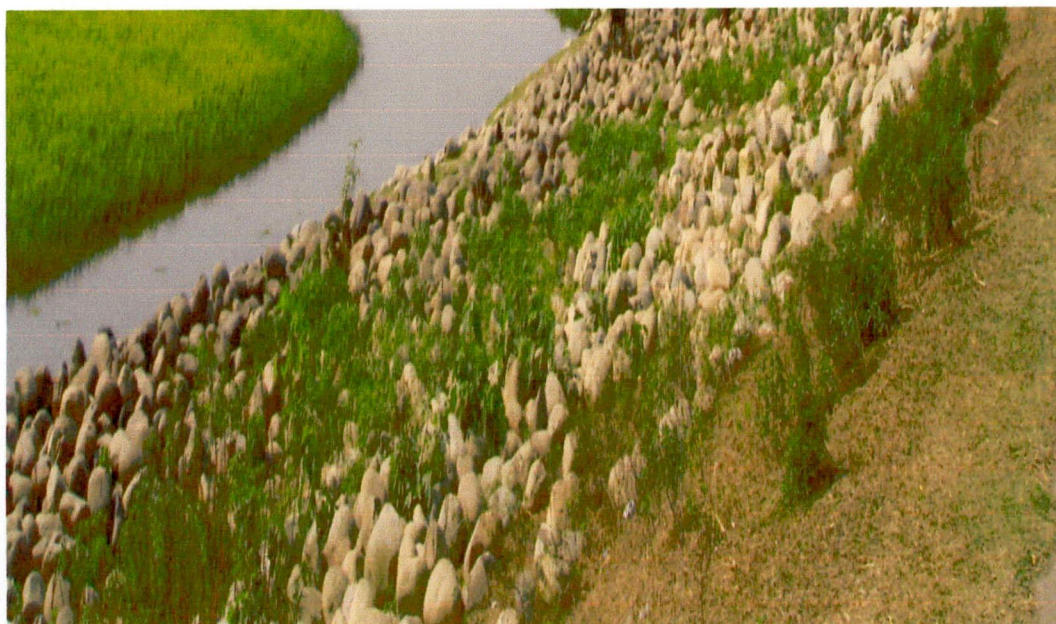


Figure 2.11 Use of Boulders (Source: Diggelmann, 2007)

2.4.3 Quarried Rocks

Quarried Rocks or angular rocks are obtained from quarries in the Chittagong Hills. For reasons similar to boulders, they are very expensive and their usage is decreasing.

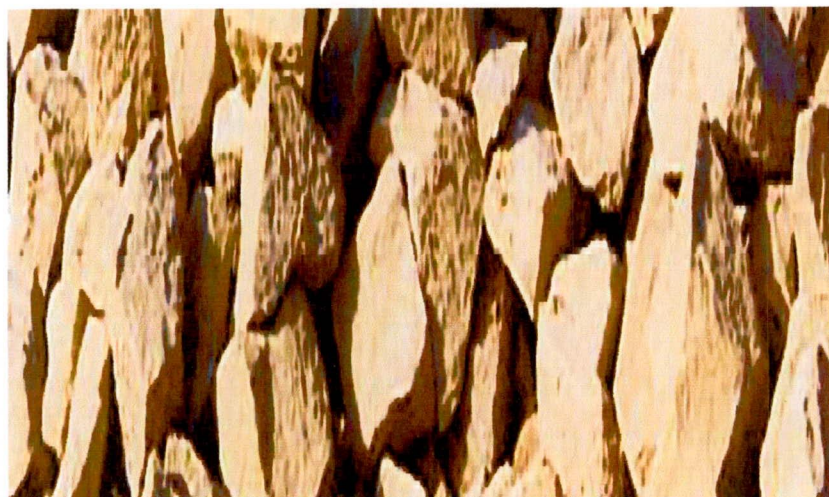


Figure 2.12 Quarried rocks (Source: www.huddersfieldgeology.supanet.com)

2.4.4 CC-Blocks

CC-Blocks are the most widely used revetment material in Bangladesh. They are manufactured on site normally in cubic shapes with dimensions ranging from 0.3 m up to 0.6 m. They require a comparatively long time for hardening and cannot be used immediately. The compressive strength of these blocks is approximately 50 MPa (Aitken, 1992).

2.4.5 Geotextile Bags

Geotextile Bags or geobags do not have a long history in Bangladesh. They were first introduced at the Chandpur Town Protection Site early 1990. The primary advantage of geobags is the low cost. They can be filled up directly at the site using the existing sand. And filling, stitching and dumping of ten thousands of bags can be done in a few days (Oberhagemann et al., 2006). Geobags contain filter characteristics and retain the fine underlying subsoil, which means that no filter is needed for the difficult subsoil conditions in Bangladesh.

2.4.6 Slope of Launching Apron

The design parameters such as materials, dimensions and implementation methods developed and changed from time to time, but the principle itself remained constant. The idea is to store protective elements (e.g. concrete blocks or geobags) at the toe of the structure. After the scour undercut the store at the toe, the protective elements roll down and protect the new developed slope. The inclination of the developing slope depends on the soil conditions and on the stored protective elements. This slope is part of the developing scour hole. Hence, the scour hole in front of a structure depends on the development of the Launching Apron.

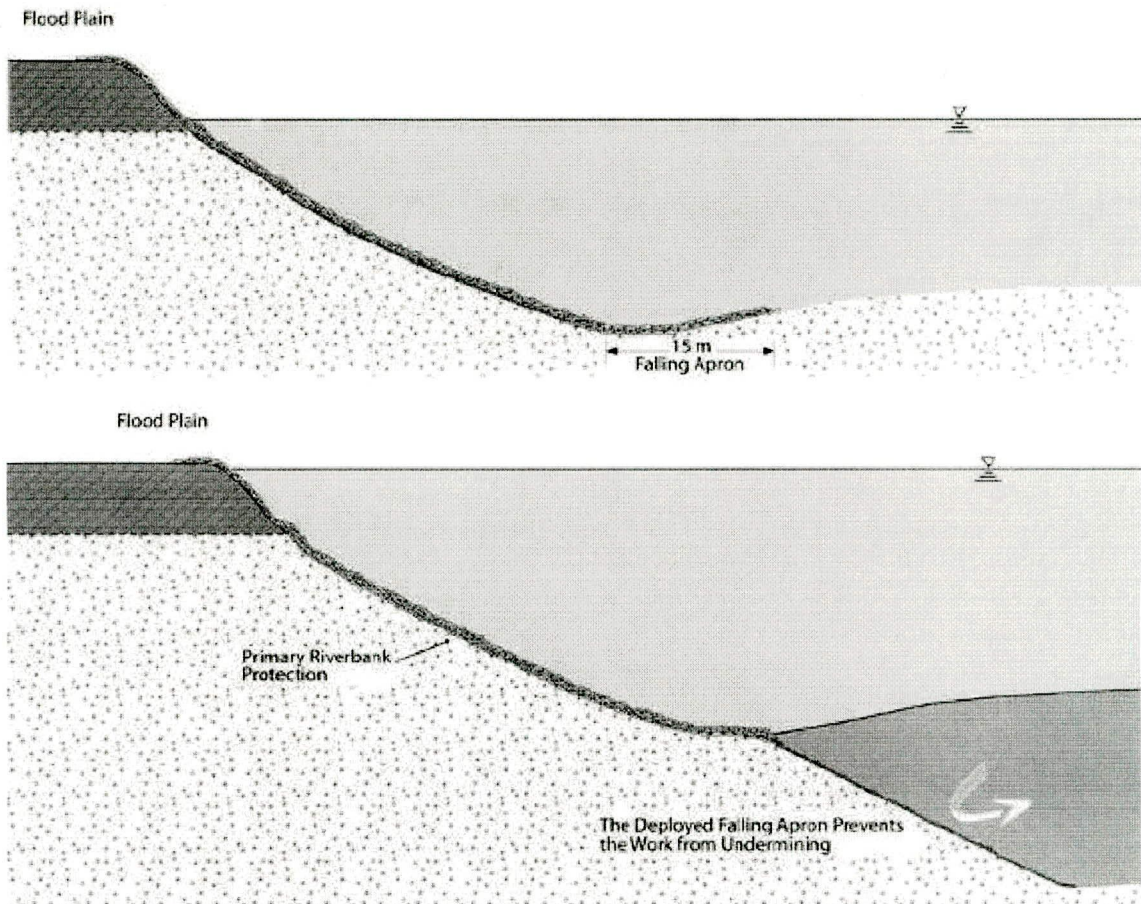


Figure 2.13 Development of Launching Apron(Source :BRTC 2008)

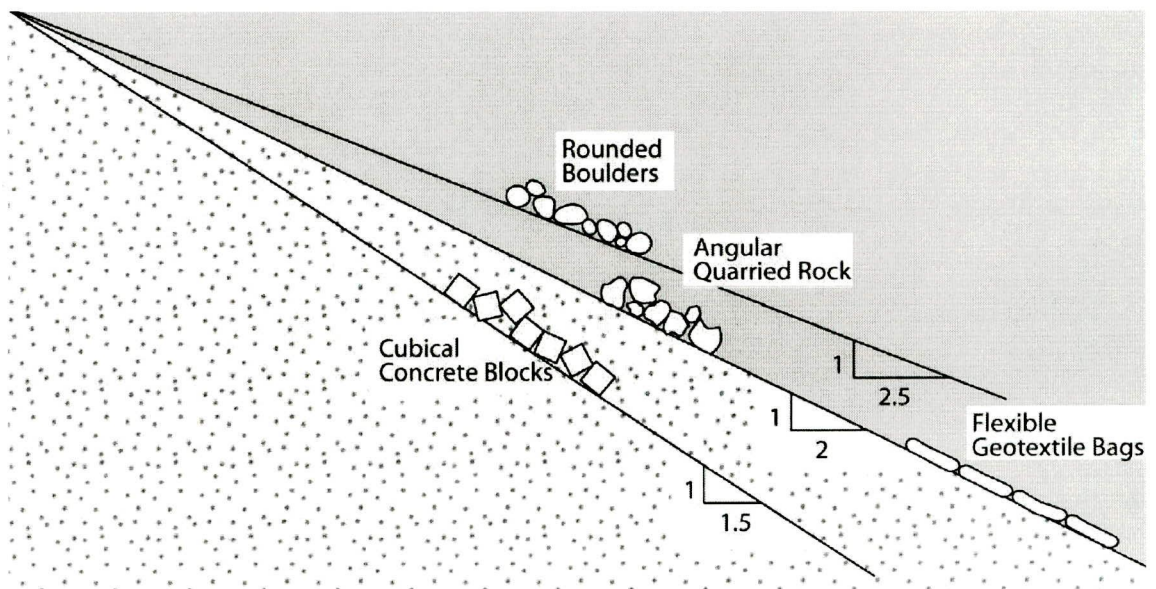


Figure 2. 14 Slope angles of developed Launching Aprons(Source :BRTC 2008)

2.4.7 Launching process

As a short introduction to the launching process of Launching Aprons a description made by Sir Robert Gales (1917) is given below.

“What appears to take place, when the first slip occurs at the outer edge of such an apron, is that the weight of the strip of apron assists to shear the compacted sand in a plane, vertical at the inner edge but curving out to the vertical face of sand at the depth of 30 feet. After the strip of apron has dropped a short distance, the slip comes to a stop resting on the toe of the slip which has been pushed out into the channel, the toe of now loose sand is rapidly scoured away and at the further movement of the slip the packed structure of the sand breaks up and the apron-stone drops nearly vertically through the dissolving sand, spreading slightly forward and protecting the rest of the slip.”

During the years of 1935-1937 numerous model experiments were carried out at the Hydrodynamic Research Station in Poona, India. These experiments were requested of the Railway Board due to unsatisfactory behaviour of the guide banks at the Hardinge Bridge. They were cautiously led by Inglis, 1937. Hence the description he made of the launching apron process is more detailed than that of Gales. In the model test layout is shown in figure 2.15 with pitching stones (boulders), which were laid horizontally on a berm.

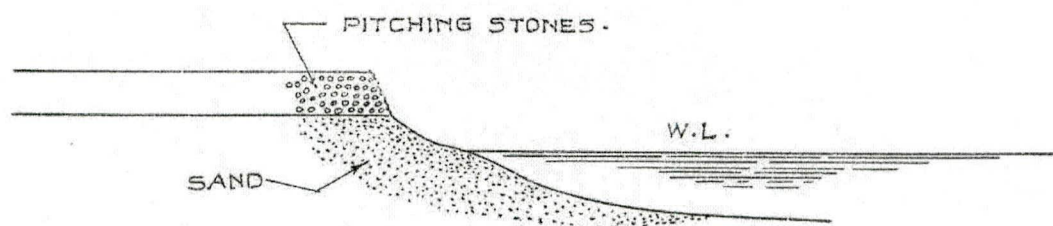


Figure 2.15 Model Test Layout (Inglis, 1937)

The discharge was increased, the channel began to deepen and widen. As a result the apron was undermined by scour at A causing the undermined stones to settle on the

slope shown in the figure 2.16. The stones weren't yet enough to prevent scour of the sand at A, therefore further scour took place, causing the horizontal layer of stones to be again undermined.

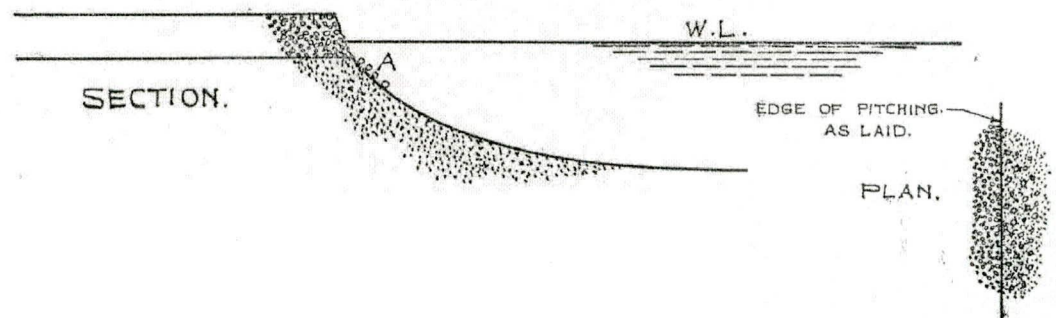


Figure 2.16 Scour caused due to more discharge (Inglis, 1937)

Gradually more stones were set in motion. Some were remaining with the previously fallen stones at A and others rolling down to B until a stage was reached, where the scouring at A stopped. Scouring was still continuing at B as shown in figure 2.17.

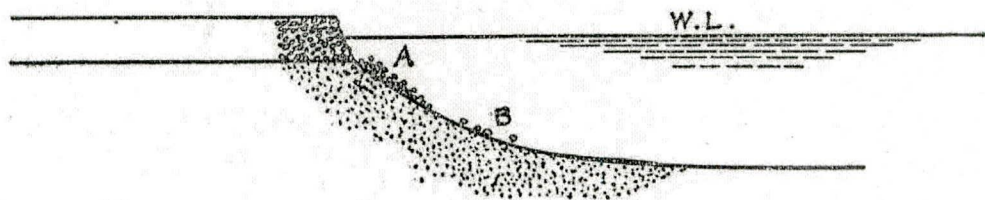


Figure 2.17 Scour caused by stones in motion (Inglis, 1937)

After a time, scour at B led the bank at A being undermined, and stones from A rolled or slid down to B shown in figure 2.18.

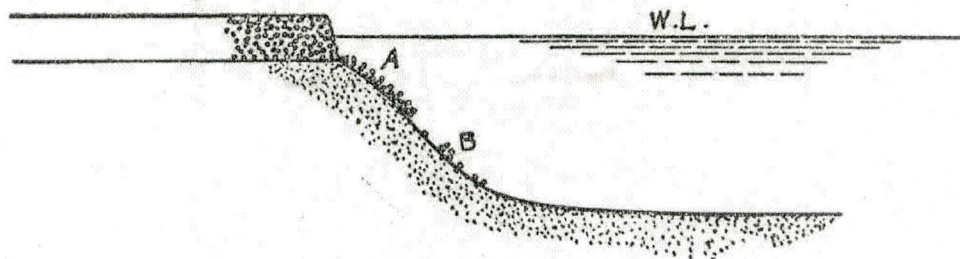


Figure 2.18 Scour continued to develop (Inglis, 1937)

And a few went beyond to C as shown in figure 2.19.

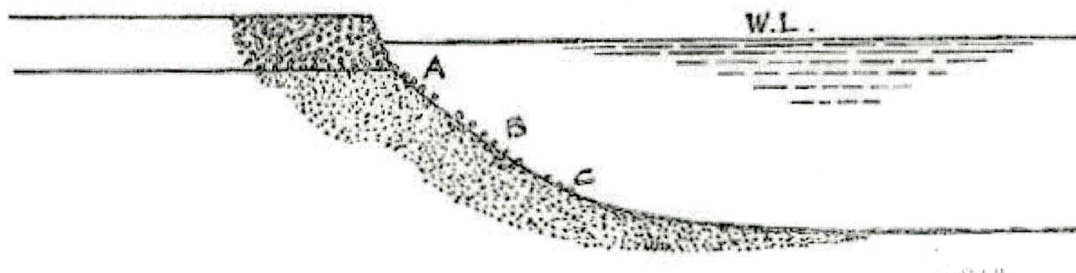


Figure 2.19 Scour developed at C(Inglis, 1937)

Consequently the sand was again exposed at A and further scour occurred, so the undermining of the horizontal apron continued and more stones fell, which covered the sand again at A. The scour stopped again. Meanwhile, scour was occurring at C, until stones rolled down from B, uncovering sand there, and so allowing scour, which undermined A. This process went on, the stones extending deeper and deeper as bed scour progressed, the apron stone all together receding towards the bank. Inglis (1937) remarked that the stones subsided straight down the slope, without any significant movement along the channel (in flow direction). The increasing of the slope angle stops at the point, where the rolling or sliding of the stones breaks off. He also stated that a steeper slope develops, if the bank is being attacked. If that happens, the shear stress at the bank is increasing (the velocity near the bed is relatively higher than in axial flow) and therefore the bank toe scours more rapidly, thus a steeper slope develops.

“At the edge of the settled apron [launched Launching Apron] the stones are more exposed to the flow. Here it was obvious that extra erosion had taken place, in addition to the general lowering of the sand bed - the imposed scour. It appears that the flow around the individual stones caused turbulence around them, like that around a bridge pier. Apparently, the gradient inside the rock layer is high enough to transport the sand. When this transport takes place, the sand grains in the top layer lose contact with surrounding grains and loss of friction will result. The rock layer can slide into this fluidized sand water mixture layer, thus following the subsiding riverbed. The rock at the edge of the slope is therefore constantly ahead of the sand bed position. This mechanism appears almost complete coverage on the slope and thus there is little or no unprotected sand slope .

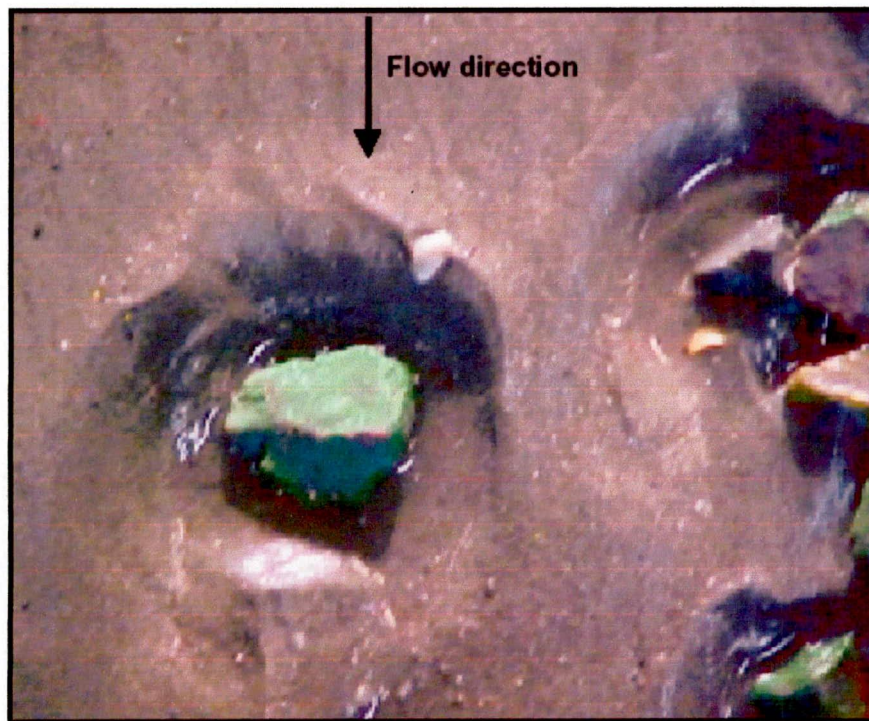


Figure 2.20 Erosion around an individual stone (van de Hoeven, 2002)

Van de Hoeven (2002) mentioned that the rock layer on the establishing slope remained limited to a very thin layer. Only a single layer of rock ended up on the slope. The explanation lays in the mechanism of the Launching Apron. Immediately after the beginning of the launching the material is still lying on two or more layers. The angle of internal friction (angle of repose) of similar material is higher (steeper) than the angle of internal friction between the revetment material and the underlying

sand. Therefore it is obvious that the sliding of the material on the sand will occur first. The upper layer will sack to the underlying sand, after the underlying material slid down resulting in just a single layer of protective material.

2.5 ANGLE OF ROLLING STONES

Another series of experiments were done by Inglis (1937) with a thick layer of stones laid on a “tilting board”, to determine natural angles of the stones in water with various velocities of flow, so-called angle of rolling stones Ω . The arbitrary criterion Inglis set was at 50 % and more of the stones are rolling down.

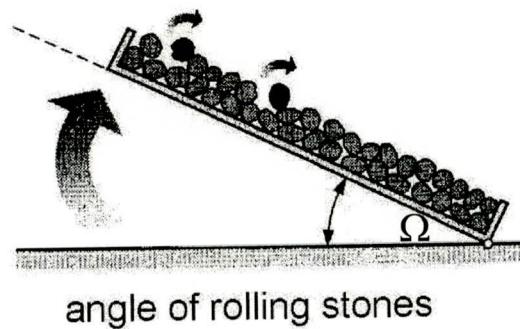


Figure 2.21 Angle of rolling stones Ω with similar material (Bezzola, 2005)

The following results from Inglis were obtained in still water and therefore needs to be used carefully.

Table 2.1 Test results on tilting board obtained in still water (Inglis, 1937)

Types	Angle of rolling stones
Rounded stones laid on similar stones (boulders)	31°
Angular stones laid on similar stones (quarried rocks)	34°
Rounded stones laid on Ganges sand (boulders)	25°

2.6 ANGLE OF REPOSE

The angle of repose ϕ was tested by Inglis (1937) too; this angle of repose (= angle of internal friction) is defined as the borderline slope, which occurs on a tilting board on which the stones are satisfactorily lying on a loosely packed heap, which consists of similar material.

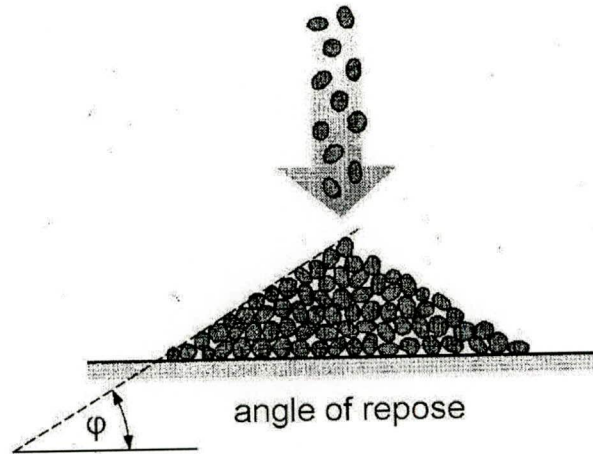


Figure 2.22 Angle of repose ϕ with similar material (Bezzola, 2005)

Table. 2.2 Test results on tilting board in still water (Inglis, 1937)

Types	Angle of repose
Rounded stones laid on similar stones (boulders)	37°
Angular stones laid on similar stones (quarried rocks)	40°
Rounded stones laid on Ganges sand (boulders)	31°

Later Lane (After Bezzola, 2005) found that the angle of repose depends on the size and shape of the particle. He also noted that the angle of repose of large grains (e.g. stones) doesn't differentiate anymore in wet or dry environment. On the other hand for smaller grains like sand the angle of repose decreases in water. The distribution of the grains, packing density and the consistence (e.g. mica) have also an influence.

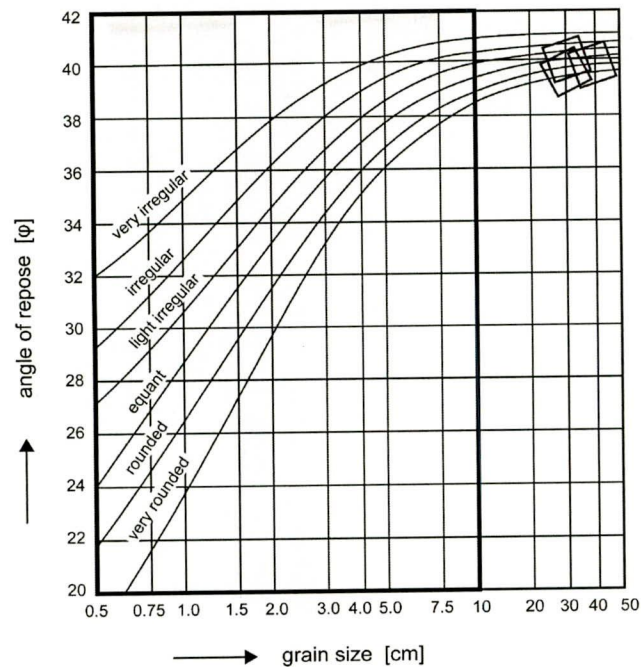


Figure 2.23 Angle of repose according to Lane in 1950 (Bezzola,2005) and extension

As expected angular stones have a steeper angle of repose than rounded ones. CC-Blocks and quarried rocks have therefore similar angles of repose due to their similar angularity. In Figure .10 it is pointed out in which area the CC-Blocks ($D_{50} \approx 0.3-0.45$ m) and quarried rocks ($D_{50} \approx 0.3$ m) are lying. The key parameter for understanding development of the Launching Apron slope is the angle of repose.

Table 2.3 Summary of angle of repose (Mannerstrom et al., 2006)

Angle of repose					
protective material		>	between protective material and fine subsoil	>	underlying fine subsoil
Geobags ¹	50°				soil = f (consolidated, unconsolidated, presence of mica and clay)
Quarried rocks ²	40°				
Boulders ³	35°				
CC-Blocks ⁴	40°				

2.7 DESIGN OF LAUNCHING APRON

Spring's (1903) launching apron design shows that scour prediction and its protection study are in practice since hundred years or may be more. Scour has been a subject of interest and importance to people from the time of the earliest civilizations. Probably the first recorded references to the subject appear in the Leonardian manuscripts. According to Lim (1997), there are three different approaches to scour depth prediction. Later Rahman (1998) also showed same classification of scour depth prediction. They are shown below:

- (a) The regime theory, which relates the scour depth to $2/3^{\text{rd}}$ power of the unit discharge ($D_s \propto q^{2/3}$) in the upstream approaching flow (Lacey, 1929; Ahmad, 1953; Breusers and Raudkivi, 1991).
- (b) The dimensional concept, where the relevant dimensional parameters are correlated (Garde et al., 1961; Melville, 1992).
- (c) Analytical or semi-empirical approaches, which is based on the balance of the approaching flow and the increased flow around revetments (Laursen, 1963; Gill, 1972; Lim, 1997; Rahman, 1998).

For design of apron, initially maximum scour depth is predicted. Then, to create a protective layer of stone rip-rap on the slope of the scour hole, volume of apron material is calculated. This volume of apron is then laid horizontally around the structure to be protected. The existing formulae that are in use include Spring (1903), Gales (1938) and Rao (1948). Even the latest one is half a century old, but forms the basis of modern concepts and theories. In the Hydraulic and River Engineering laboratory of DWRE, BUET, some studies were carried out on scour. For example, Study of River Bank Stabilisation in a Bend by Groin (Hossain, 1981); An Experimental Study of Confluence Scour (Bhuiyan, 1991); "An Experimental Investigation of Scour Protection Using Launching Apron Around bridge Abutment" (Hossain, 2007); "An Experimental Study on the Effect of Submerged Vane on Scour and Flow around Revetment." (Kabir, 2007); "An Experimental Study On flow field and Scour around Bell mouth Groin." (Uddin, 2009) etc. However, some study was also carried out on launching apron. Scouring is a natural phenomenon caused by the

flow and turbulence of water in the river. Scour relates to deeper parts of the river caused by specific flow patterns, most of the time imposed by the planform of the river.

Two approaches have been outlined in the following articles for the estimation of design scour depth. These are:

- a. Scour calculation based on local geometry of the river and
- b. Lacey's regime approach.

In the following methods associated with this computations of various types of scour are discussed.

2.7.1 Local Scour at Revetment

The local scour in front of and downstream of a revetment can be treated analogous to the local scour at the abrupt transition at the tip of an impermeable structure in combination with bed protection. It is therefore, recommended to use Ahmad's formula with $K = 2.6$. Utilizing sediment size of revetment location, Neil's formula may also be used for comparative assessment. Floating debris does not have to be considered.

2.7.2 Lacey's Regime Approach:

Lacey's regime formula is widely used in this sub-continent to find out scour depth in unconstricted alluvial rivers. This empirical regime formula is:

$$R = 0.47(Q/f)^{1/3} \quad (2.1)$$

With $D_s = XR-h$

Where,	D_s	(m)	Scour depth at design discharge
	Q	(m ³ /s)	Design discharge
	h	(m)	Depth of flow, may be calculated as (HFL-LWL)
	f	(-)	Lacey's silt factor = $1.76 (d_{50})^{1/2}$
	d_{50}	(mm)	Median diameter of sediment particle.

X (-) Multiplying factor for design scour depth (Table 2.4)

The water surface level corresponding to Q must be known in order to determine scour level from the above equation. The above equation gives only an estimated mean depth across the channel section. To estimate the maximum natural scoured depth, a multiplying factor must be used as shown in Table 2.4.

Table 2.4 Multiplying Factors for Maximum Scour Depth by Lacey's approach

Nature of location	Factor (X)
Straight reach of channel	1.25
Moderate bend	1.50
Severe bend	1.75
Right angle abrupt turn	2.00
Noses of piers	2.00
Alongside cliffs and walls	2.25
Noses of guide banks	2.75

It is to be noted here that the designer should consider above mentioned two approaches to estimate the design scour depth. Observed data, if available, can also be used to compare the calculated value to determine reasonable design scour depth. Observed scour depth, for example, at the upstream side of Sirajganj hard point was found to be -33 m PWD which caused severe damage during the flood of 1998. In 2005, this scour depth attained at -40 m PWD. Also extremely deep scour (-) 40.00 m PWD occurred at Sailabari groyne in the river Jamuna. In designing Jamuna Bridge guide bundh maximum scour depth of magnitude of 40 to 45m was taken. At Tajumuddin, Bhola in the river Meghna, maximum scour depth at the end of the revetment was considered as -32.50 m, PWD. (BRTC 2008)

2.7.3 Remarks on Design Scour Depth

Assumed scour development is of major importance for the design of a riverbank protection structure. The tools for the estimation of scour in design are empirical

formulas, physical modeling and mathematical modeling. Empirical formulas developed by different authors to estimate scour depth are mostly for one type of scour though different types of scour have to be considered. The results of different formulas have to be considered to yield logical results. The major problem with these types of formulas is the selection of design flow velocity. As the range of flow velocity distribution in meandering/braided channel of a river is very wide, so the representation of the flow velocity by a depth averaged flow velocity in meandering or braided channel in different formulas may not produce the actual field scenario. Therefore, the design values for the scour depth should be selected carefully using design experience and judgment.

2.8 SCOUR DEPTH WITHOUT LAUNCHING APRON

2.8.1 Breusers and Raudkivi

Breusers and Raudkivi (1991) showed that the total scour depth $h+D_s$ could be compared with Lacey's Regime depth, R (Lacey, 1929). Satisfactory results can be obtained from empirically determined values of K in the equation

$$h + D_s = Kq_1^{2/3} \quad (2.2)$$

with a value of $K = 2.0 \pm 15\%$ for a nearly vertical spur-dike. Here, h denotes initial water depth, D_s is the scour depth from initial bed level and q_1 is upstream unit discharge. Suitable correction factors modify this result for other conditions. K_1 is used for spur-dike angle, K_2 is used as shape factors and K_3 is used as factor for position of dike. Factor for spur-dike angle α (measured from downstream bank side):

α	30°	45°	60°	90°	120°	150°
K_1	0.8	0.9	0.95	1.0	1.05	1.1

Shape factor of dike:	K_2
Vertical board	1.0
Narrow vertical wall	1.0
Wall with 45° side slopes	0.85

However, the formula shows that depth of scour varies with discharge. But, the maximum scour should occur at critical velocity when, the ratio of bed shear stress to the critical bed shear stress, $\tau^*/\tau_{*c} \approx 1$, shown by Pilarczyk (1990) and others. Factor for position of dike, K_3 is not discussed here as the study was carried out in a straight channel. Shape factors are only applicable for few specific slopes.

2.8.2 Laursen

Laursen's formula (1963) is based on dimensional analysis of flow continuity equation. According to him, in an imaginary long contraction, the flow continuity equation in section (I) and (II) of fig. 2.1 can be written as

$$Q = uh(b + B_s) = u_s h_s B_s, \quad B_s = \alpha D_s \quad (\alpha = \text{constant})$$

where, Q = flow discharge

Similarly, the energy balance equation can be written as

$$D_s/r + h + u^2/2g = h_s + u_s^2/2g + H_L, \quad H_L = K(u_s^2/2g - u^2/2g) \quad (2.3)$$

where, H_L = total energy loss head, K = energy loss coefficient, r = empirical constant, and g = acceleration due to gravity.

After considering,

- (1) The difference in velocity head loss through the transition at revetment is negligible,
- (2) At equilibrium $u_s = u_c$ (u_c = the critical velocity for sediment movement) and
- (3) Value of $r = 12$ and $\alpha = 2.75$ (corresponding to the rest angle $\phi = 20^\circ$)

$$D/h = 2.09 \sqrt{(b/h)}, \quad D \text{ is the maximum or equilibrium scour depth}$$

Laursen's paper has been quoted extensively in literatures. However, the downstream reference section (II) of the imaginary contraction channel of Laursen is not clear, because the scour depth is gradually decreasing to the downstream direction and enters to the deposition reach. Therefore, the constant values of r and α in his model seem difficult to determine (Rahman, 1998). Moreover, the formula did not consider any shape factor for slope.

2.8.3 Melville

Melville's equations (1992) are also based on dimensional analysis of hydraulic parameters. His design curve is an envelope curve of experimental data. Therefore, always they tend to over predict the scour value. He gave three equations. These are:

$$\text{for } b/h \leq 1: \quad D/h = 2 \sqrt{b/h} \quad (2.4)$$

$$1 < b/h < 25: \quad D/h = 2 \sqrt{b/h} \quad (2.5)$$

$$b/h \geq 25: \quad D/h = 10 \quad (2.6)$$

Above equations are for vertical-wall revetments. For structures other than vertical wall type, he introduced a number of shape factors. Beside the shape factors, Melville introduces various factors for different hydraulic conditions (Melville, 2000). For example, K_{yb} for depth and revetment size, K_I for flow intensity, K_d for sediment size, K_θ for revetment alignment, K_G for channel geometry and K_t for time.

2.8.4 Lim

Lim's formula (1997) is based on laboratory experiment. He assumed that within the scour region, flow concentration is same both at initial and equilibrium stages.

$$\text{at } t = 0: \quad uhB = u_a h B_s + Q_n \quad (2.7)$$

$$\text{at } t = t_e: \quad uhB = u_s (h + D_s/2) B_s + Q_n \quad (2.8)$$

where, t and t_e = times at arbitrary stage and at the equilibrium stage, and u_a = mean velocity in B_s for flat bed.

From (2.7) and (2.8), the following relation is obtained

$$u_a = u_s (1 + D_s / 2h) \quad (2.9)$$

Lim's assumptions were:

- (1) He assumed power law of mean velocity formula

$$u / u_* = m(h / k_s)^n, \quad k_s = 2d \quad (2.10)$$

where, u_* = shear velocity, k_s = equivalent roughness, d = sediment diameter, m and n = constants.

- (2) $u_{*s} = u_{*c}$ (u_{*c} = critical shear velocity for sediment movement)

- (3) $n = 1/3$ and $m = 3.9$

Therefore, his original expression for scour depth can be,

$$(1 + D_s / 2h)^{n+1} = \{ (u / u_*) / m(h / 2d)^n \} \{ 1.2 (b / h)^{0.5} + 1 \} \quad (2.11)$$

after simplification by applying the above assumptions, written as

$$D_s / h = 2 \{ [1.2 (b / h)^{0.5} + 1]^{3/4} - 1 \} \quad (2.12)$$

2.8.5 Rahman (1998)

Rahman considered that the blocked flow only at equilibrium stage, not at initial stage, is concentrating in the restricted region (flatest area) of the scour hole.

$$\text{Inflow (ABCD area)} = (b + h/2\tan\theta + b_s + D_s/\tan\theta)uh \quad (2.13)$$

$$\text{Outflow (EBFG area)} = \{ h^2/2\tan\theta + (bs + D_s/\tan\theta)h + (b_s + D_s/2\tan\theta)D_s \} u_s \quad (2.14)$$

$$b_s = \beta B_s = \{ \beta / (1 - \beta) \} (D_s / \tan\phi) \quad (2.15)$$

where, $b = b_0 + (2H - h)/2\tan\theta$, u = approach flow velocity, u_s = velocity in the EBFG area, ϕ = angle of repose of bed material, β = constant (<1). Now, equating inflow and outflow and considering

- (1) At equilibrium state of clear water scouring, $u_s = u_c$

- (2) $u/u_c = (\tau^*/\tau_c^*)^{0.5}$ and

- (3) $\tau^*/\tau_c^* = 1$ at critical condition,

a simplified expression for scour depth can be obtained as follows:

$$D_s/h = \sqrt{\{C(b/h)\}}, \quad C = \{\beta / \tan\phi (1 - \beta) + 1/2\tan\theta\}^{-1} \quad (2.16)$$

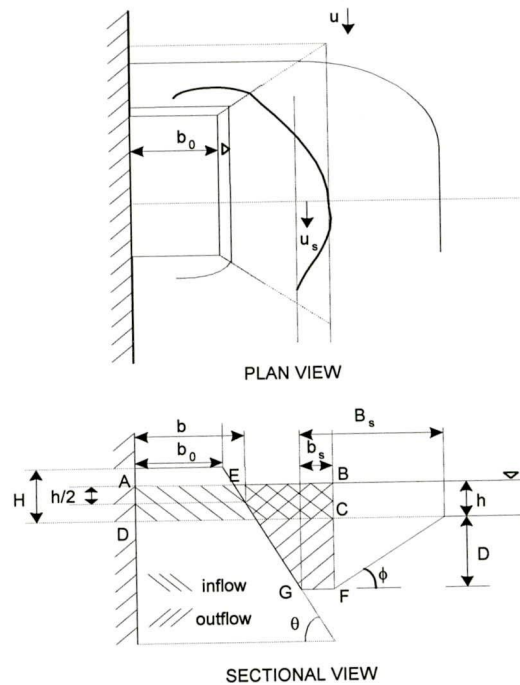


Figure 2.24 Definition sketch of the restricted concentration flow model

When $\tan\phi = 0.5$ and $\beta = 0.2$, values of C for vertical face and slopes of 1V:1H, 1V:2H and 1V:3H are:

C (vertical) =	2.0
C (1V:1H) =	1.0
C (1V:2H) =	0.67
C (1V:3H) =	0.5

Rahman's formula considered both angle of repose of bed material and slope of structure of any value. However, among the discussed formulae no one fits the cases of structures used for the study. That is, used structures had a slope up to initial bed level and then have a vertical face. The sloping faces of these structures were not extended up to a level below maximum scour depth.

From the foregoing discussions it appears that no such formula could be found out for scour prediction around revetment when launching apron is placed to protect it. Generally, scour is predicted for structure considering without apron case. Then, apron volume is calculated to protect it. However, this seems illogical. Because, when apron material is placed around a structure, definitely it behaves in a flow

condition differently than that of without apron case. Therefore, some factor should be incorporated in scour prediction formulae or the shape factor may be modified to include the effect of submerged flow restriction by the apron material.

2.9 LAUNCHING APRON DESIGN

2.9.1 Existing Methods

Launching apron is placed at the foot of revetment to protect it from failure due to undermining. When the bed is erodible, scour cannot be prevented from occurring. To protect structures against scour in sand bed, use of launching apron is the most economical method. Apron is the stone cover laid horizontally on the bed around the structure at its foot. When undermining occurs it starts at the farthest end and gradually works backward towards the slope (Varma, 1989). The apron material then launches to cover the face of the scour slope. As the materials are launched it is called launching apron. For designing launching apron, so far three types of formula are known and they are discussed below.

2.9.2 Spring's Method (1903)

Spring's Method is probably the oldest among the known formulae for designing launching apron. In Bangladesh, this method was successfully used in protecting the famous 'Hardinge Railway Bridge'. It may be mentioned here that even after 90 years of construction that bridge still remains protected. Design sketch of Spring's method is shown in fig. 2.25.

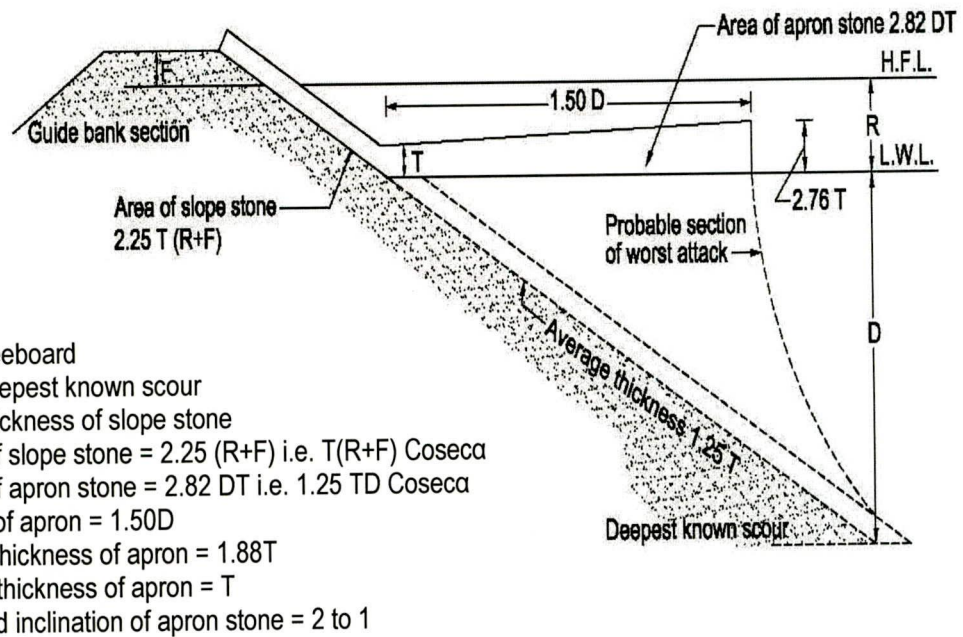


Figure 2.25 Shape of apron suggested by Spring (1903)

2.9.3 Gales' Method (1938)

Gales' method provides a berm at the beginning of the apron, thickness remains throughout $1.5 T_1$ and slope of launched apron is assumed to be $1V : 2H$. Prospective slope length $2.24 D$ from which thickness of launched apron is T_1 . Width of berm is different for different rivers. This berm is unnecessary if the design of apron is proper (Varma, 1989).

2.9.4 Rao's Method (1946)

In Rao's method, slope is assumed to be $1V : 2H$. He modified shape of apron area that is provided by Spring.

The change in design is shown in fig. 2.26.

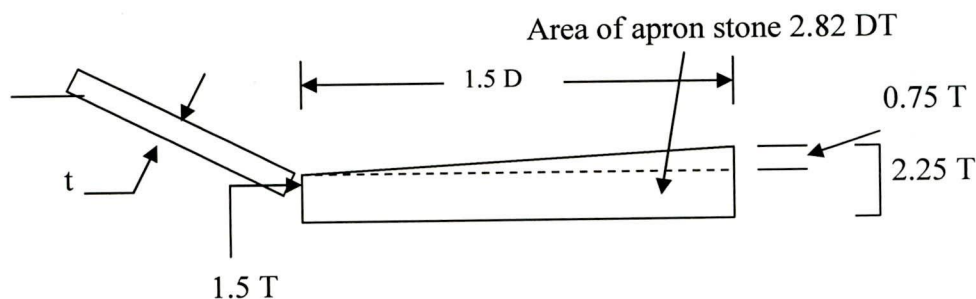


Figure 2.26 Dimensions of launching apron (Rao)

In the dimensions, t depends on flow rate. In case of a guide bank section the formulae used in Indian subcontinent are as follows (Garg, 1995):

$t = 0.06 Q^{1/3}$, t is the thickness of stone pitching in ft and Q is the discharge in cfs.

$T = 1.9 t$, is the thickness of apron when laid. This is considered when the cross section of laid apron is rectangular. In the field, since launching begins at the outside perimeter, the apron is laid in a wedge shape. The dimensions of inner and outer sides are as shown in the fig. 2.21. In these figures D , the maximum scour depth, is calculated usually with Lacey's Regime method. However, it may be calculated with any reasonable formula that is suitable in the prevailing situation. The thickness of launched apron is considered to be $1.25 T$ as the minimum. If the situation is considered to be severe then it may be increased. In that case, all other dimensions will also be changed.

2.9.4 Slope of Launching Apron

According to Ray (Ray, 1941), "The materials of the armour on the bank-slope and in apron act only as a 'face wall'. The bank-slopes should, therefore, be stable by themselves, without any external support. To ensure this, the slope should have the same angle as the 'angle of repose' of the bed material." Model observations (C. W. P. R. S, 1947) have shown that an apron does not launch satisfactorily unless angle of repose of the underlying material is flatter than that of protective work. In most cases

the average slope approximates to 1V:2H. According to Neill (Neill, 1975), model tests (Inglis, 1949) have indicated that such a slope is realistic for sand beds, but little definite field confirmation seems to have been reported.

2.9.5 Size of Stone

Various methods are available for determining size of stone. Of them, Neill's formula is widely used. The formula is derived from Neill's curve and the equation takes the form as, $D_e = 0.034 V^2$ (in metric units). Here, D_e is the equivalent spherical diameter of stone for specific gravity of between 2.4 and 2.9. D_e is defined by Neill as, $D_e = 1.24 (\text{volume})^{1/3}$. Flow velocity may be taken as approximately two-third of the cross-sectional mean, where channel is straight. (Neill, 1975). Size obtained from formula gives mean diameter (D_{50}). Stone sizes should form smooth gradation curve when plotted against their weight percentage. Stone shape should be as near to the cubical as practicable. In particular, thin slab shaped stones should be avoided (Varma, 1989).

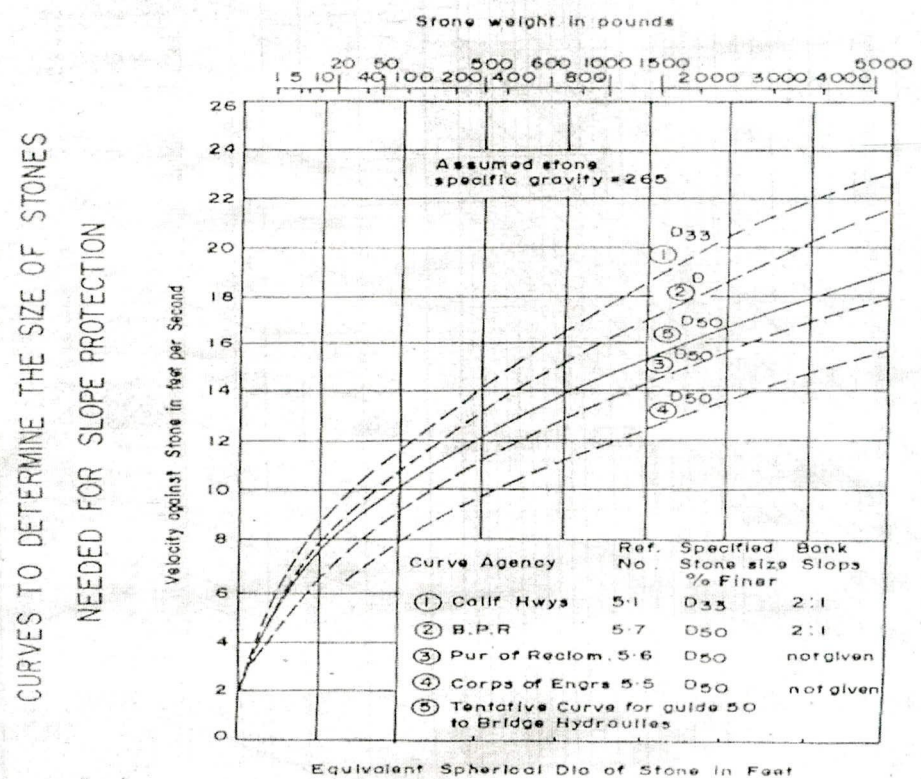


Figure 2.27 Neill's curve for apron stone size

2.9.6 Thickness of Launched Apron

Proposed thickness of launched apron is assumed to be $1.25 T$, where T is the revetment thickness (Rao, 1946 and Spring, 1903). T depends on discharge. It was suggested that where attack is severe, thickness might be increased to $1.5 T$ or even higher. Gales have suggested different thickness for different discharge and is widely used in India .

2.9.7 Geometry of Launching Apron

A $1.5 D$ width appeared optimum. Design proposed by Rao is widely used. The theoretical dimensions are already shown in figs. 2.25 and 2.26. To ensure filtration for the bed material either geotextile mat is used or smaller stones are laid as bottom course.

CHAPTER THREE

EXPERIMENTAL SETUP, DATA COLLECTION AND METHODOLOGY

3.1 GENERAL

To carry out the Experimental Study of Launching Apron the existing sand bed flume situated in the hydraulics and river engineering laboratory of DWRE was utilized. However to fulfil the requirements as set in the objectives a number of modifications in the test facility was required. These include contractions of the sloping part of flume in such a way to develop velocity sufficient to initiate movement of various sizes of falling apron materials etc. A chronology of the changes and modifications that were made to the existing facility are given below.

3.2 RECONSTRUCTION OF LABORATORY CHANNEL

During the laboratory channel reconstruction other structures were also constructed simultaneously, for example, sloping revetments and fabrication of apron materials. Depending on the flow volume, estimated scour depth, pump capacity, measuring devices, reservoir capacity and duration for test runs etc, hydraulic parameters were selected. Bed material was analysed. Because of the bed material size, there was ripple formation. During the test runs section-wise flow measurements were taken to see whether the flow was maintained at the theoretical value or any variation occurred. If any variation created, necessary corrections were made. For test in mobile bed the change of depth was measured every after half an hour. It was observed that after six hours of run the scour depth did not increase any further. Therefore, for each application of falling apron, the flow was run for 8 hours. Moreover, there was no stand by pump in the laboratory and the only available one pump can run for maximum 8 hours continuously.



Figure 3.1 Reconstruction of the laboratory channel

3.3 THEORETICAL ASPECTS TO DETERMINE SIZE OF FALLING APRON

In the first phase, the scour study was carried out. This was performed to see the scour geometry and the scour depth developed in each experiment within 8 hours. For this study, firstly the slope of revetment 1:1.25 was selected. From the values of scour depth obtained in the first phase of the experiment the volume of apron material is calculated using Rao's method (1941). In the second phase, at first, slope of revetment 1:1.5 was selected. For this the volume calculation for apron material was as below:

$$Q = 40 \text{ l/s} = (40 * 10^{-3}) * 3.28^3 = 1.41 \text{ ft}^3/\text{s}$$

$$t = 0.06Q^{1/6} \text{ ft} = 0.06 * 1.41^{1/6} * 12 * 2.54 = 1.94 \text{ cm}$$

$$T = 1.9t = 1.9 * 1.94 = 3.686 \approx 3.7 \text{ cm}$$

$D = 21 \text{ cm}$, the maximum scour depth

$$\text{Area of apron material} = 2.82 DT = 2.82 * 21 * 3.7 = 220 \text{ cm}^2$$

The extent of apron should be up to $1.5 D = 31.5 \text{ cm}$ from the structure.

For making wedge shape the inner edge height was $1.5T = 5.5 \text{ cm}$ and the outer edge height was $2.25T = 8.3 \text{ cm}$

As the water depth was 8cm, the inner and outer edge height were given 3 and 4.5cm respectively. Since the scour study showed that at the downstream of the structure there is deposition instead of undermining. The behaviour of apron material was also studied under different set ups. This experiment was also run for 8 hours in conformity with scour study. In this phase, velocity vector measurements were taken with the help of computer and analysed.

3.4 APRON MATERIAL SIZE

3.4.1 Sand-Cement Block

Neill's Equation, $D_e = 0.034 V^2$, where, D_e is equivalent diameter of stone, V is average velocity in m/s near the stone (0.35 m/s assumed). Here, instead of stone, sand-cement cube was used. Therefore, calculated diameter was converted to cube size. Specific gravity for stone, S_s was considered to be 2.65. Specific gravity for sand-cement cube, S_c was measured to be 2.07. Submerged unit weight ratio was $= (S_s - 1) / (S_c - 1) = 1.542$

$$D_e = 0.034 * (0.35)^2 * 1000 = 4.165 \text{ mm} = 1.24 \text{ (volume of cube)}^{1/3}$$

Therefore, Volume of cube = $37.89 \text{ cubic mm} * 1.542 = 58.42 \text{ cubic mm}$

$$\text{Dimension of cube} = (58.42)^{1/3} \text{ mm} = 3.88 \text{ mm} \approx 4 \text{ mm}$$

After the critical size of 4 mm was found, it was decided to use launching apron smaller and some apron size bigger than the critical size. For this reason 4 different sizes were selected. As such, 3 mm, 4 mm, 5 mm and 6 mm cubes of sand-cement were prepared. For cube preparation, at first a sand-cement mortar was made (cement : sand = 1:4). Their drawing specifications are shown in figures from 3.2 to 3.4 .

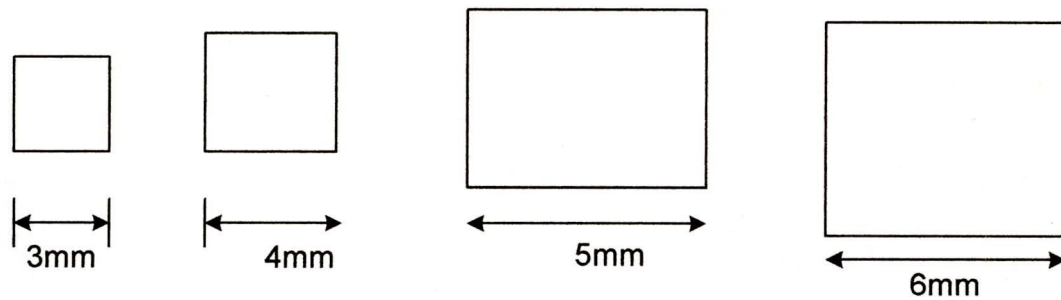


Figure 3.2 Different sizes of apron

Then the mortar was laid on glass sheet covered by polythene sheet. After some time of drying the mortar was cut to required sizes with the help of scale and knife. After that they were left open for curing for one day. The next day when these were dried, then the cubes were separated and stored. Preparation of apron cube is shown in the following figures.



Figure 3.3 Preparation of cubes



Figure 3.4 Different types of cubes

3.4.2 Preparation of Geobags

Geobags were prepared of Grade 4 whose weight is 1 gm, length 17 mm and width 13 mm. Size of geobags were taken from Van Coevar model test as shown in Figure 3.5. Lowest size was taken as it is difficult to fabricate below this size. Geobags were prepared in Faridpur River Research Institute.



Figure 3.5 Preparation of Geobags (Grade 4, length 17 mm, width 13 mm)

3.5 EXPERIMENTAL SET UP

In every experiment, the set up includes the laboratory channel, different hydraulic parameters, bed material, the equipments used, etc. These elements make every experiment different from others. Boundary conditions or limitations together with the experimental set up actually define the problem under study. Experimental set up for the problem under study is discussed in the subsequent paragraphs.

3.5.1 Preparation of Slopes in the Laboratory Channel

The original channel used in the previous test was a 11m long, 2m wide rectangular channel. Few preliminary trial test run revealed that the prevailing velocity was not enough to produce velocity sufficient to initiate the launching apron materials. As a result the channel was reconstructed with a bed width of 1 m. Water entered the channel smoothly from an inlet reservoir, and a secondary reservoir was placed at the end connected to a tailgate. Through the tailgate water goes to a sump. From this sump, the water was recirculated through a return system. From the tailgate, water was allowed to fall into the sump through a reboke weir for measuring the flow. The main channel was made of plastered brick wall and brick soling. Plastering was carried out with sand-cement mortar of ratio 5:1 (sand : cement) to ensure no water seepage and at the same time the wall can be easily broken for remodelling the channel for other tests. The slope of the revetment was constructed as 1:1.25, 1:1.5 and 1:2. This represented the slope of the bank of model channel as shown in the figures from 3.6 to 3.12.

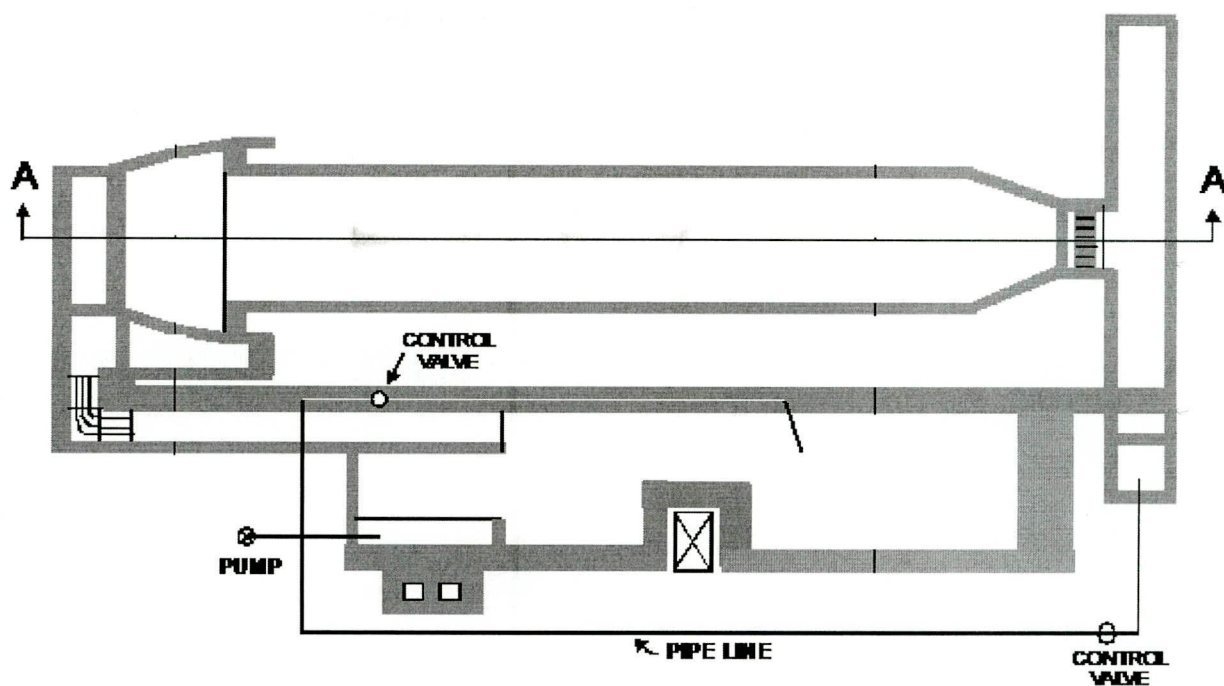


Figure 3.6 Plan of Laboratory channel

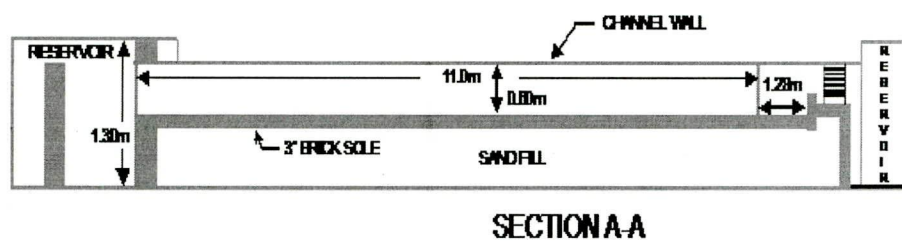


Figure 3.7 Layout of Section A-A

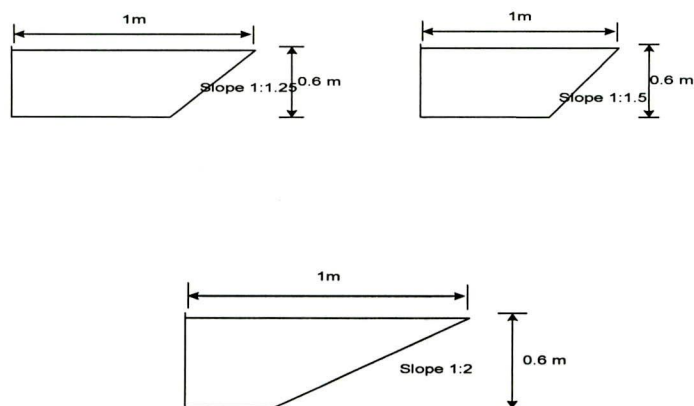


Figure 3.8 Experimental slope of revetment for test runs

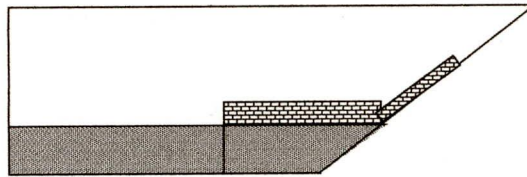


Figure 3.9 Experimental slope of revetment with sand –cement blocks

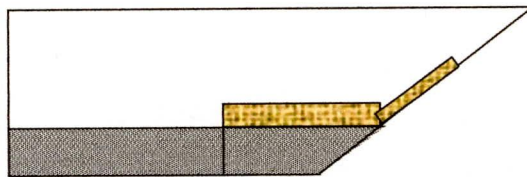


Figure 3.10 Experimental slope of revetment with geobags



Figure 3.11 Placement of Blocks at the toe of the revetment



Figure 3.12 Placement of Blocks at the toe of the revetment

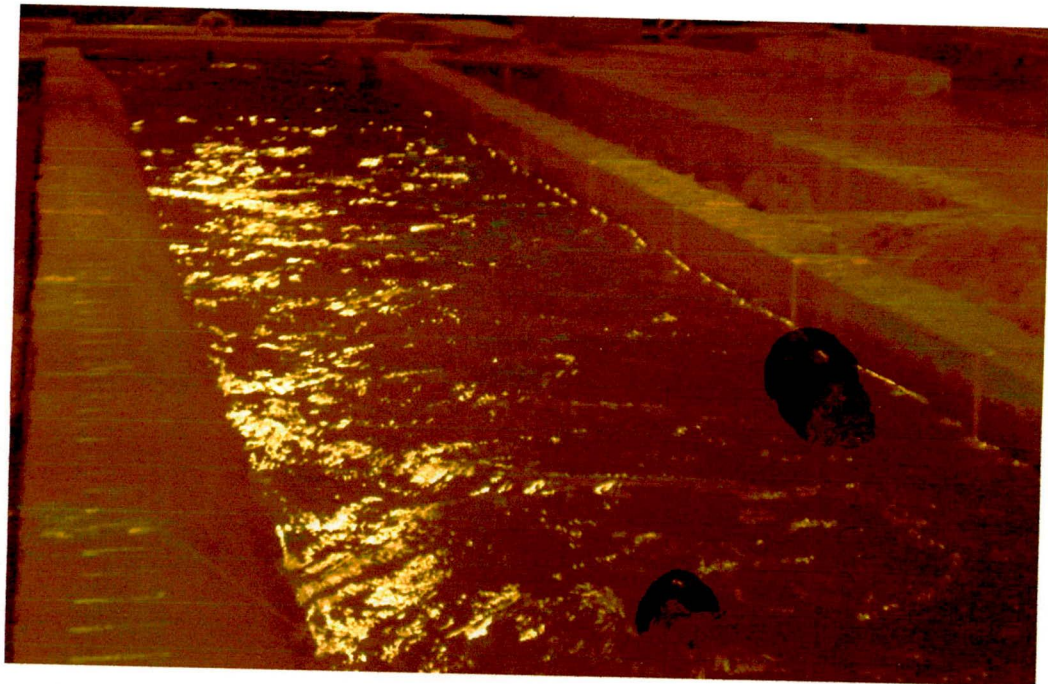


Figure 3.13 Few test runs in the constructed channel



Figure 3.15 Test run in the Channel without apron

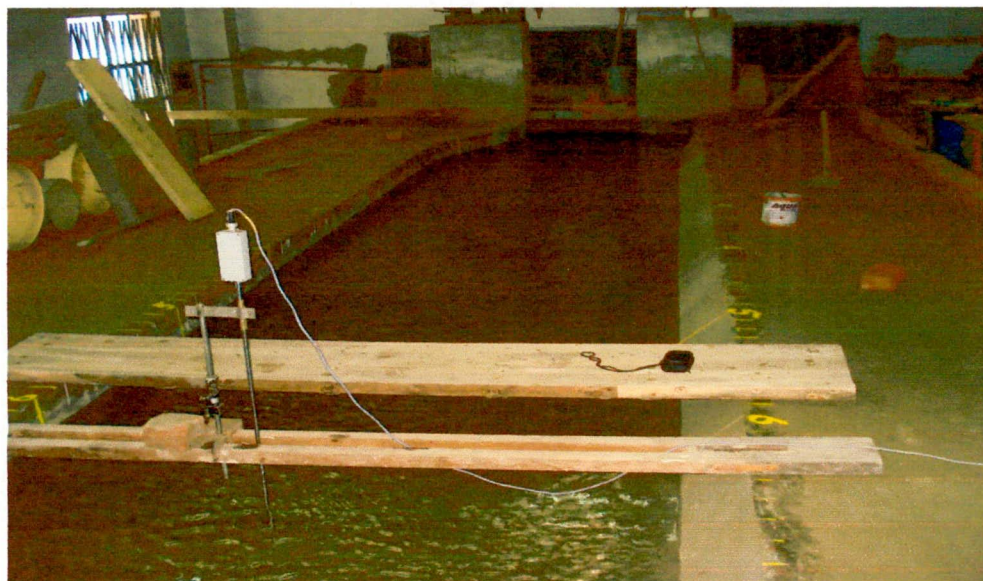


Figure 3.16 Velocity measuring by PEMS

3.6 SETTING BOUNDARY CONDITIONS

The laboratory facility used for the purpose of conducting the test runs are a recirculating system composed of upstream reservoir, downstream reservoir, a flow channel, pumping devices etc. The facility is equipped with pumps which can supply a maximum discharge of 90 l/s. However a maximum discharge of 70 l/s is convenient to use. Considering different hydraulic parameters like flow-rate, velocity, bed shear stress, freeboard, water depth, etc, discharge range 40 l/s to 70 l/s was maintained. Since maximum scour should occur at $\tau^*/\tau_c^* \approx 1$, this will be the main consideration in selecting discharge ranges for the test. The pump used for water circulation can run for 8 hours at a stretch.

Table 3.1 CONSIDERATIONS OF TEST PARAMETERS

B	h	A	Q	U	D ₅₀	n	S	U*	U* _c	U*/U* _c	τ^*/τ_c^*	Bed level
(m)	(cm)	(m ²)	(l/s)	(m/s)	(mm)			(m/s)	(m/s)			Differ (mm)
1	12	0.12	40	0.125	0.28	0.012	0.00004	0.0068	0.016	0.431	0.185	0.38
1	15	0.15	40	0.1	0.28	0.012	0.00002	0.0052	0.016	0.332	0.110	0.19
1	5	0.05	50	0.4	0.28	0.012	0.00128	0.025	0.016	1.594	2.542	11.76
1	8	0.08	50	0.25	0.28	0.012	0.00027	0.0145	0.016	0.921	0.849	2.66
1	10	0.1	60	0.2	0.28	0.012	0.00013	0.0111	0.016	0.710	0.504	1.27
1	12	0.12	60	0.1667	0.28	0.012	0.00007	0.009	0.016	0.574	0.330	0.69
1	15	0.15	70	0.1333	0.28	0.012	0.00003	0.0069	0.016	0.443	0.196	0.33

Considerations and Formula

In this table following considerations and formulae are used:

$$B = 1\text{m}; \quad h = 5, 8, 10, 12, 15\text{cm}; \quad Q = 40, 50, 60 \text{ and } 70 \text{ l/s}; \quad U = (1/n)(h^{2/3} * S^{1/2});$$

$$n = (1/21.1)(d/1000)^{1/6}; \quad S = [\{(U)*(n)\}/h^{2/3}]^2; \quad U_c^* = \text{SQRT}(8.41 * D^{11/32});$$

$$U^* = \text{SQRT}(ghS); \quad \text{Bed level difference between upstream and downstream ends} - S * 10 * 1000;$$

$$\tau^* = \rho U^{*2}; \quad U^*/U_c^* = 0.9 \sim 1.0; \quad \tau^*/\tau_c^* = 0.8 \sim 1.0;$$

3.6.1 Bed Materials

The bed material used was medium sand. Frequency Modulus was 1.32, D_{50} was 0.28mm, D_{90} was 0.39mm. The grain size distribution chart is shown as fig. 3.17. This bed material formed ripples, as D_{50} was less than 0.7mm (Melville, 2000).

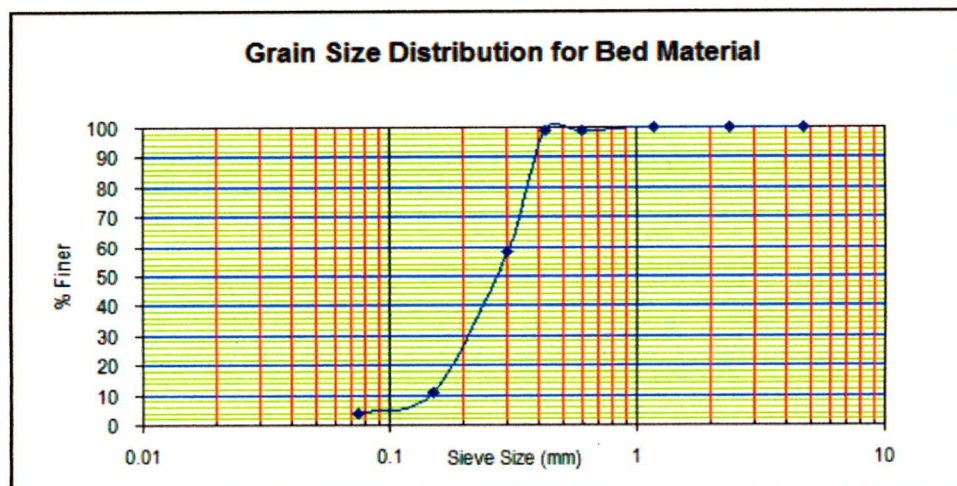


Figure 3.17 Sieve analysis result of bed material at surface

3.6.2 Velocity Meter

For the measurement of velocity a programmable 2-D electromagnetic liquid velocity meter was used. The name of the meter is "P.E.M.S.", made in Netherlands, year of manufacture is 1993. Serial number of the equipment is E271. Velocity ranges are 0.1 m/s to 2.5 m/s. The probe has four-quadrant response that enables direction-independent measurements. By changing the absolute value notations velocity vector can be measured. This is in fact the inside-out version of the well-known pipe flow meter employing Faraday's Induction Law for measurement of the velocity (V) of a conductive liquid moving through a magnetic field. The magnetic field is induced by a pulsed current through a small coil inside the body of the sensor. Two pairs of diametrically opposed platinum electrodes (e) sense the Faraday-induced voltages produced by the flow past the sensor. The sensor has been designed in such a way that these voltages are proportional to the sine (V_y) and cosine (V_x) of the magnitude of the liquid-velocity (V_e) parallel to the plane of the electrodes. By means of advanced electronics the low level output signals of the probe are converted to high level output

signals from which the magnitude of the velocity and its direction (referred to a reference) can be derived by application of common trigonometry. The device has a display window from where data can be directly read. For continuous data the device can be attached to a computer and data can be registered very easily. For the present study, 50 to 60 data were recorded for a single point and later the average of these values are taken as the velocity of that point.



Figure 3.18 Control Unit of Electro Magnetic Velocity Meter (PEMS)

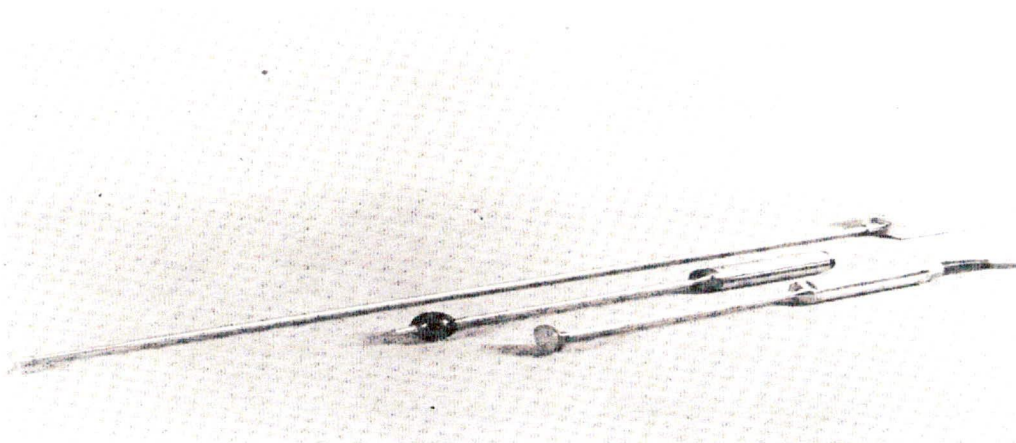


Figure 3.19 Probes of Electro Magnetic Velocity Meter (PEMS)

3.7 DISCHARGE COMPUTATIONS

A section-wise discharge was calculated to see the variation from the theoretical discharge. Observed discharge variation was only 2.85% higher than the theoretical discharge. Because of formation of ripple the average depth was changed to 7.31cm from an initial depth of 8cm and velocity was changed to 0.24 m/s from theoretical value of 0.25 m/s. The section-wise discharge calculation is shown in Table 3.2.

Table 3.2 Discharge Calculation at Different Section

Distance from left water edge (cm)	Average width W (cm)	Depth h (cm)	Velocity V (m/s)	Segmental discharge Q (cm ³ /s)	Q (l/s)
5	10	9.47	0.31	1111	2.93570
15	10	8.48	0.23	1950.40	1.95040
25	10	9.49	0.33	3131.70	3.13170
35	10	9.40	0.30	2820.00	2.82000
45	10	9.15	0.24	2196.00	2.19600
55	10	8.90	0.30	2670.00	2.67000
65	10	8.15	0.29	2363.50	2.36350
75	10	7.75	0.24	1860.00	1.86000
85	10	7.15	0.31	2216.50	2.21650
95	10	6.50	0.27	1755.00	1.75500
105	10	5.60	0.25	1400.00	1.40000
115	10	5.65	0.21	1186.50	1.18650
125	10	5.75	0.27	1552.50	1.55250
135	10	5.85	0.26	1521.00	1.52100
145	10	6.55	0.30	1965.00	1.96500
155	10	6.75	0.27	1822.50	1.82250
165	10	7.10	0.31	2201.00	2.20100
175	10	6.70	0.31	2077.00	2.07700
185	10	5.65	0.31	1751.50	1.75150
195	10	6.10	0.29	1769.00	1.76900
		7.25	0.24	1997.24	39.14

3.8 TEST RUNS

Following test runs were conducted to show the scour, flow pattern and extent of aerial coverage around launching apron. Three different discharge and slopes of the revetment were considered in the present study. Twenty seven tests were planned under varying conditions. Table 3.3 shows the summary of test programme. Water depth have been controlled by adjusting the tailgate at the down stream. The actual numbers of test conducted are more than the number mentioned in the programme. The results and behaviour for 5mm,6mm and 7mm are found same in this flume. The data obtained from the test runs are given in appendix A,B and C.

Table 3.3 Summary of the Test Runs

Run no	Types of Bed/Bank condition	Slope of Revetment	Size of falling apron	Discharge (l/s)
1	Fixed Bed	1:1.25		60
2				50
3				40
4		1:1.5		60
5				50
6				40
7		1:2		60
8				50
9				40
10	Sand Bed(0.28mm)	1:1.25	3 mm sand-cement blocks and Geobag separately	60
11				50
12				40
13		1:1.5	4 mm sand-cement blocks	60
14				50

15			and Geobag separately	40
16		1:2	5 mm sand-cement blocks and Geobag separately	60
17				50
18				40
19	Sand Bed(0.28mm)	1:1.25	5 mm sand-cement blocks and Geobag separately	60
20				50
21				40
22		1:1.5	4 mm sand-cement blocks and Geobag separately	60
23				50
24				40
25		1:2	3 mm sand-cement blocks and Geobag separately	60
26				50
27				40
28		Fixed Bed	1:1.25	5 mm sand-cement blocks and Geobag separately
29	50			
30	40			
31	1:1.5		4 mm sand-cement blocks and Geobag separately	60
32				50
33				40
34	1:2		3 mm sand-cement blocks and Geobag separately	60
35				50
36				40

3.9 DATA COLLECTION

Tests were conducted in 3 types of slopes with different apron materials as discussed earlier. Data were collected on: 1) Velocity, 2) Scour, 3) Launching behaviour, and; 4) Aerial coverage. The numbers of tests originally proposed and actually completed under each category were as follows:

<u>Data Collection</u>	<u>Number of Proposed Tests</u>	<u>Number of Completed Tests</u>
1) Fixed Bed Tests (without apron)	9	12
2) Fixed Bed Tests (with apron)	9	12
3) Mobile Bed Tests (without apron)	18	18
4) Mobile Bed Tests (with apron)	18	18
5) Launching Tests	30	30
6) Velocity Data	1200 sets	1800 sets
7) Scour Data	1200 sets	1800 sets
8) Aerial Coverage	30 sets	30 sets

3.9.1 Velocity Measurement

Velocities were measured using the programmable 2-D electromagnetic liquid velocity meter. The probe was placed at a constant depth of 0.6y from the water surface for all the measurements. Velocity measurements were taken for comparison between the cases of with and without apron. For velocity measurement same wooden bridge was used. But in place of needle, velocity meter probe was used. The probe was placed at a constant depth of 2 cm from the water surface for all the experiments. The areas selected for velocity measurement were around the structure. These areas were divided into grid system. Measurements were taken at each grid points. For each point total 50 or 60 readings were taken with the help of computer. Each velocity reading has been taken as the average velocity of 60 seconds duration. Two velocity components, i.e. V_x and V_y , with standard deviations are read from the display screen of the control unit at a time.

3.9.2 Scour Measurement

Scour measurements were taken at the grid points set according to the shape of scour patterns by using point gauge. However, in this case, equidistant grid was not used as the scour slope was not same everywhere. Depending on the slope of scour hole at some places closer data were taken and for the same reason at some places dispersed data were taken. Measurements were used to study the scour pattern, maximum depth, and its location and to draw the scour contour. Extents of measured area were selected depending on the extents of scour hole. With the help of a point gauge on a platform that slides on a wooden bridge measurements were taken. The initial bed level was used as reference data. Any data found to be below this reference point is taken as negative value and indicated scour. Similarly, any data found to be above the same reference point is taken as positive value and indicated deposition. Then these data were processed to generate grid data and to plot scour contour. The longitudinal and lateral scour profiles at the maximum scour depth were also plotted as graph. Photographs were also taken to visualise the scour hole. In the scour contour plot the initial bed level, that is the reference or 0 value, is shown with green colour. The deepest scour value was represented by blue and the maximum positive (deposition) value was represented by red. In between the two extreme values gradually colour was changed.

Scour Contour for Revetment with 1V:1.25 Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

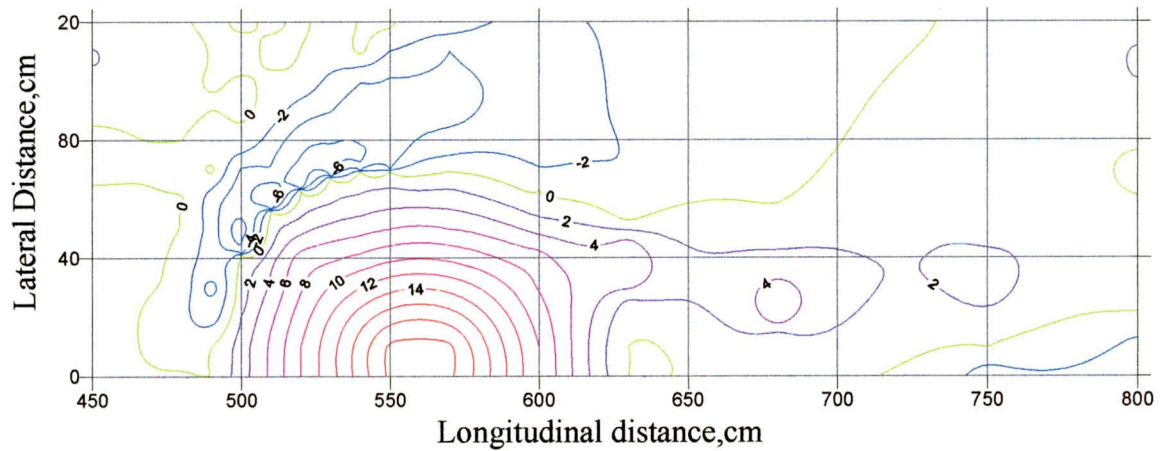


Figure 3.20 Scour Contour for Revetment with 1V:1.5 Slope with 3 mm

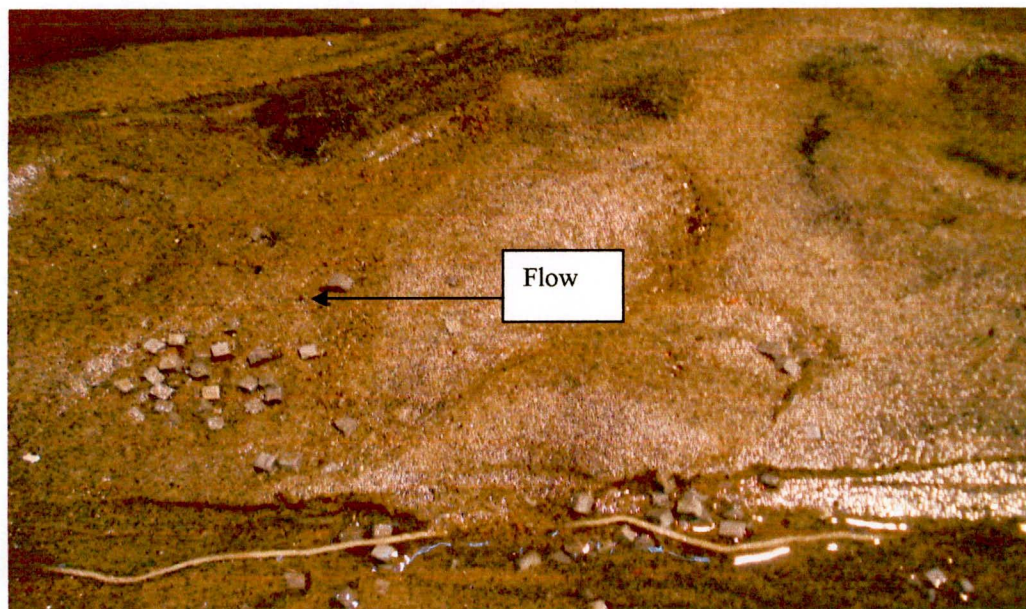


Figure 3.21 Revetment and launching apron with 1V:1.25 H slope

Scour Contour for Revetment with 1V:1.5H Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

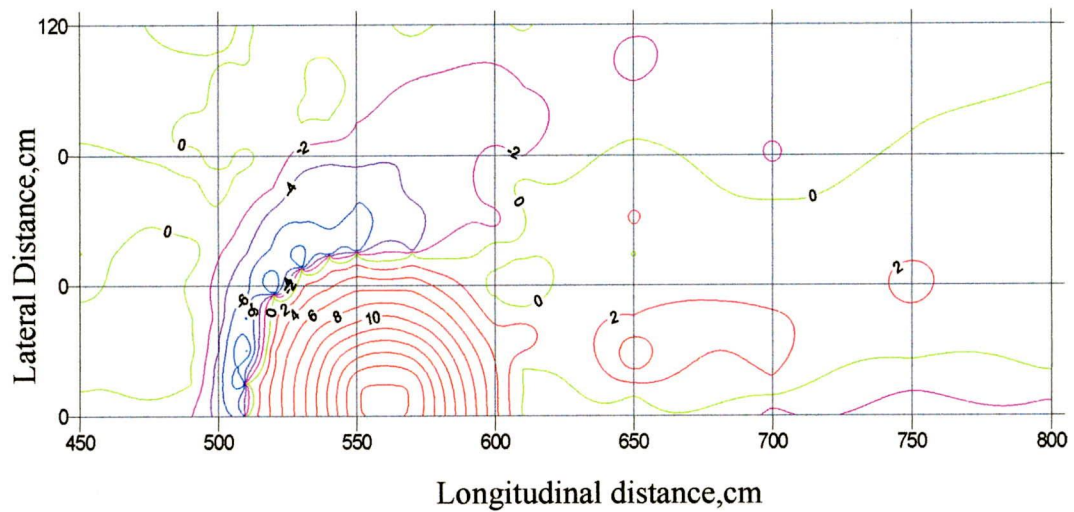


Figure 3.22 Scour Contour for Revetment with 1V:1.5 Slope with 4 mm

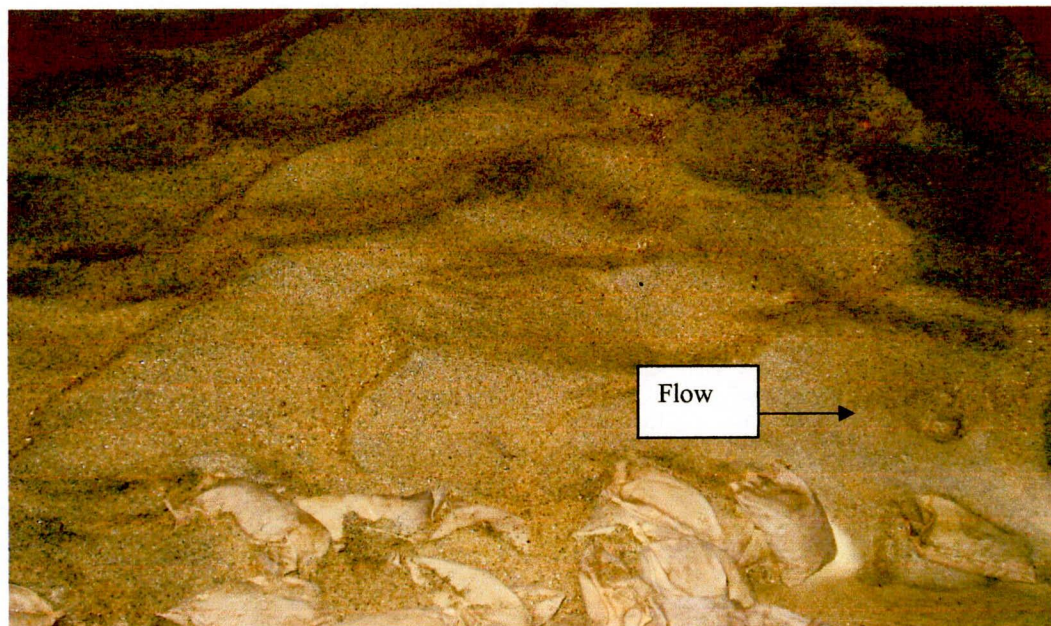


Figure 3.23 Scour for revetment with 1V:1.5H slope with geobags

107530

Scour Contour for Revetment with 1V:2H Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

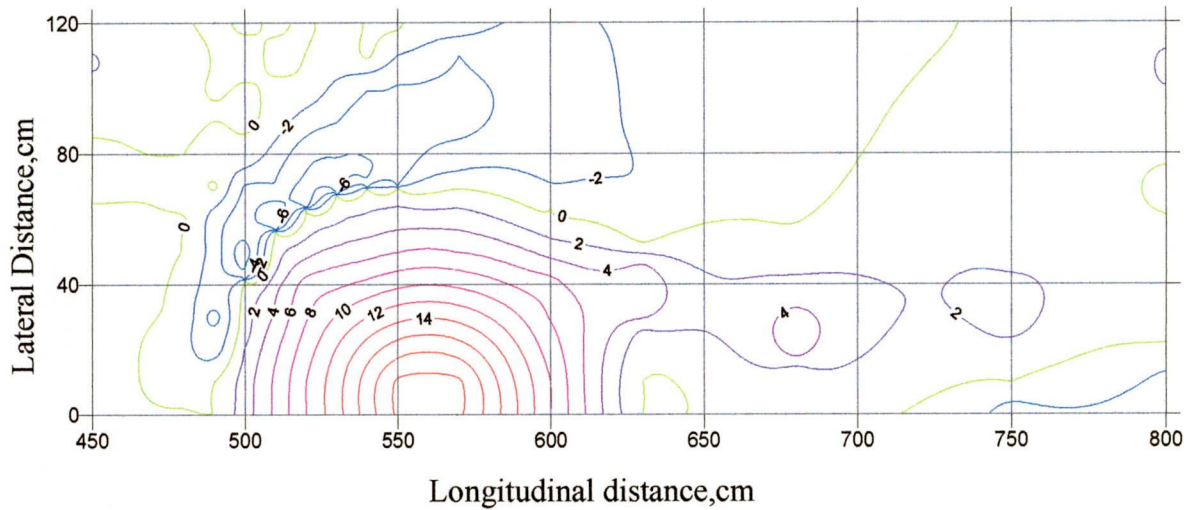


Figure 3.25 Scour Contour for Revetment with 1V:1.5 Slope with 5 mm

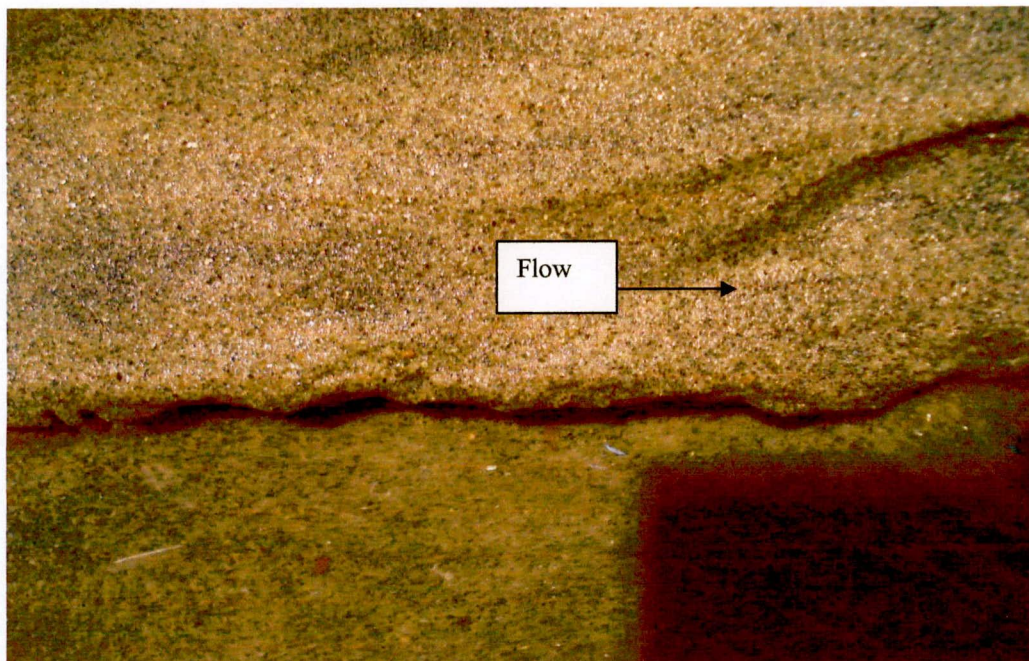


Figure 3.24 Flow over the Launching apron in 1:1.5 slope

Scour Contour for Revetment with 1V:1.25 Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

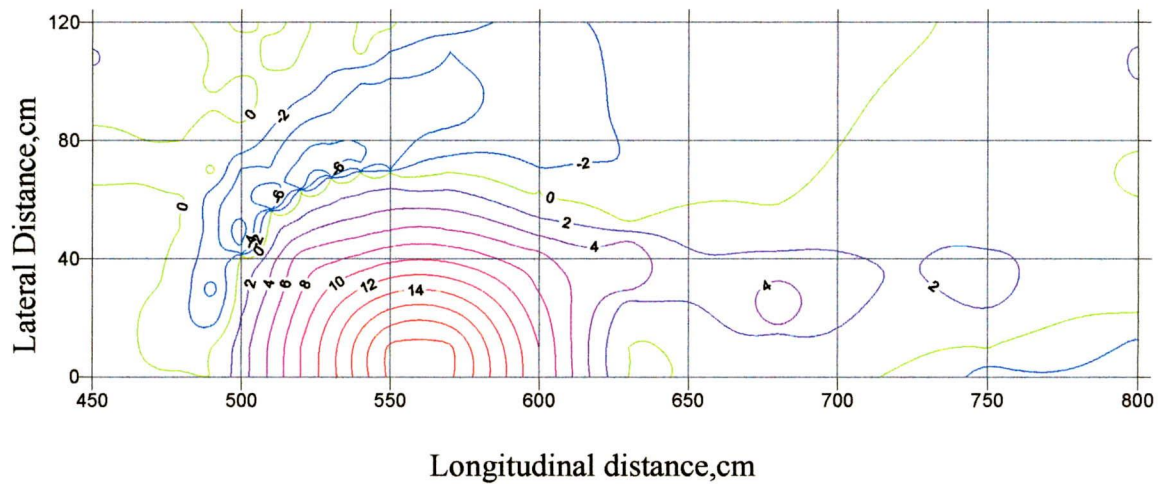


Figure 3.26 Scour Contour for Revetment with 1V:1.5 Slope with 4 mm

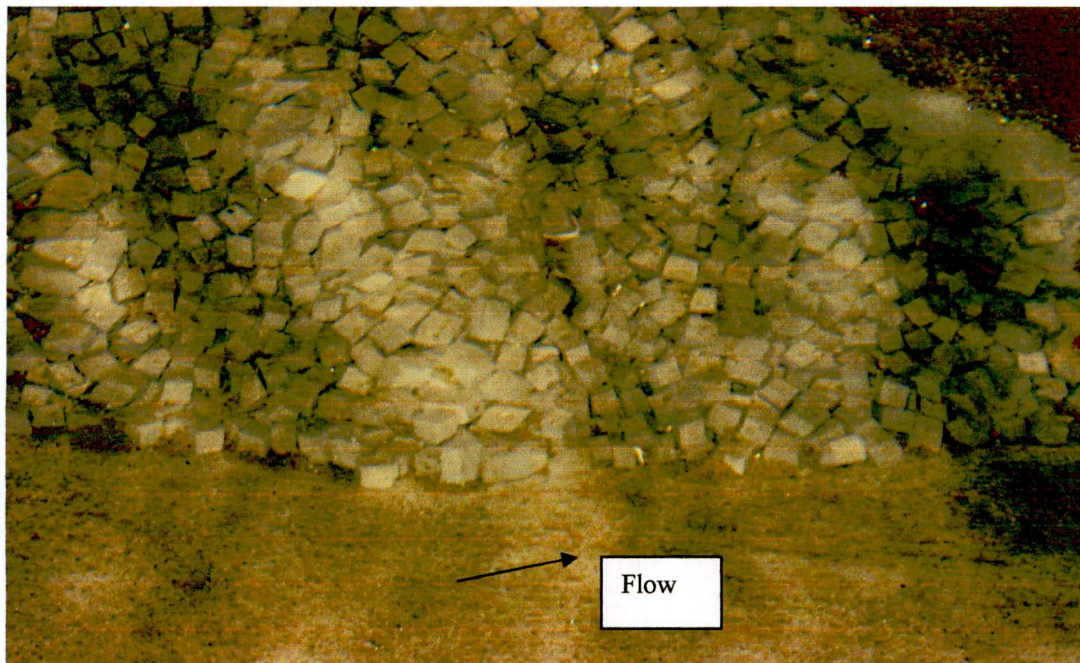


Figure 3.27 Revetment and launching apron with 1V:1.25 H slope

Scour Contour for Revetment with 1V:1.5H Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

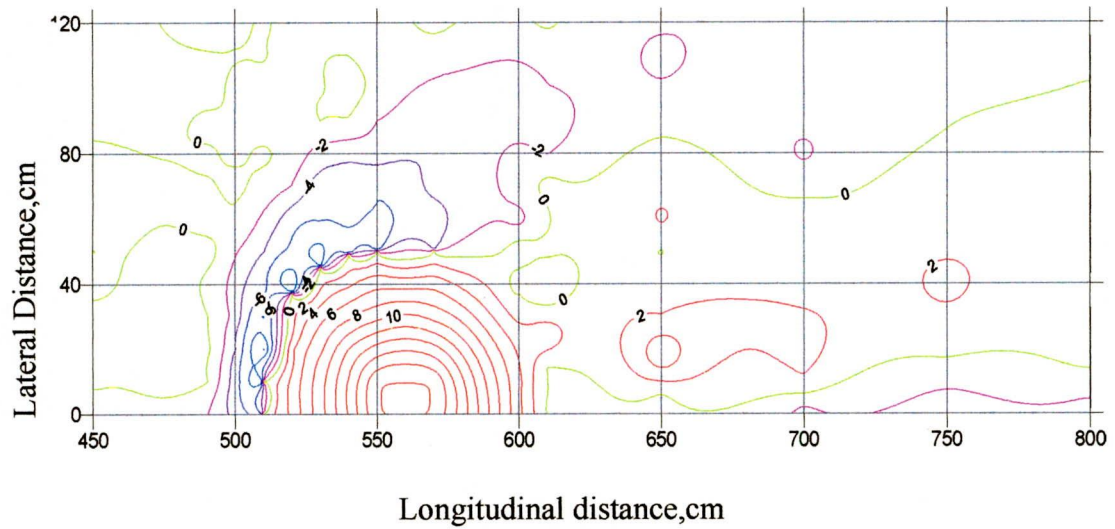


Figure 3.28 Scour Contour for Revetment with 1V:2 Slope with 3 mm

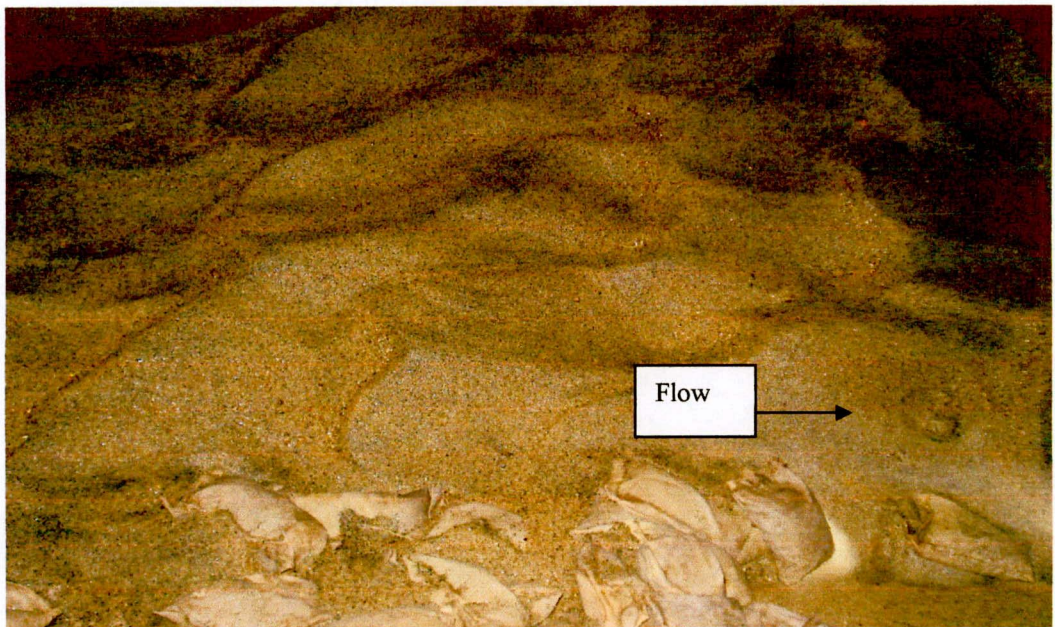


Figure 3.29 Scour for revetment with 1V:1.5H slope with geobags

Scour Contour for Revetment with 1V:2H Slope

Contour Unit : cm
 Initial Bed Level : 0
 (+)ve : Deposit
 (-)ve : Scour

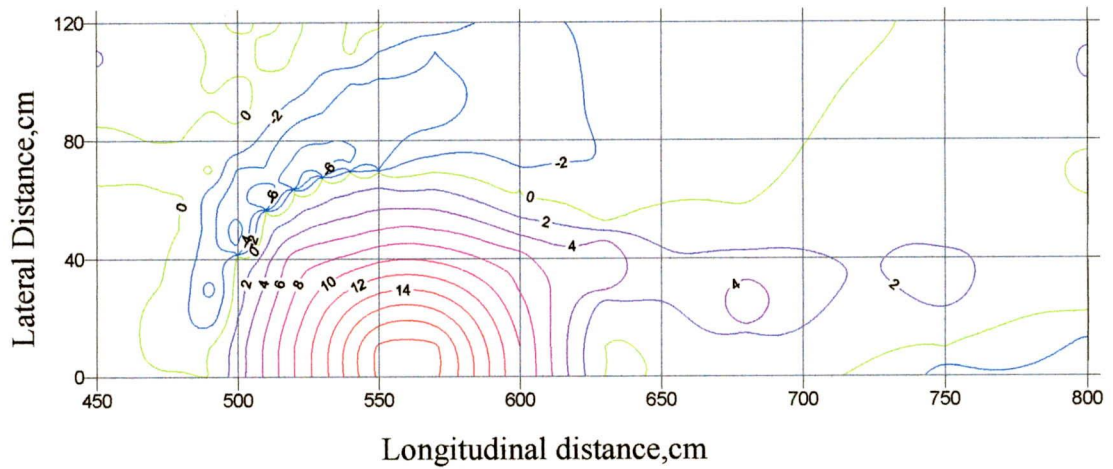


Figure 3.31 Scour Contour for Revetment with 1V:2H Slope with goebags



Figure 3.30 Flow over the Launching apron in 1:1.5 slope

3.9.3 Measurement of Ripple Height

For ripple measurement, an area was selected and grid data were collected for bed elevation. The area was bounded by longitudinal coordinate values, $X = 300$ and 360 cm measured from the upstream start point of the laboratory channel. The lateral coordinate values were, $Y = 0$ and 100 cm measured from the left bank. This area was divided into a grid of 10 cm intervals. Then at each grid point bed elevation was measured. Initial bed level was taken as 0 cm and used as reference value. Initially, the flow was run for 8 hours. Then the water was drained out. After that the bed level measurements were taken. A wooden bridge was placed across the channel. On this bridge, a sliding platform was placed, from which a point gauge was mounted in such a way that the needle with the scale could be moved up and down with the help of a screw. The vernier scale moved along a fixed main scale. By sliding the platform over the bridge and by sliding up and down the needle the entire grid data of the selected area were taken. From these data the maximum elevation was found to be 5.12 cm, maximum depth of ripple was found to be 2.98 cm and the average value of all data was 0.46 cm. Therefore, the average ripple height was 0.23 cm. Finally photographs were taken of the ripples. The photographs of ripples and wooden bridge with measuring needle are shown below as figure 3.32.

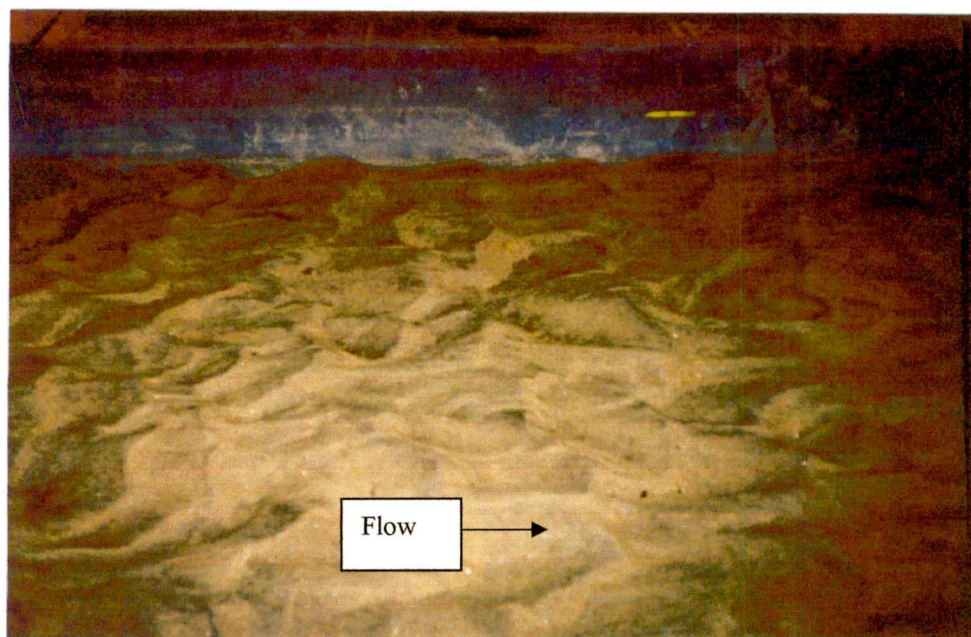


Figure 3.32 Photographs of Ripple formation

3.9.4 Observation on Aerial Coverage

Extent of aerial coverage was measured of different types of launching apron as shown in the table 3.4.

Table 3.4 Aerial coverage of Different Test Materials

Test No.	Material	Side Slope 1V:	Discharge	Aerial Coverage cm (Out of 240 cm)
1	3mm	1.25H	60 l/s	150
2	4mm	1.25H	50 l/s	175
3	3mm	1.5H	40 l/s	170
4	4mm	1.5H	60l/s	180
5	3mm	2H	50 l/s	170
6	4mm	2H	40 l/s	160
7	5 mm and 6 mm	1.25H	60 l/s	200
8	5 mm and 6 mm	1.5H	50 l/s	205
9	5 mm and 6 mm	2H	40 l/s	195
10	Geobag	1.25H	60 l/s	195
11	Geobag	1.5H	50 l/s	210
12	Geobag	2H	40 l/s	190



Figure 3.33 Even settlement of apron on the upstream side (4mm Apron)

CHAPTER FOUR

ANALYSIS, RESULTS AND DISCUSSIONS

4.1 FLOW BEHAVIOR ANALYSIS

In this experiment two velocity components namely, streamwise velocity (V_x) and transverse velocity (V_y) have been measured at selected grids with the help of a programmable electromagnetic velocity meter (P-EMS). In order to examine the changes in flow conditions around revetment due to different apron arrangement, a base test for without apron condition has been conducted. Changes in the flow field in relation to this apron condition have been analyzed in the subsequent paragraphs. These velocity vector diagram produced by Stanford Graphics Software in XY plane are shown to examine flow field for different flow scenario.

4.1.1 Analysis of streamwise velocity (V_x)

The variations of streamwise velocity (V_x) is analyzed for different apron sizes and for no apron condition. The variation for without apron test has been incorporated for the purpose of comparison. The streamwise velocity for without apron condition is found uniform along the revetment in fixed bed. The streamwise velocity for without apron condition in mobile bed is also found be uniform along the revetment. But for the case with apron material the velocity decreases near the apron material and increases again towards downstream. The streamwise velocity may have regained its original velocity to a considerable extent. It may be noticed from the figure that the trend remains more or less the same but with reduced magnitude up to middle of the channel and with increased magnitude from then onward. The velocity vector was not uniform near the apron material. The velocity vector is similar for 5mm and 6mm apron tests than other aprons tests. Most stable launched apron was 4 mm and had reduced scour.

The vector plots also show a reduced resultant velocity in the upstream of the revetment. Perhaps these two phenomenon of reduced circulation width and decreased velocity upstream of the revetment occurred due to the placement of the apron are the main cause of the corresponding reduced scour depth and increased deposition around revetment. These velocity records were then processed to produce velocity vectors by the use of Stanford Graphics Software. Velocity vectors around revetment with and without launching apron are shown in the Figures 4.1 to 4.12.

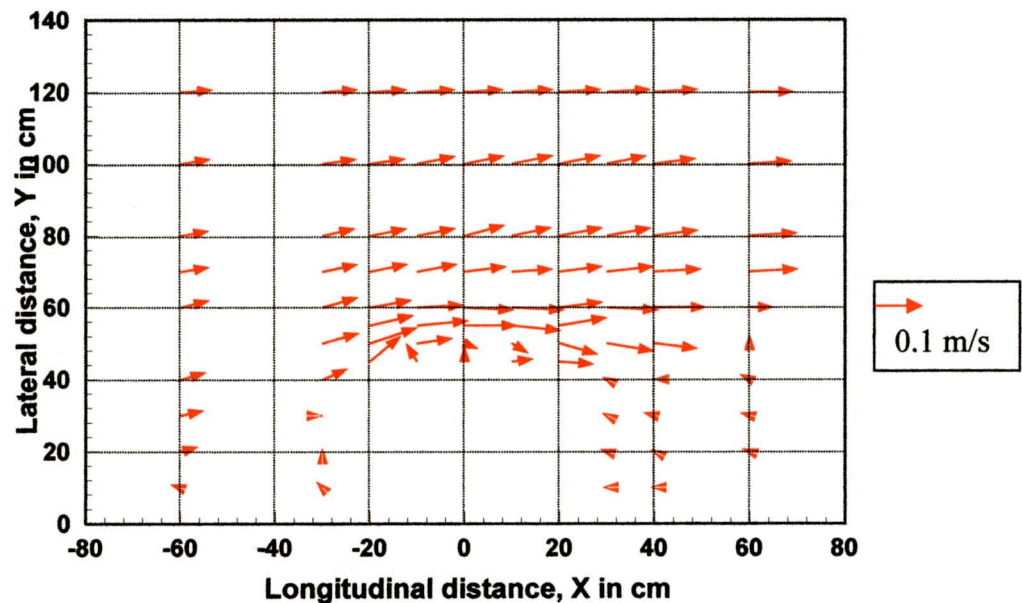


Figure 4.1 Velocity vector for 3mm apron around 1:2 sloped revetment in mobile bed

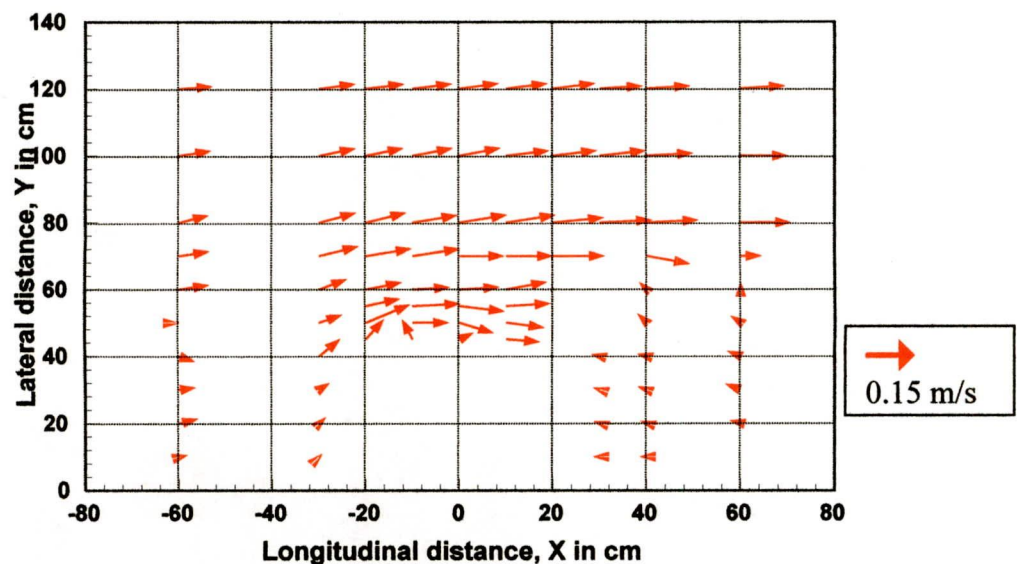


Figure 4.2 Velocity vector for 3mm apron around 1:1.5 sloped revetment in mobile bed

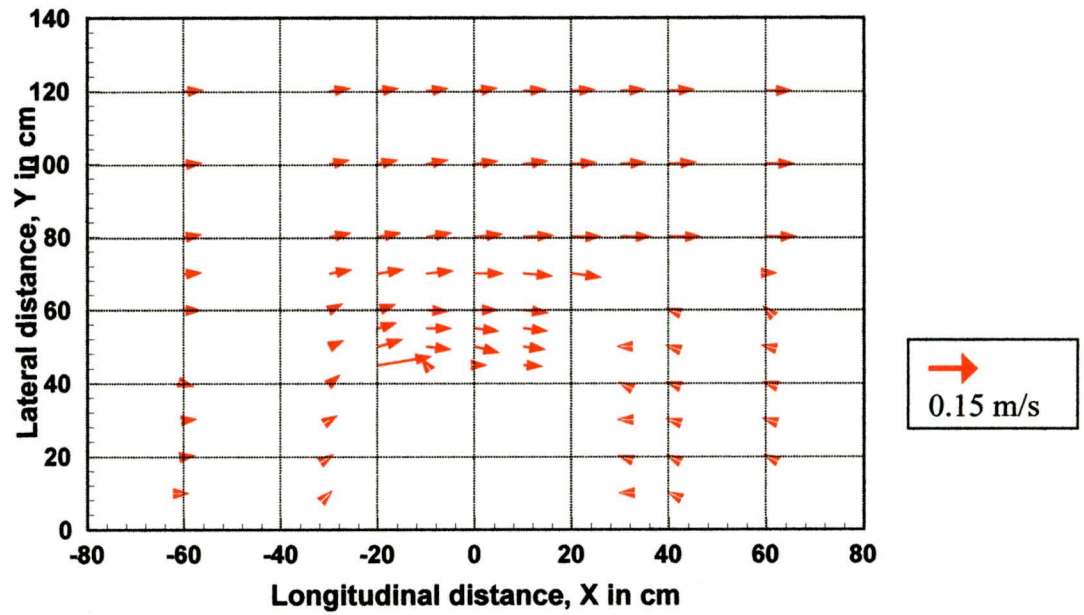


Figure 4.3 Velocity vector for 3mm apron around 1:1.25 sloped revetment
In mobile bed

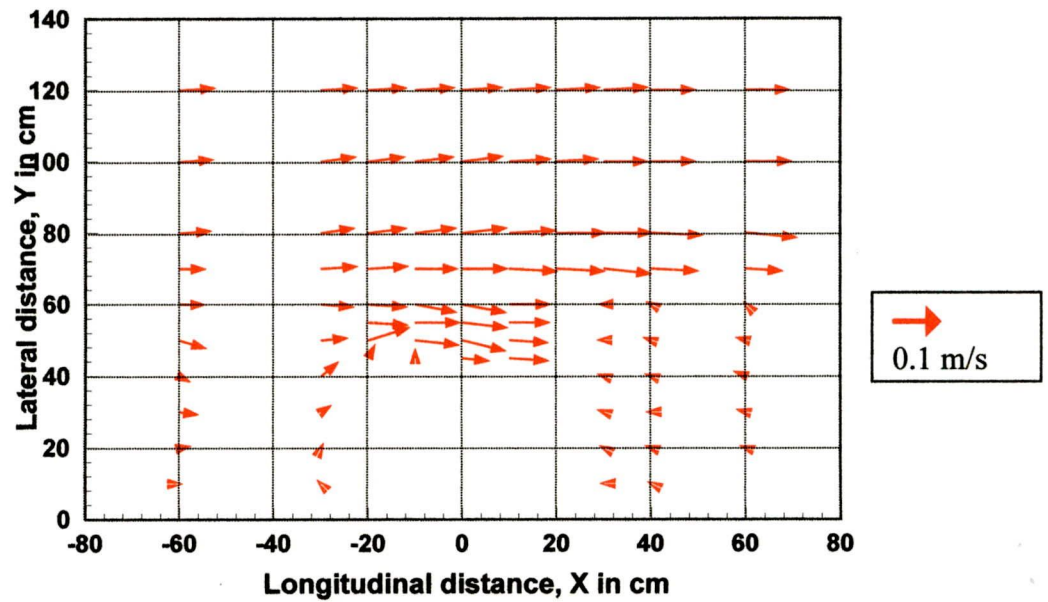


Figure 4.4 Velocity vector for 4mm apron around 1:2 sloped revetment
in mobile bed

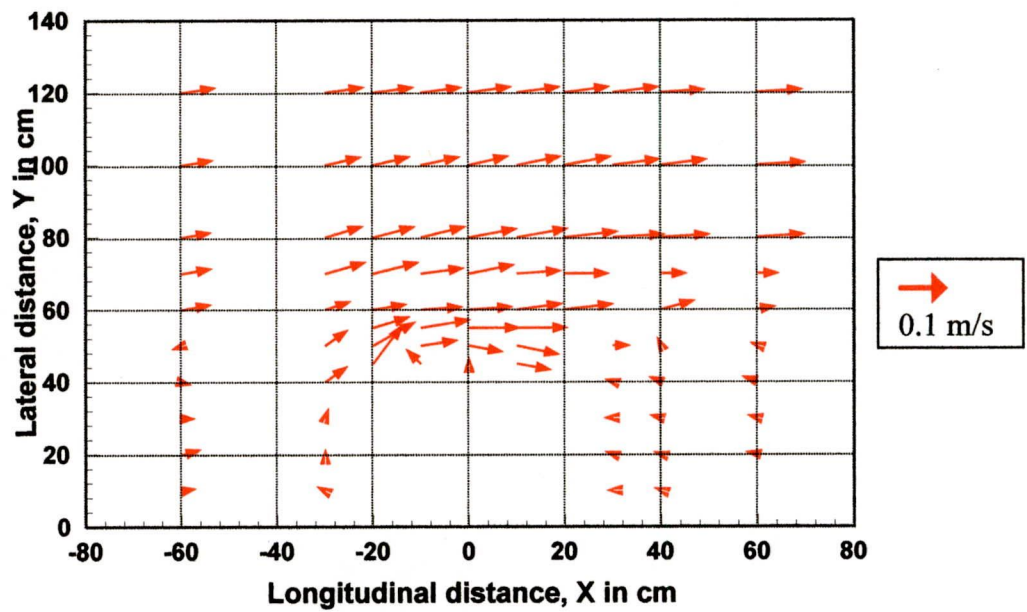


Figure 4.5 Velocity vector for 4mm apron around 1:1.5 sloped revetment in mobile bed

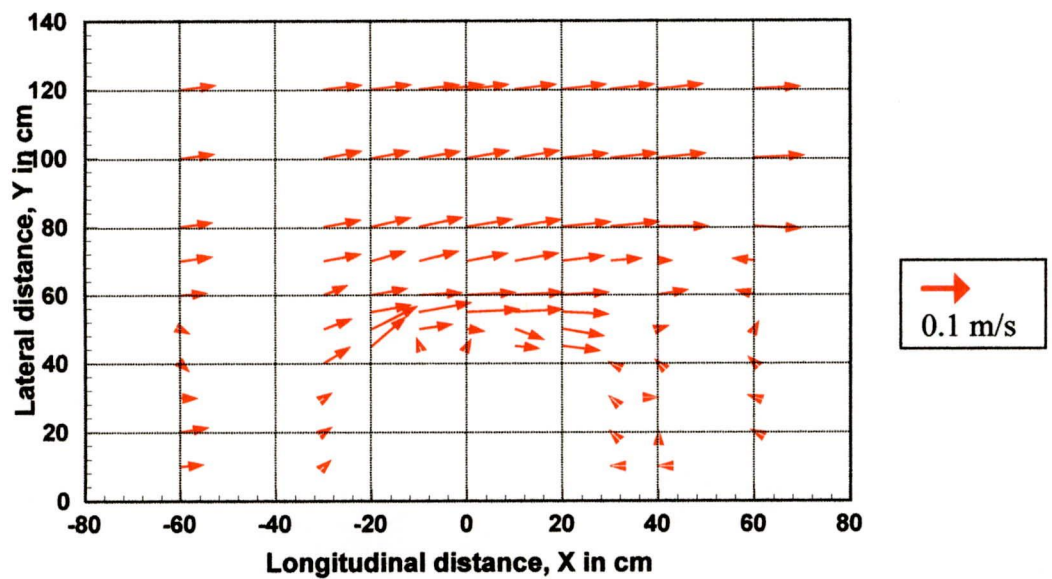


Figure 4.6 Velocity vector for 4 mm apron around 1:1.25 sloped revetment in mobile bed

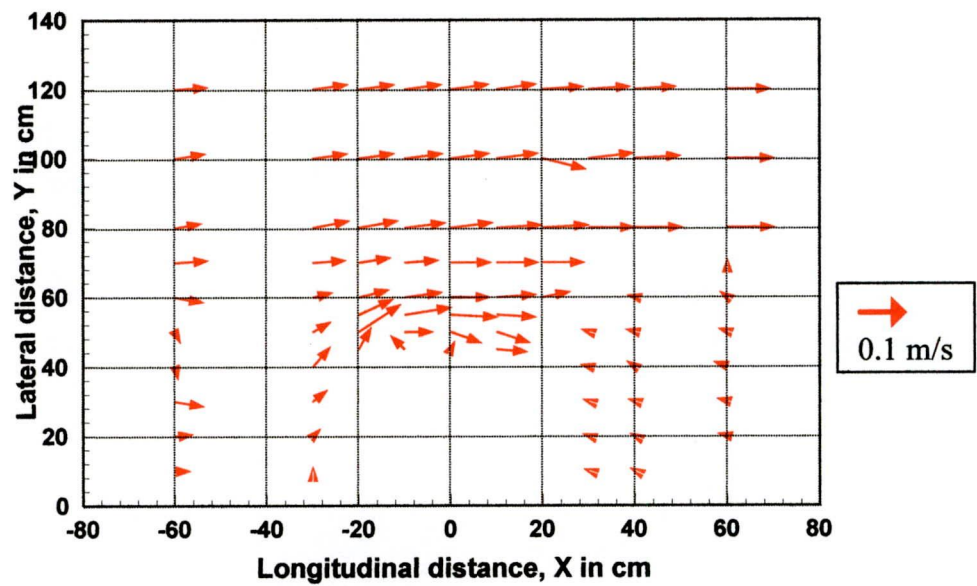


Figure 4.7 Velocity vector for 5 mm apron around 1:2 sloped revetment in mobile bed

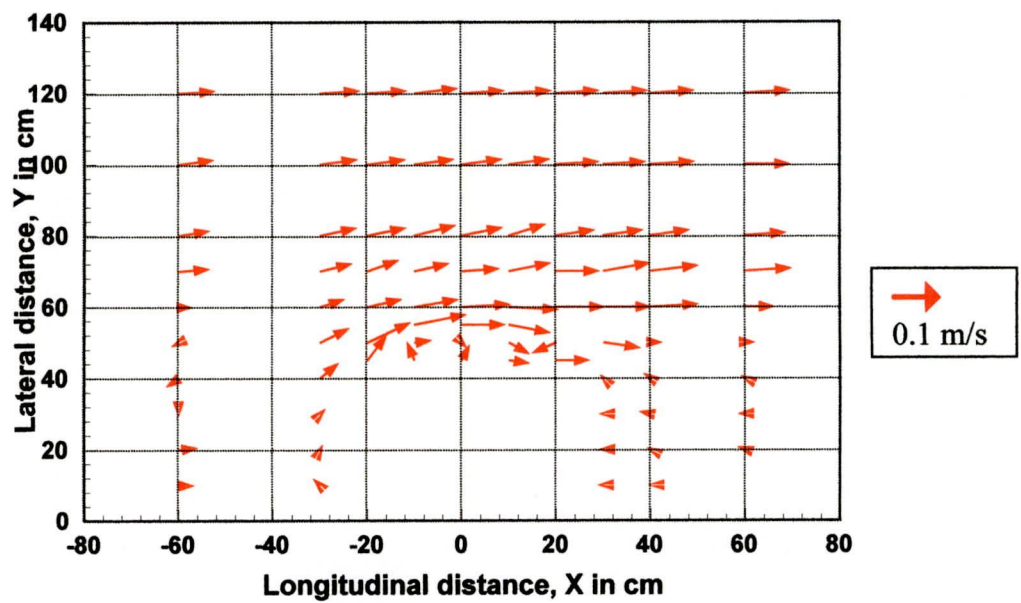


Figure 4.8 Velocity vector for 5 mm apron around 1:1.5 sloped revetment in mobile bed

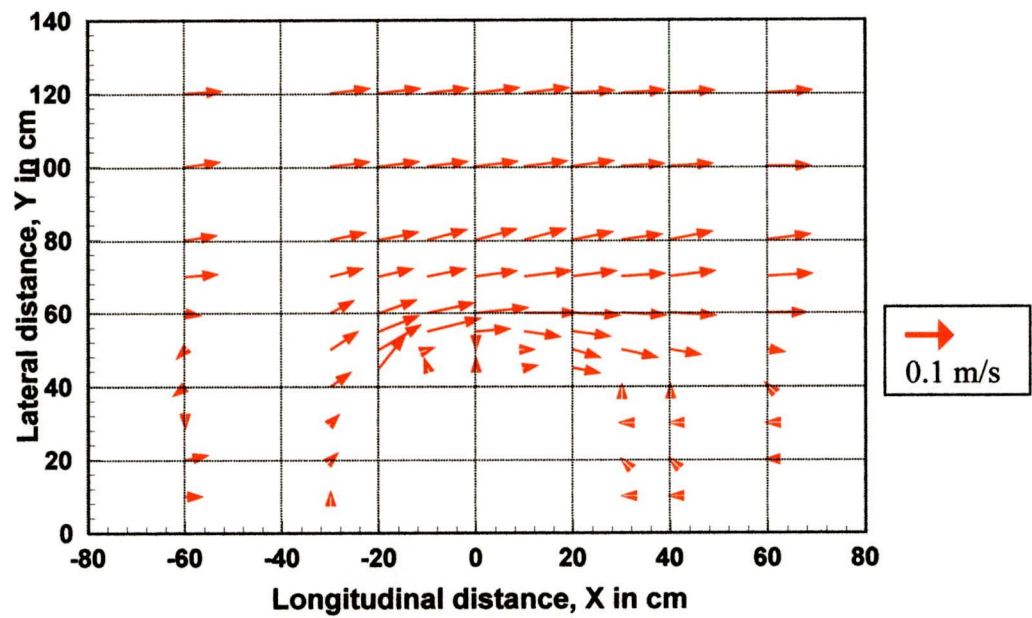


Figure 4.9 Velocity vector for 5 mm apron around 1:1.25 sloped revetment in mobile bed

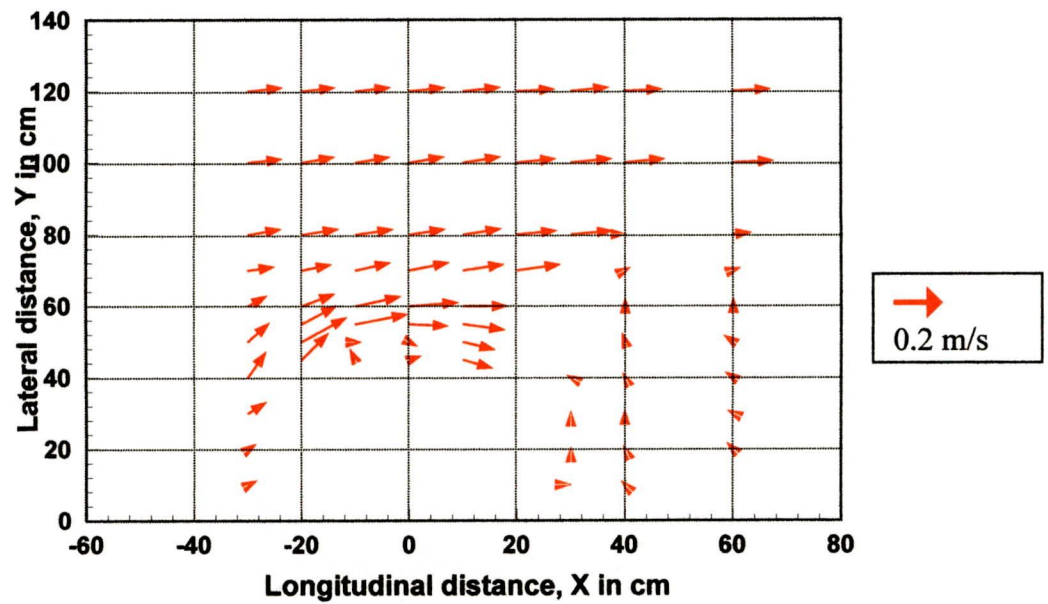


Figure 4.10 Velocity vector for geobags around 1:2 sloped revetment in mobile bed

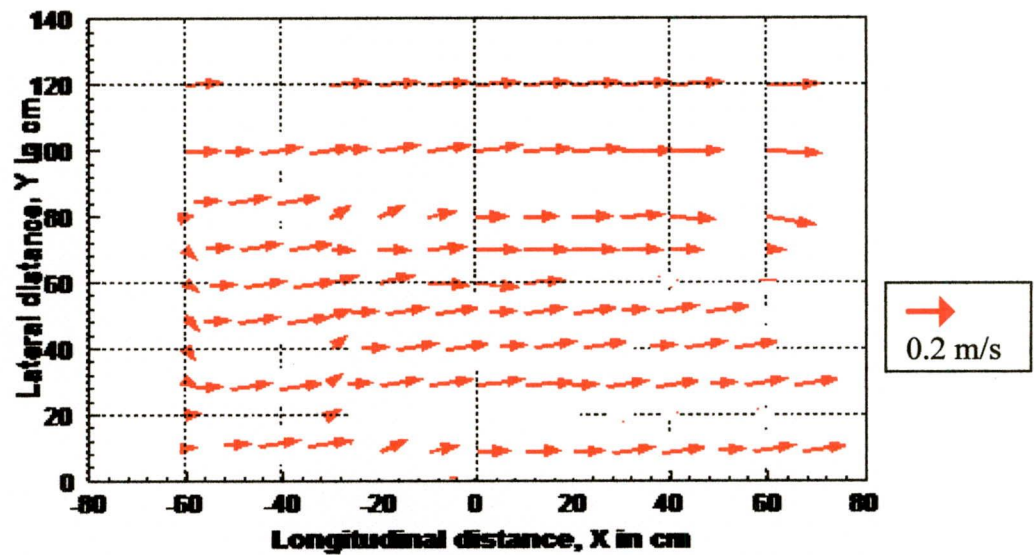


Figure 4.11 Velocity vector around revetment without apron in fixed bed

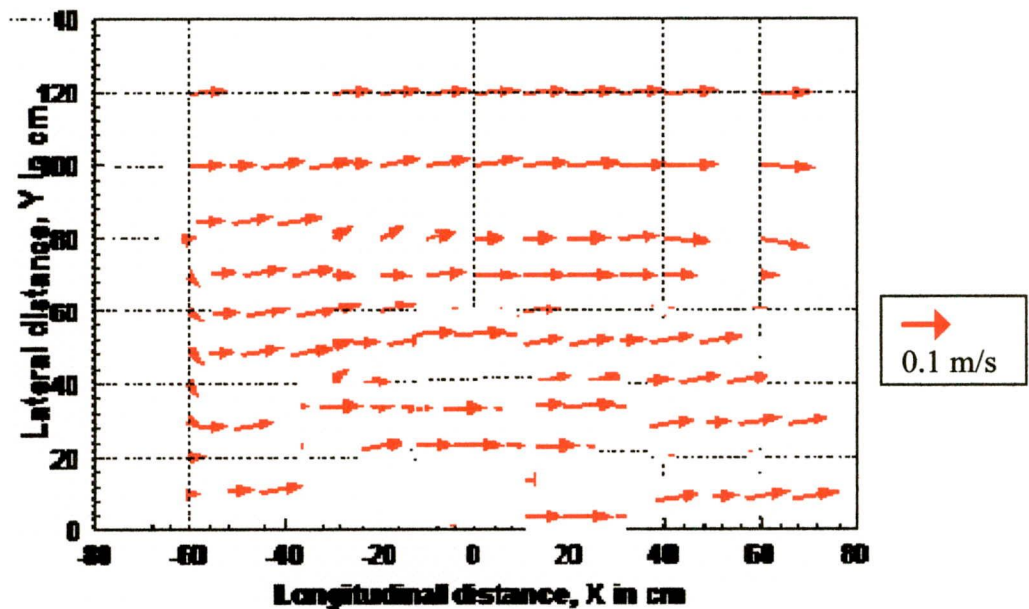


Figure 4.12 Velocity vector around revetment with apron in fixed bed

4.1.2 Variation in vertical direction(V_y)

While analyzing the vertical velocity distribution in the scour hole at the maximum scour depth, it was observed that the effect of this submerged flow restriction was quite significant. The analysis was done by comparing the velocity profile of without apron case with that of apron cases. The velocity profile for without apron case was

taken from the doctoral thesis of Rahman (1998). It was observed that, when there was no apron, the velocity distribution was very close to normal log-law profile. On the other hand, when there was apron, the velocity gradually decreased towards bed, but before reaching bed suddenly it increased and then again decreased near scoured bed. This sudden increase in velocity was due to the presence of apron. In general the trends for without apron condition and with apron condition are almost same within the revetment width shows a reduced magnitude. The most generalized trend is a decrease in transverse velocity in comparison to without apron condition.

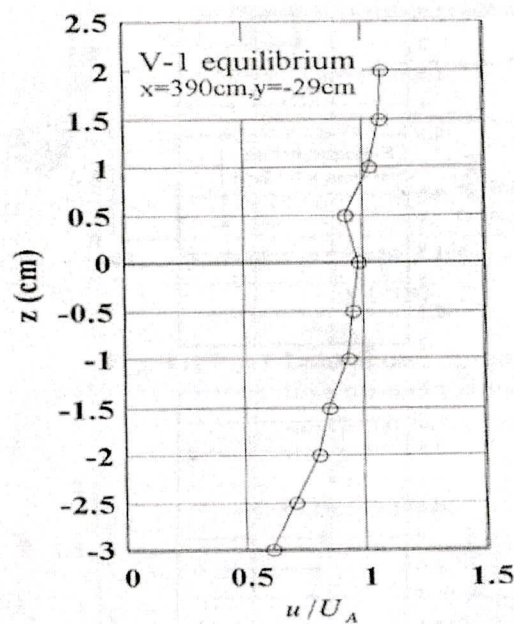


Figure 4.13 Velocity distribution for no apron case (Rahman, 1998)

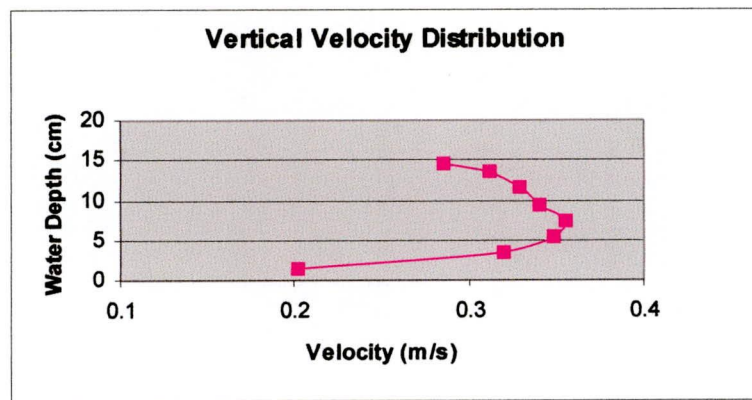


Figure 4.14 Velocity distribution for no apron setting in fixed bed

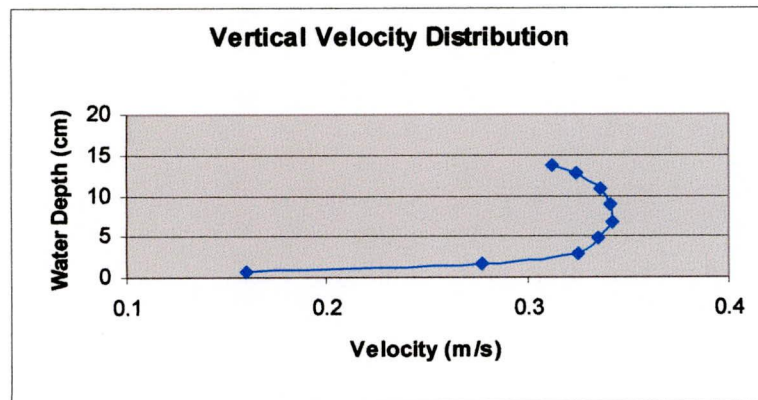


Figure 4.15 Velocity distributions for no apron setting in mobile bed

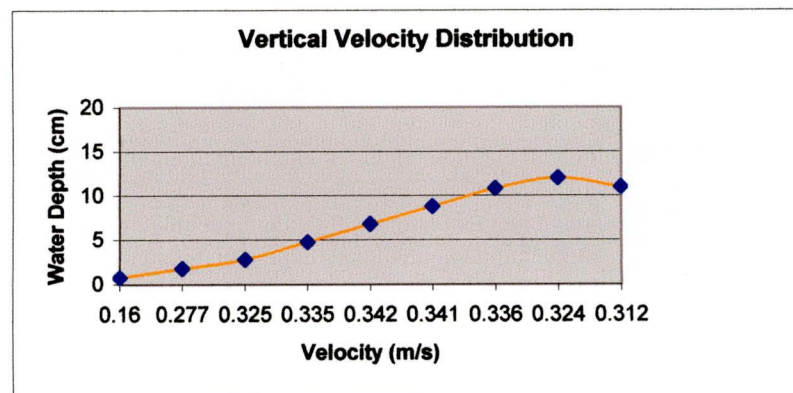


Figure 4.16 Velocity distributions for 3mm apron setting in mobile bed

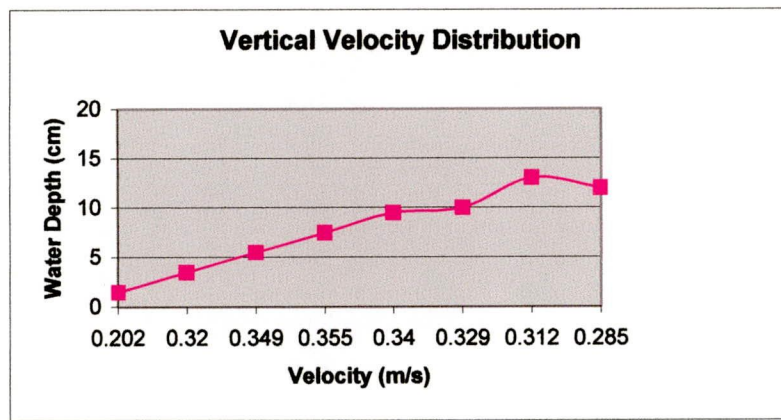


Figure 4.17 Velocity distributions for 4mm apron setting in mobile bed

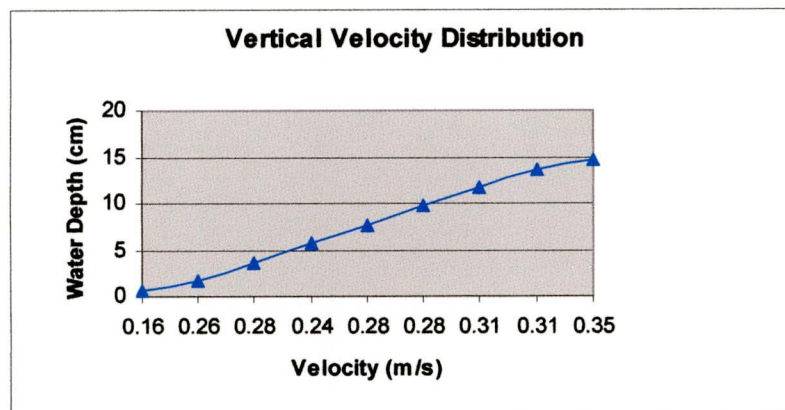


Figure 4.18 Velocity distribution for 5mm apron setting in mobile bed

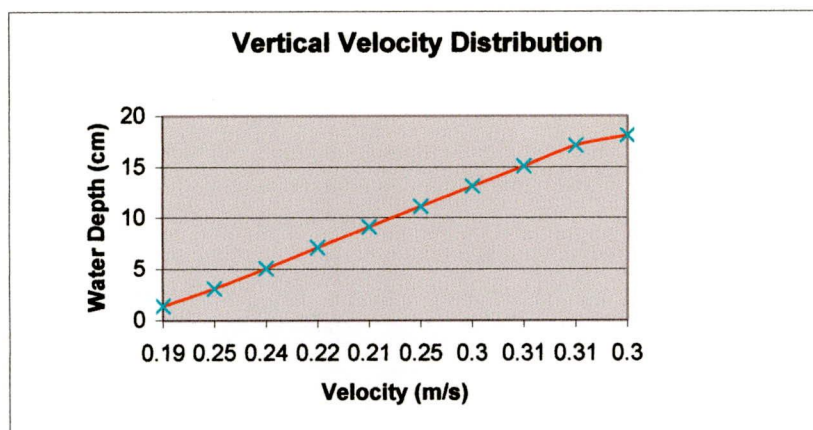


Figure 4.19 Velocity distributions for 6 mm setting in mobile bed

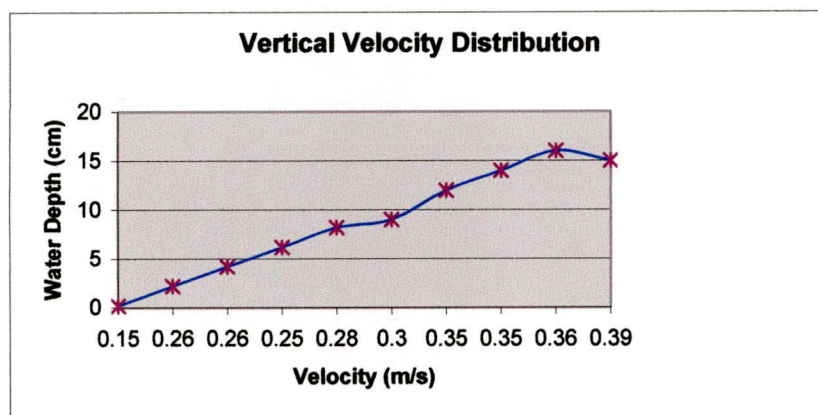


Figure 4.20 Velocity distribution for geobags setting in mobile bed

4.1.3 Launching of Apron

Launching of apron material starts from upstream edge. Initially, the apron cubes were rolled towards downstream only. Gradually when scour hole developed, apron cubes were launched towards the maximum depth. When few cubes were launched, the inner cubes replaced their locations. In this way, the scour hole extent increases backward. This process did not continue for long. As soon as the depth of maximum scour became more or less stable, the process stopped or seemed to stop. Even at that time, continuous layer of launched apron was not found on the slope of scour hole. Sometimes sudden flow was given. At that time some cubes were washed away from upstream side of the apron extent. The deposition on the upstream side also got washed away during the sudden flow and after some time again the deposition occurred. The portion of the apron, that was in the upstream side and away from the bank, lost apron cubes at first. Since this portion of the apron layout takes the maximum thrust, this is the most severe place of water flow attack on the apron setting. The same thing was observed when apron cube size was made bigger. The downstream side of the apron layout was almost unaffected especially at places near the structure.



Figure 4.21 Launching of 3mm apron

4.1.4 Scour With Apron

Scour data are collected by using point gauge around the apron material. Scour measurements are carried out with respect to the initial bed level. These processed data are then used to produce spectral contour diagrams by using Stanford Graphics software. These spectral diagrams can clearly depict the variations of channel bed level due to local scour around the revetment. Maximum equilibrium scour depths are also expressed with respect to the initial bed level. Difference in average mobile bed level from the initial bed level varies from 0.02 cm to 0.14 cm depending on the hydraulic conditions of the experiment.

The maximum depth of scour is located close to the channel boundary at the upstream face when there is no protection around the revetment. The shapes of scour hole developed in different conditions are identical. Due to the passage of bed form, negligible variation occurred around the periphery of the scour holes. With increasing flow, the extent of scour hole is found to increase gradually. Depth of scour has also increased with increasing flow. The slope of the scour hole is the steepest at the upstream face of the revetment. This slope is relatively less in lateral direction. The value of X in the following figures is the distance taken from the upstream reservoir.

However, due to change in flow and distance from the upstream the scour depth gradually shift towards the downstream as shown in the figures 4.22 to 4.24.

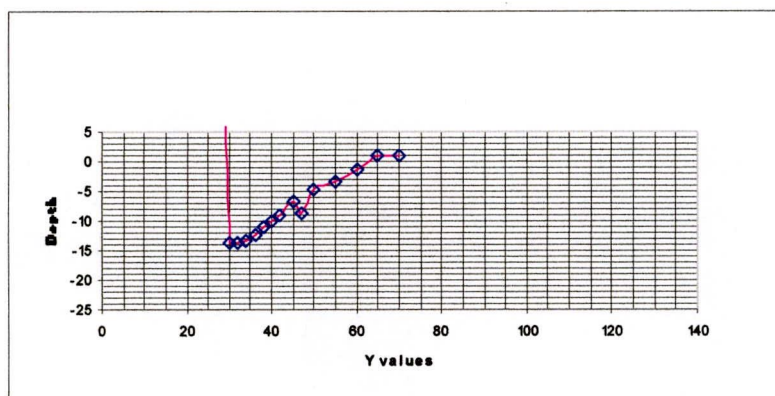


Figure 4.22 Lateral scour profile Y vs Z at X = 542.75cm location

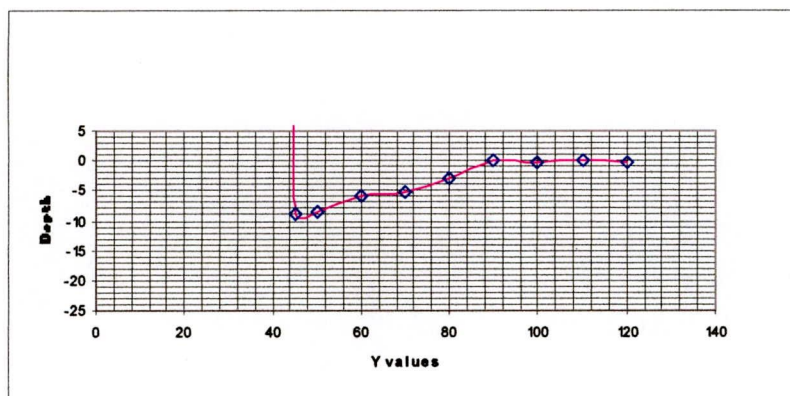


Figure 4.23 Lateral scour profile Y vs Z at X = 530cm location

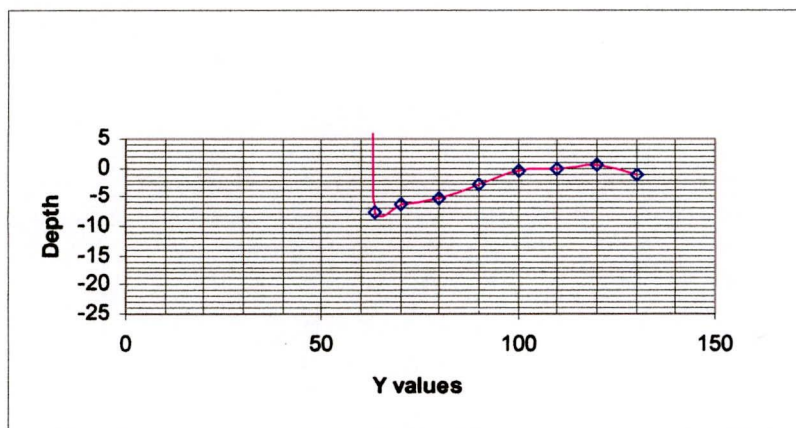


Figure 4.24 Lateral scour profile of Y vs Z at X = 520cm location

It was found that, when apron material was placed around structure, the maximum scour depth location was away from the structure and at a place downstream from the structure. Therefore, the structure may not be within the extent of scour hole. In case the extent of apron material is narrow and full width of apron is launched in the scour hole, the structure would be at the edge of the scour hole. The longitudinal scour profile is shown in the figures from 4.25 to 4.27.

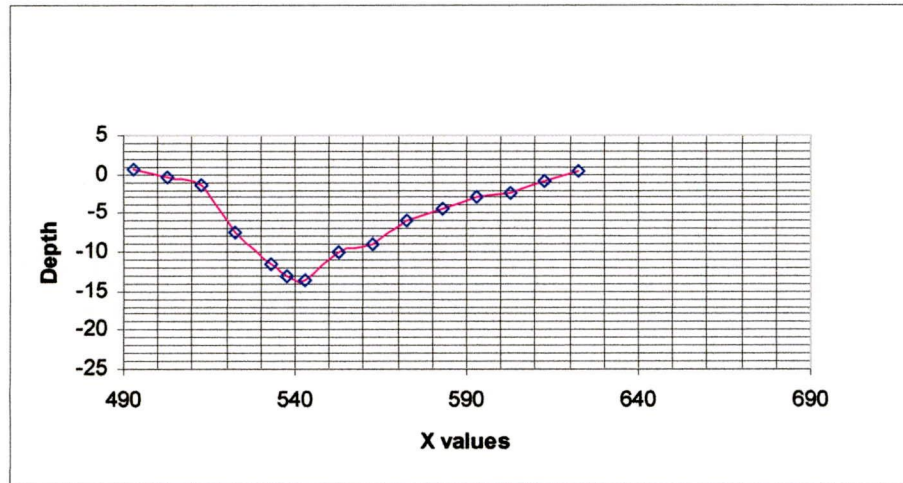


Figure 4.25 Longitudinal scour profile of X vs Z at Y = 30cm from left bank

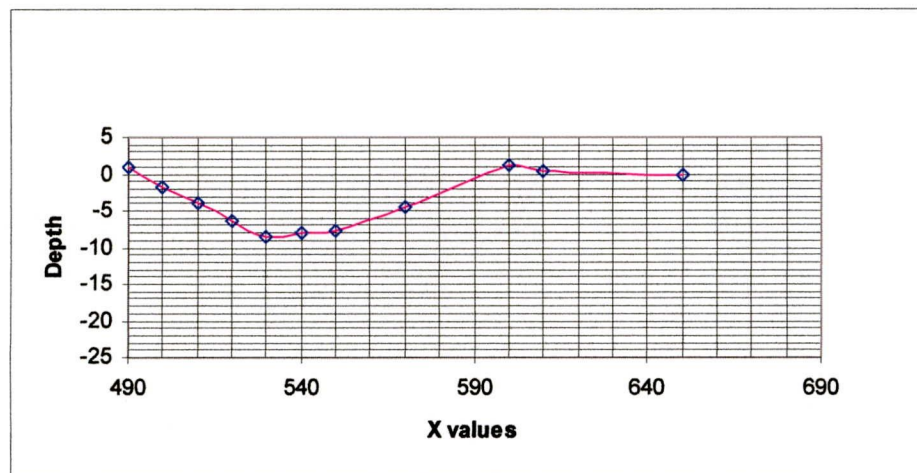


Figure 4.26 Longitudinal Scour Profile of X vs Z at Y = 50cm from left bank

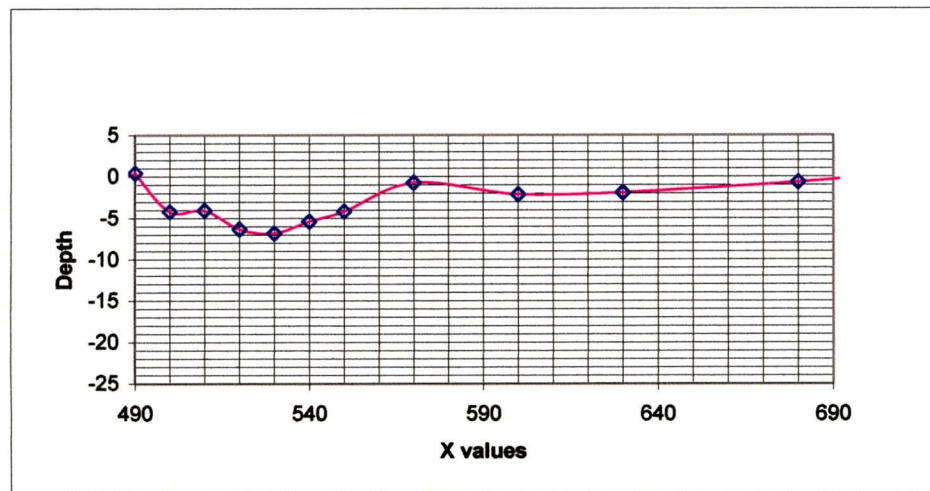


Figure 4.27 Longitudinal scour profile of X vs Z at Y = 70cm from left bank

For the revetments without apron the scour measurements were taken as above. For the revetments with apron the scour measurements the lateral scour profile data were taken. Photographs were also taken of scour for both the cases for comparison.

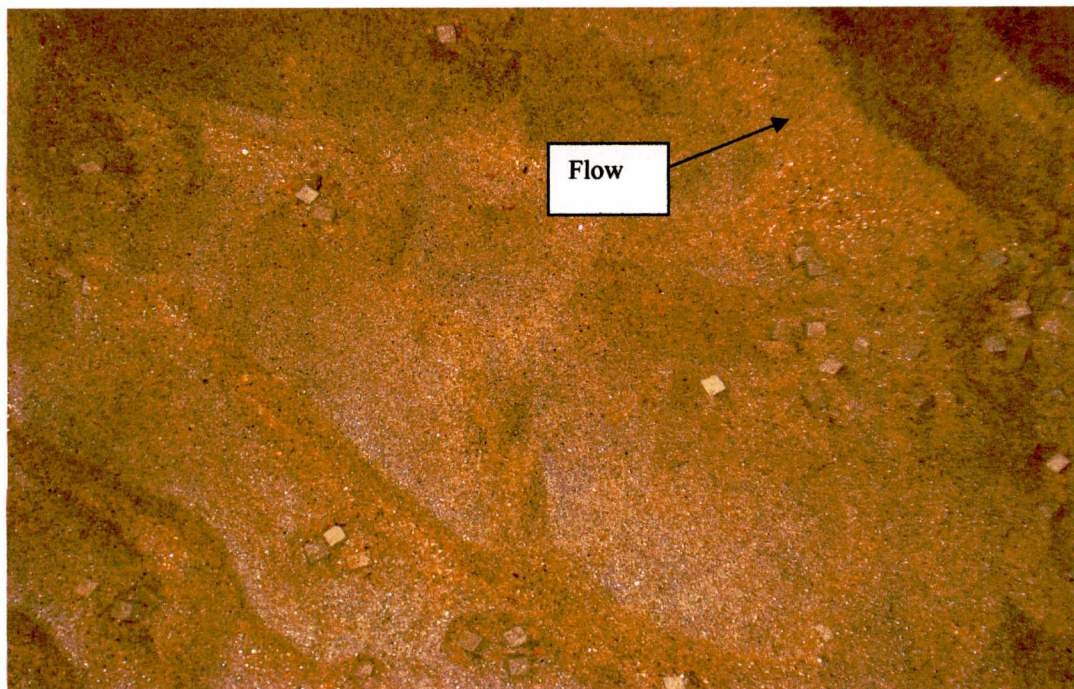


Figure 4.28 Scattering of the launching aprons due to flow

Velocity measurements were also taken for vertical distribution of velocity at maximum scour depth location. In this case, the velocity meter probe was set at different depths for these observations. Existence of vortex and tremendous amount of turbulence can be identified from the observation of vertical velocity distribution profile (Figure 4.31). Because of rotational movement of water close to the foundation structures, velocity profiles have no particular trend. However, with the reduction of scour by apron material, velocity distribution profiles are found to attain more or less regular trend (Figure 4.32 to Figure 4.36).

These vertical velocity distributions are shown in figure 4.29 to 4.36.

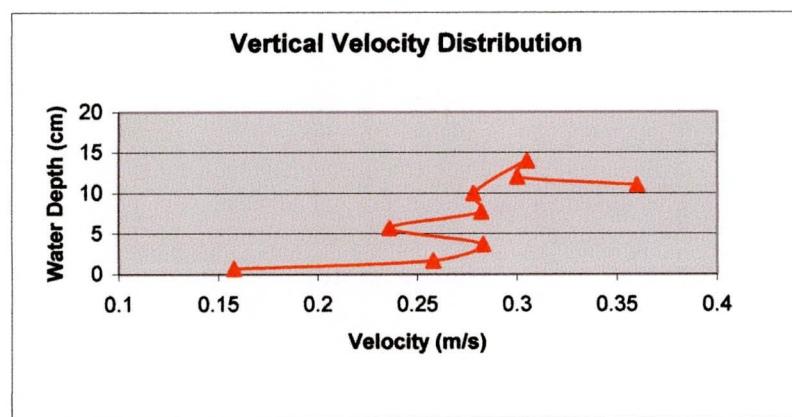


Figure 4.29 Velocity profile at maximum scour depth location for
3 mm apron setting

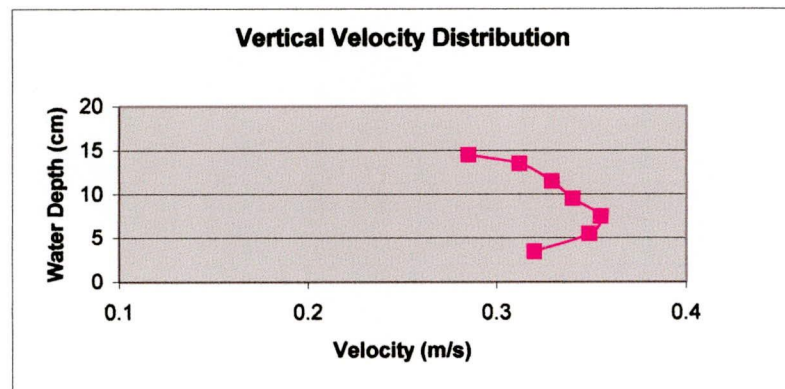


Figure 4.30 Velocity profile at maximum scour depth location for
4 mm apron setting

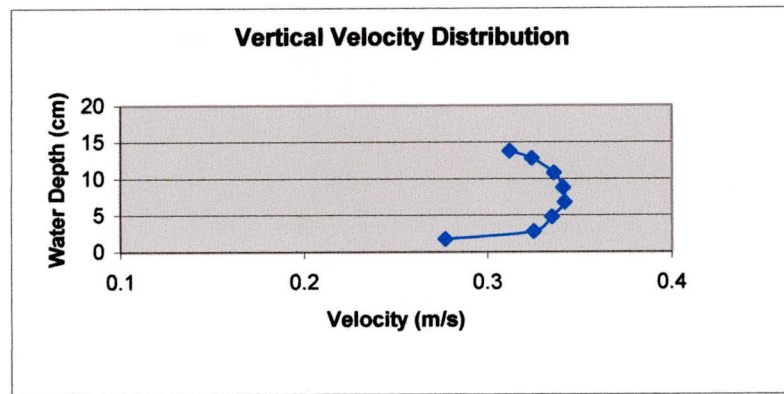


Figure 4.31 Velocity profile at maximum scour depth location for
5 mm apron setting

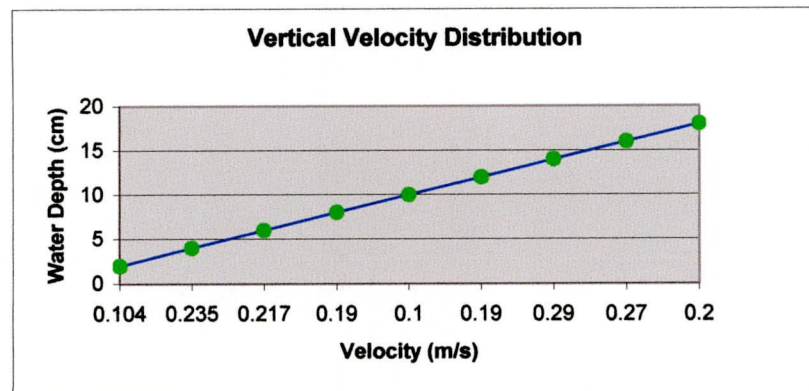


Figure 4.32 Velocity profile at maximum scour depth location for
no apron setting

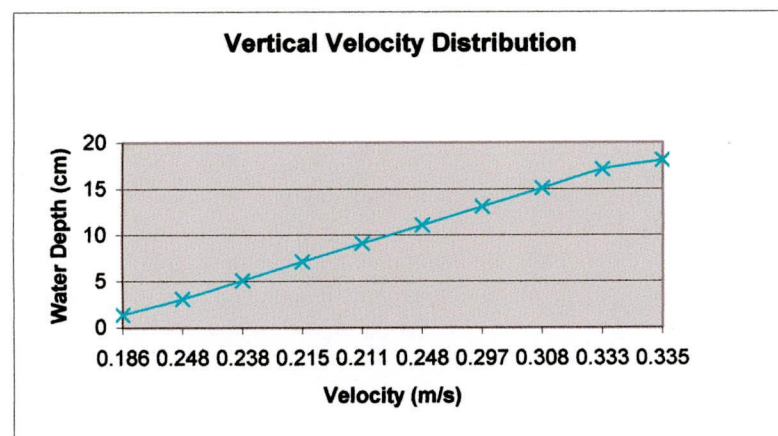


Figure 4.33 Velocity profile at maximum scour depth location for geobag

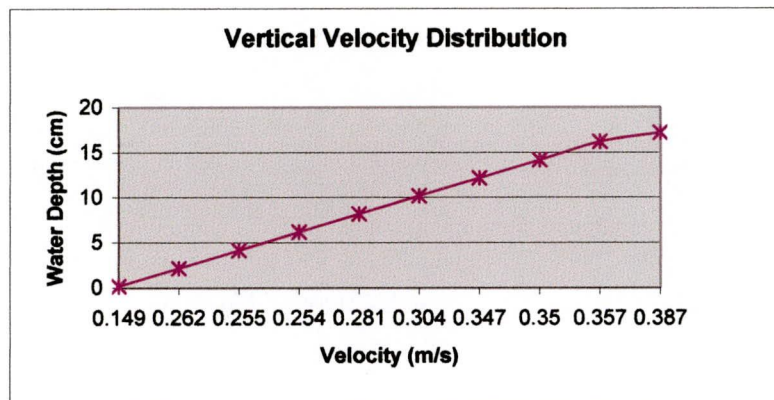


Figure 4.34 Velocity profile at maximum scour depth location for
6 mm apron setting

4.1.5 Scour Profile Variation

The longitudinal and lateral scour profiles shows that the scour depth increases when the flow concentration or velocity also increases. Therefore, the scour depth increased. Since the effect of slope was more prominent, it emphasises the need for an accurate shape factor in scour depth prediction formula.

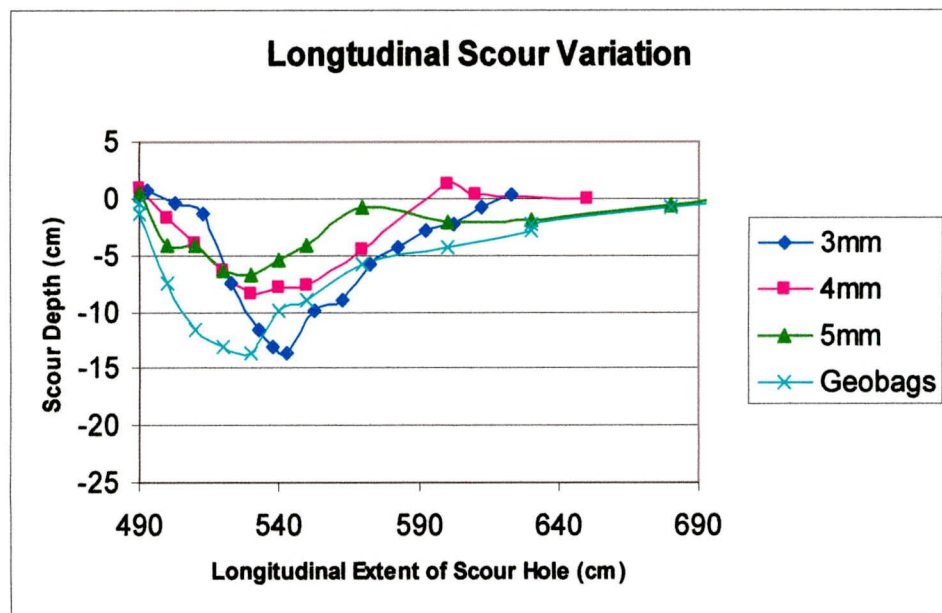


Figure 4.35 Longitudinal scour variation

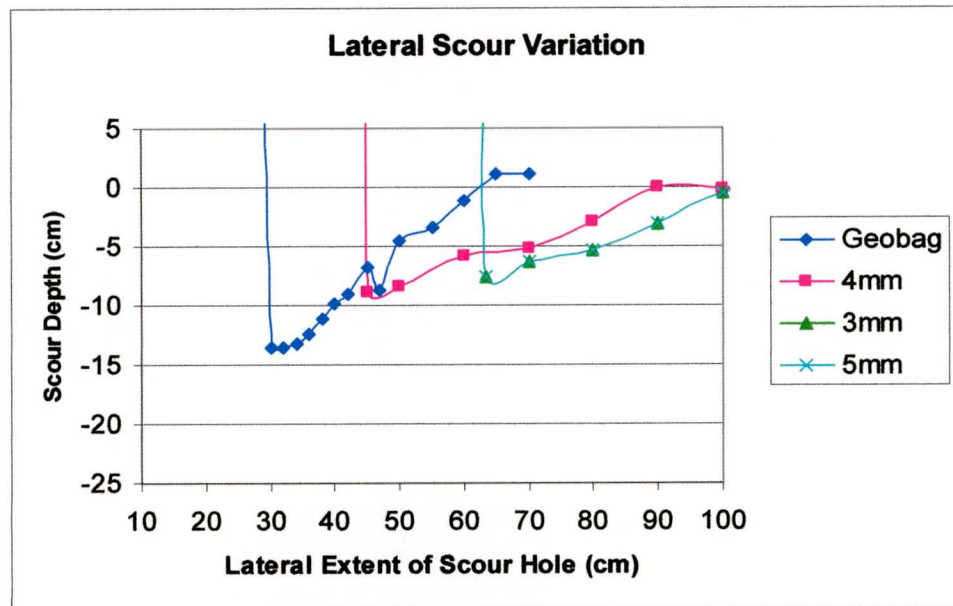


Figure 4.36 Lateral scour variation

The photographs of the scour holes around the apron material and launching of the apron are shown in the figures in 4.37 and 4.38.



Figure 4.37 Scour hole around 3mm apron



Figure 4.38 Launching of apron to prevent scour

Flow concentration is observed close to the scour hole. Significant velocity amplification (about 1.5 times the average velocity) is observed up to a certain distance away from the revetment. Such amplification of velocity close to the bottom is responsible to cause local scour around apron material. Because of the flow obstruction, the flow velocities are very low near the revetment. In addition to the flow obstruction, recirculation of flow behind the structure can be considered to be the causes of sediment deposition at the downstream region. These observations are found similar to those of the experimental results presented by different researcher (Melville 1994, after Rahman et al. 2001).

Apron materials also settled unevenly when bed material was lost from underneath the apron cubes. This happened when apron material was large enough permitting circulation of water through the pores of cubes. In the figures 4.39 to 4.43 dimensionless parameters z/h and q/q_{av} from the left bank is plotted to observe that the maximum amount of flow passes through the maximum depth location and maximum amount of flow concentrates in the scour hole while passing.

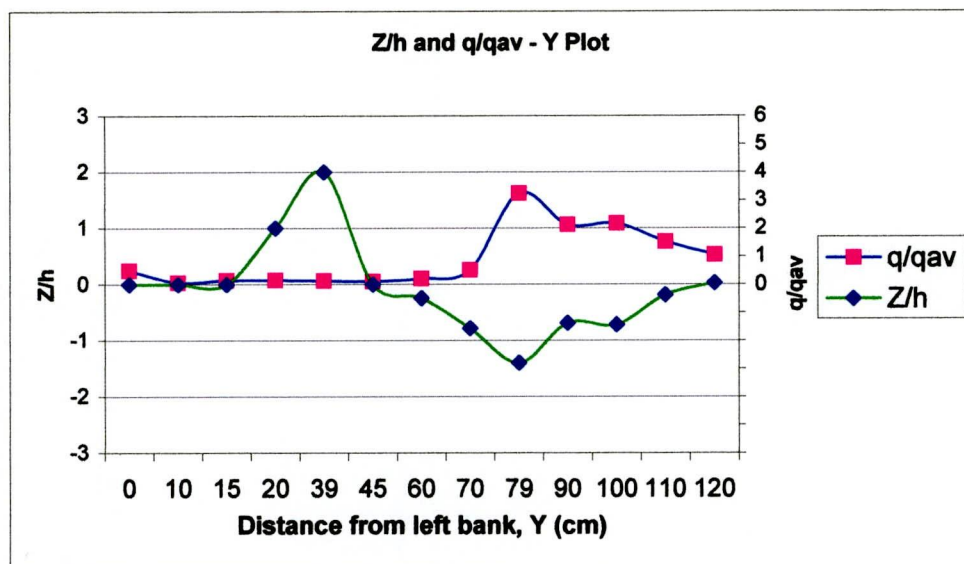


Figure 4.39 Flow concentration within scour hole

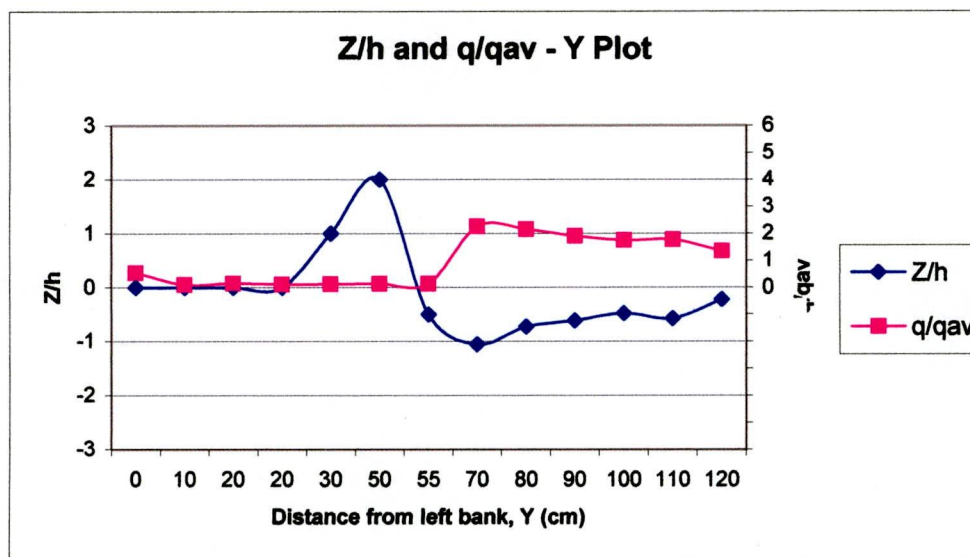


Figure 4.40 Flow concentration within scour hole

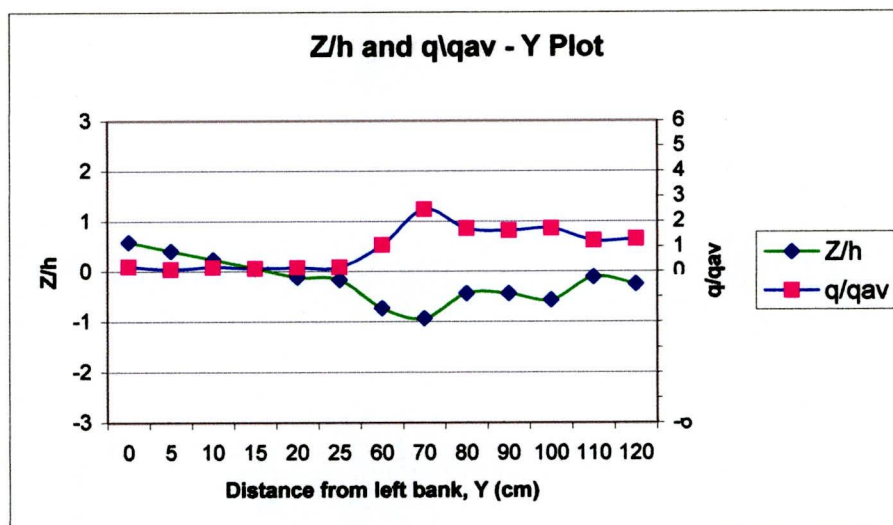


Figure 4.41 Flow concentration within scour hole

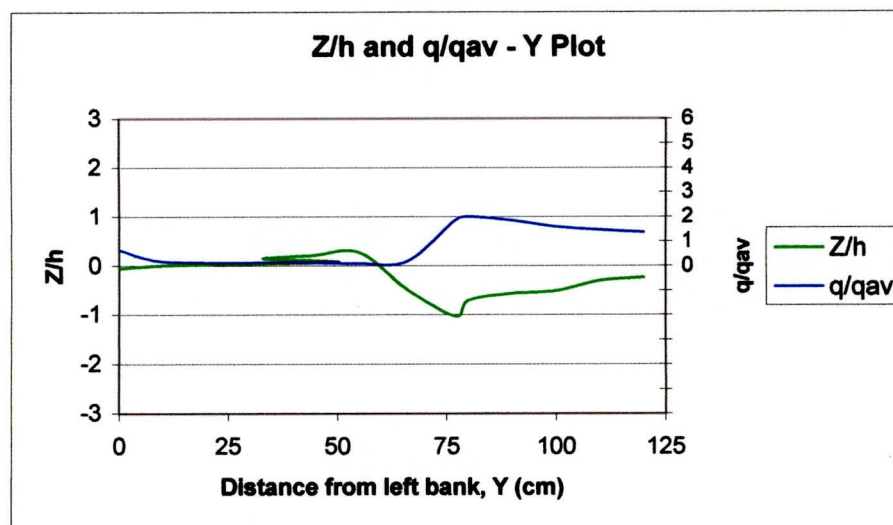


Figure 4.42 Flow concentration within scour hole

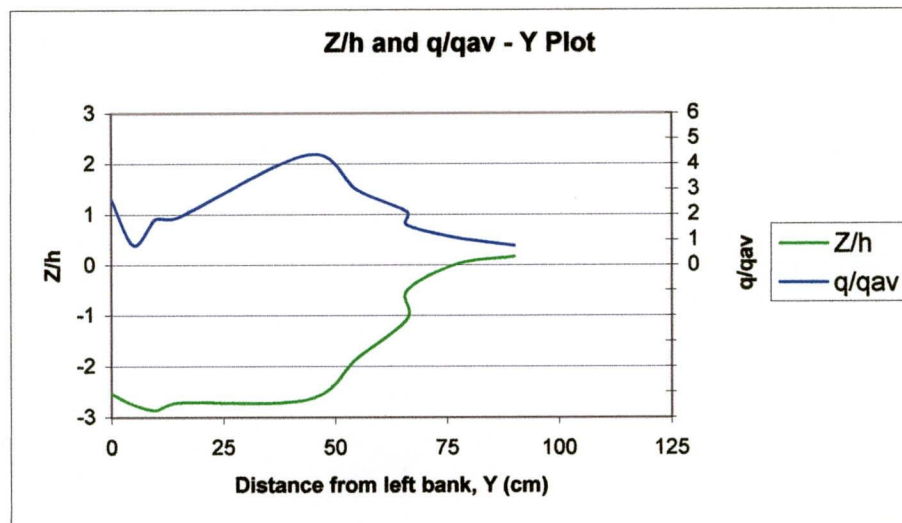


Figure 4.43 Flow concentration within scour hole (No Apron)



Figure 4.44 Photographs of launching of 4mm apron

Due to this circulation finer bed material easily got washed away and the structure was under threat of failure. To avoid this the apron material might be made well graded. In addition to filtration, this variation of size could be done with as many numbers as possible within the range limited by the maximum required size of apron and the size of bed material. Uneven settlement on the upstream side of the apron is shown in Figure 4.45.

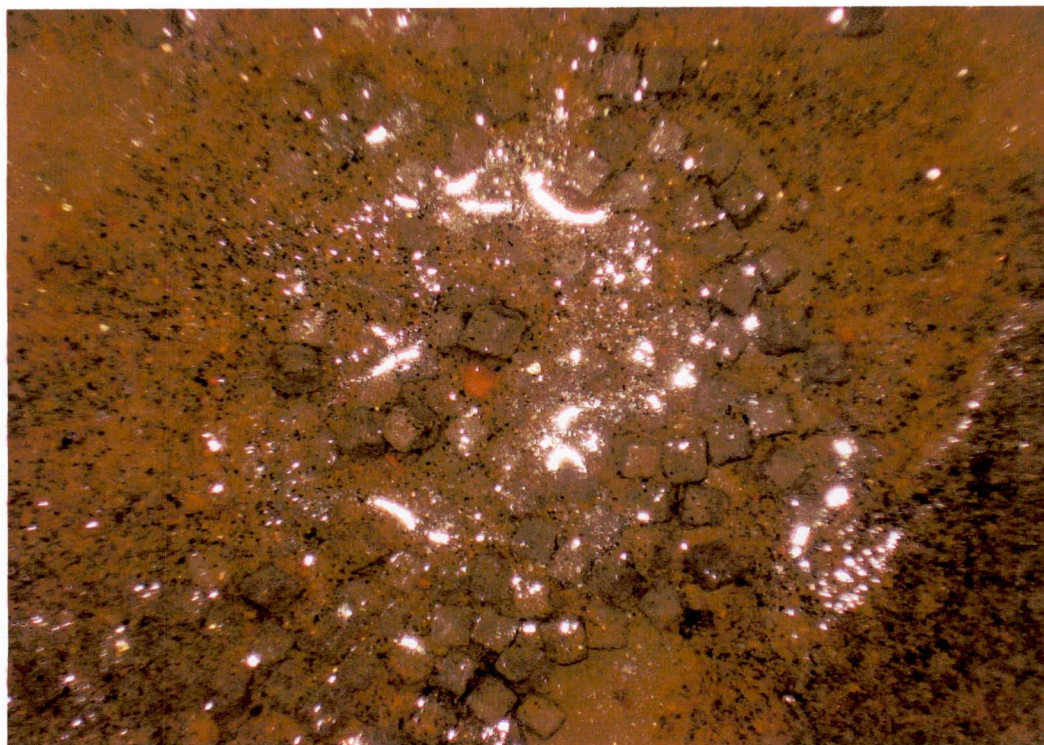


Figure 4.45 Uneven settlement of apron on the upstream side (5 mm Apron)

4.1.6 Aerial Coverage by Launching Apron

The observations were made during the test is shown in Table 4.1 :

Table 4.1 Aerial coverage of Different Test Materials

Test No.	Material	Side Slope 1V:	Discharge	Aerial Coverage at the End of test	% of Area Coverage
1	3mm	1.25H	60 l/s	Approx. 25 blocks displaced	62
2	3mm	1.5H	50 l/s	Approx. 20 blocks displaced	73
3	3mm	2H	40 l/s	Approx. 22 blocks displaced	70
4	4mm	1.25H	60 l/s	Approx. 15 blocks displaced	75
5	4mm	1.5H	50 l/s	Approx. 14 blocks displaced	70
6	5 mm	2H	40 l/s	Approx. blocks displaced	66
7	5 mm and 6 mm	1.25H	60 l/s	Approx. blocks rocks displaced	83
8	5 mm and 6 mm	1.5H	50 l/s	Approx. blocks displaced	85
9	5 mm and 6 mm	2H	40 l/s	Approx. 17 blocks displaced	81
10	Geobag	1.25H	60 l/s	Approx. 14 blocks displaced	82
11	Geobag	1.5H	50 l/s	Approx. 13 blocks displaced	79
12	Geobag	2H	60 l/s	Approx. 10 blocks displaced	87

**Figure 4.46** Measurement of Aerial Coverage by the thread

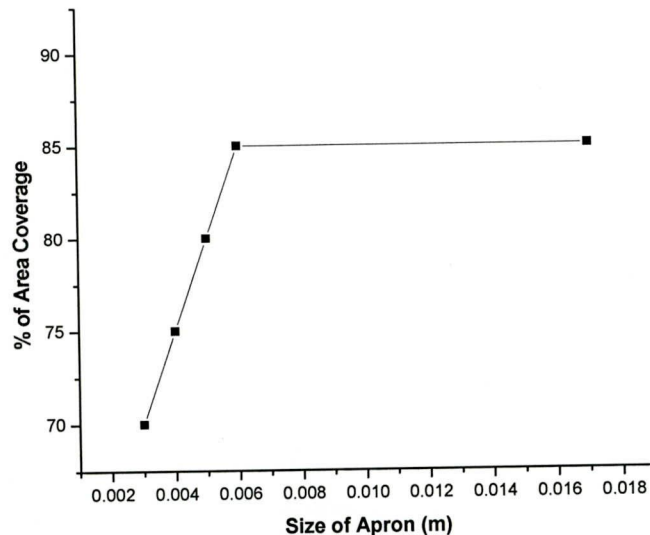


Figure 4.47: Graph of % of Area Coverage vs Size of Apron

Following are the major findings from the observation on aerial coverage :

- a. The launched apron of larger sizes (5mm, 6mm) covered approximately 80 % of the scoured slope area, the remaining 20% being unprotected.
- b. The launched apron of smaller sizes (3mm, 4mm) covering approximately 70 % of the scoured slope area, the remaining 30 % being unprotected.
- c. The largest unprotected spots had areas equivalent to 15 to 20 single blocks.
- d. Blocks both slid and rolled down the scoured slope, forming a non-uniform surface.
- e. Nearly the entire apron was launched.
- f. The geobags were launched properly and covered an area of 80% , the remaining 20% being unprotected .

4.2 MATHEMATICAL EXPRESSION BY REGRESSION ANALYSIS FOR ASSESSING THE EFFECT OF APRON ARRANGEMENT

The results of scour depth were compared with the curves of Laursen, Melville and Rahman. The results were also compared with data obtained from the experiments of Dongol (1994), Gill (1972) ,Tey (1984), Wong (1982) and Rahman (1998).It is seen that the formula represented by the curve of Melville and Laursen predict greater

values of scour depth than that of Rahman. Laursen's formula incorporated two empirical values of α and r that would be difficult to determine as already discussed in Chapter 2. For Melville, his curve is an envelope of the experimental data. Therefore, his formula is supposed to predict higher values of scour. Rahman's formula incorporated angle of repose of the bed material. Moreover, his assumption of flow concentration region within the scour hole might be reasonable. However, the finding is that the experimental data were closer to the Rahman's curve.

An attempt has been made to establish relationship between scour around revetment with the area of apron placed of various sizes and shapes. For this Rayleigh method for dimensional analysis is used. The variables considered are scour depth (d_s), water depth (h), slope (s), apron length (L), angle of repose (α), area of apron (A), discharge (Q), velocity (v). To take all three variables into consideration, these are integrated into one term, i.e. area of the launching apron, as defined by:

$$A = NLs \sin \alpha \quad (4.1)$$

In this analysis, a relationship is intended to bring out how the variation of the area of apron is related to the scour around revetment. The dimensions of the variables are:

$$d_s = L$$

$$L = L$$

$$S = L$$

$$A = L^2$$

The functional relationship between the variables may be considered as:

$$d_s = f(L, s, \alpha, h)$$

$$d_s = f(A, L) \quad (4.2)$$

The above equation may be written as a power equation:

$$d_s = k(A)^a(h)^b$$

where k is a dimensionless constant. Substituting the proper dimensions,

$$L = (L^2)^a(L)^b$$

Equating the exponents dimension on both side of the equation,

$$2a+b = 1$$

or, $b = 1 - 2a$

Thus, $d_s = k(A)^a(h)^{1-2a}$

or, $d_s = k(A/L^2)^a(h)$

$$d_s/h = k(A/L^2)^a \quad (4.3)$$

Thus, Equation 4.3 shows that relative scour depth (d_s/h) is equal to some coefficient times the relative area $(A/L^2)^a$.

Using the data obtained during the experiment regression analysis has been done and the final form of the expression becomes

$$d_s/h = 0.3911(A/L^2)^{-1.3} \quad (4.4)$$

The regression coefficient for this equation has been determined as 0.4714. Regression analysis has also been performed to find a relationship between the area provided by the apron arrangement and percentage reduction in maximum scour depth. The relationship may be expressed by

$$p = 0.5213(A)^{0.61} \quad (4.5)$$

The regression coefficient for this equation has been found as 0.6865. The relation between scour depth, water depth and area of apron material was analysed. For this dimensional analysis was performed by plotting d_s/h values against A/L^2 values.

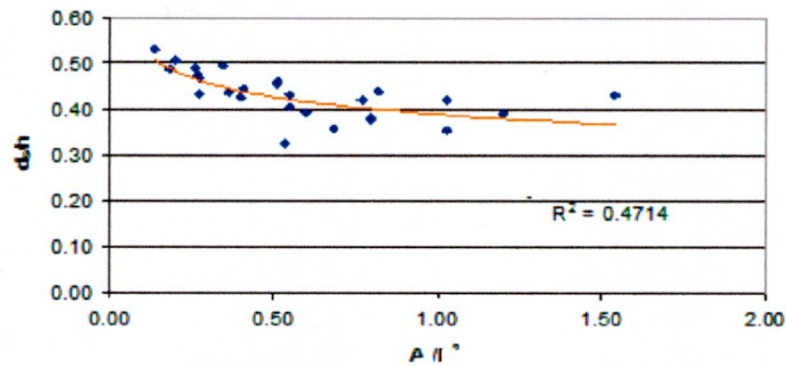


Figure 4.48 Variation of relative scour depth with relative apron area expressed in power form

Another attempt is made to establish relation between the scour depth and velocity of the measured flow. An equation is also proposed basing on the relation between scour depth and velocity. It was found that the scour depth increases with the increase of velocity of the flow.

Equation for scouring depth Vs Velocity plot,

$$y = A_1 \cdot \exp(x/t_1) + y_0$$

$$y_0 = 0.00093$$

$$A_1 = 0.00048$$

$$t_1 = 0.13053$$

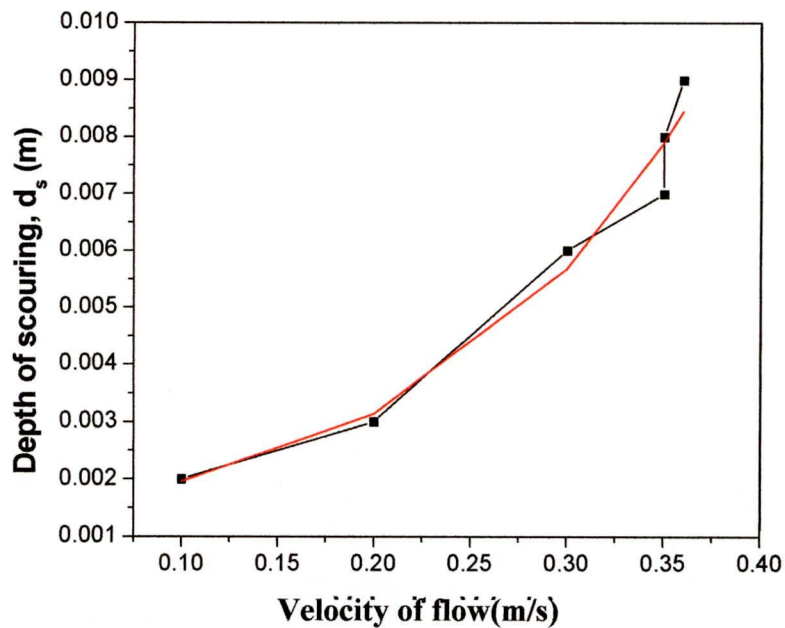


Figure 4.49 Variation of scour depth with the velocity of flow

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the forgoing deliberation and subsequent discussions the following conclusions may be drawn from the present study.

- (1) The flow was found to be more or less streamline and uniform for the case of fixed bed. In mobile bed the flow was not uniform. In mobile bed eddy was created which resulted differential velocity. The velocity profile for without apron case was observed that, when there was no apron, the velocity distribution was very close to normal log-law profile. On the other hand, when there was apron, the velocity gradually decreased towards bed, but before reaching bed suddenly it increased and then again decreased near scoured bed. This sudden increase in velocity was due to the presence of apron.
- (2) From the velocity vector it was observed that, additional flow restriction was created due to presence of apron compared to without apron material in fixed bed. In mobile bed the restriction was more significant. This flow restriction is responsible for the scour hole to be formed away from the apron material. In mobile bed, velocity vectors at different horizontal plane indicate that there is an increased turbulence close to the bottom of the channel. Vertical distribution of velocity just downstream of the scour hole indicates an increased component at the bottom of the channel away from the apron material.
- (3) From the scour study, it was also seen that the formation of scour hole was away from the revetment. The location of the maximum scour depth was close to the apron. It was located at a point slightly downstream from the apron setting. Since the maximum scour depth location was away from the revetment, the extent of scour hole was dependent on maximum scour depth. This scour hole extent was responsible in determining the amount of apron material launching. That means, whether the revetment remains protected or not, that depends on the maximum scour depth and its location.

(4) The aerial extent of launched apron of larger sizes (5mm, 6 mm) covered more area than the smaller sizes. The larger apron material covered 80% whereas the smaller apron covered about 70% of the total area. The geobags were launched properly and covered an area of about 80% , the remaining 20% being unprotected

(5) Two empirical relations have been developed. From the empirical relation it was observed that the depth of scour depends on area of apron material and its length. It was also found the scour depth increases with the increase of velocity.

5.2 RECOMMENDATIONS FOR FURTHER STUDIES

Following recommendations are made for further studies:

- (a) Similar study could be made under live-bed conditions to investigate more practical cases of Bangladesh.
- (b) Comparable study can be undertaken in the large flume and using curved channel.
- (c) The analogous type of study may be conducted for different sizes of bed materials as well as using graded apron materials.

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APPENDIX-A

SIEVE ANALYSIS RESULT

Test : Sieve Analysis of Sediment Sample of Laboratory Channel
 Sample ID : 1
 Location : Hydraulics and River Engineering Laboratory, BUET
 Depth : Surface
 Date of Collection : 1-Jan-09

TEST RESULTS

Sieve Size	Material Retained	Percent of Material Retained	Cumulative % Retained	Percent Finer	Results
(mm)	gm	%	%	%	
No.4(4.75)	0.0	0.0	0	100	F.M.=1.32 D10= 0.14mm D50= 0.28mm D84= 0.38mm D90= 0.39mm Dm= 0.219mm D65= 0.32mm
No.8(2.36)	0.0	0.0	0	100	
No.16(1.18)	2.4	0.0	0	100	
No.30(0.6)	7.0	1.0	1	99	
No.40(0.425)	0.0	0.0	1	99	
No. 50(0.3)	204.4	41.0	42	58	
No.100(0.15)	237.0	47.0	89	11	
NO.200(0.075)	35.8	7.0	96	4	
Pan	13.4	2.7			
Total	500.0				

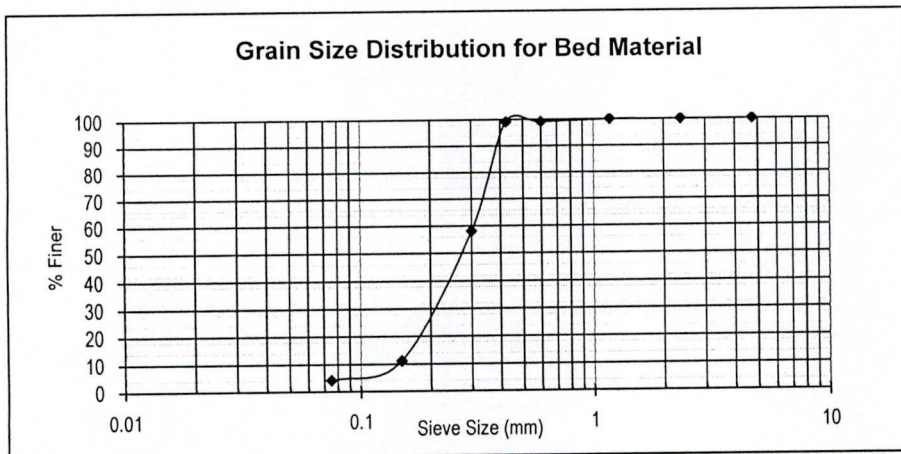


Figure Seive analysis result of bed material at surface

Discharge Calculation - sectionwise

Distance from left water edge (cm)	Average width W (cm)	Depth y (cm)	Velocity v (m/s)	Segmental discharge ΔQ (l/s) ΔQ (cm ³ /s)	
5	10	9.47	0.31	2935.70	2.93570
15	10	8.48	0.23	1950.40	1.95040
25	10	9.49	0.33	3131.70	3.13170
35	10	9.40	0.30	2820.00	2.82000
45	10	9.15	0.24	2196.00	2.19600
55	10	8.90	0.30	2670.00	2.67000
65	10	8.15	0.29	2363.50	2.36350
75	10	7.75	0.24	1860.00	1.86000
85	10	7.15	0.31	2216.50	2.21650
95	10	6.50	0.27	1755.00	1.75500
105	10	5.60	0.25	1400.00	1.40000
115	10	5.65	0.21	1186.50	1.18650
125	10	5.75	0.27	1552.50	1.55250
135	10	5.85	0.26	1521.00	1.52100
145	10	6.55	0.30	1965.00	1.96500
155	10	6.75	0.27	1822.50	1.82250
165	10	7.10	0.31	2201.00	2.20100
175	10	6.70	0.31	2077.00	2.07700
185	10	5.65	0.31	1751.50	1.75150
195	10	6.10	0.29	1769.00	1.76900
Average y, v and ΔQ -		7.25	0.24	1997.24	39.14 Total Q

V1H1	15.00	3.85	
V1H1	20.00	4.45	
V1H1	24.00	4.87	
V1H1	25.00	4.97	
V1H1	30.00	5.45	
V1H2	0.10		0.26
V1H2	0.20		0.36
V1H2	0.30		0.44
V1H2	0.50		0.57
V1H2	0.80		0.73
V1H2	0.90		0.77
V1H2	1.00		0.81
V1H2	1.50		0.99
V1H2	2.00		1.15
V1H2	3.00		1.41
V1H2	5.00		1.82
V1H2	8.00		2.30
V1H2	10.00		2.57
V1H2	15.00		3.15
V1H2	20.00		3.63
V1H2	24.00		3.98
V1H2	25.00		4.06
V1H2	30.00		4.45
V1H3	0.10		0.22
V1H3	0.20		0.32
V1H3	0.30		0.39
V1H3	0.50		0.50
V1H3	0.80		0.63
V1H3	0.90		0.67
V1H3	1.00		0.71
V1H3	1.50		0.87
V1H3	2.00		1.00
V1H3	3.00		1.22
V1H3	5.00		1.58
V1H3	8.00		2.00
V1H3	10.00		2.24

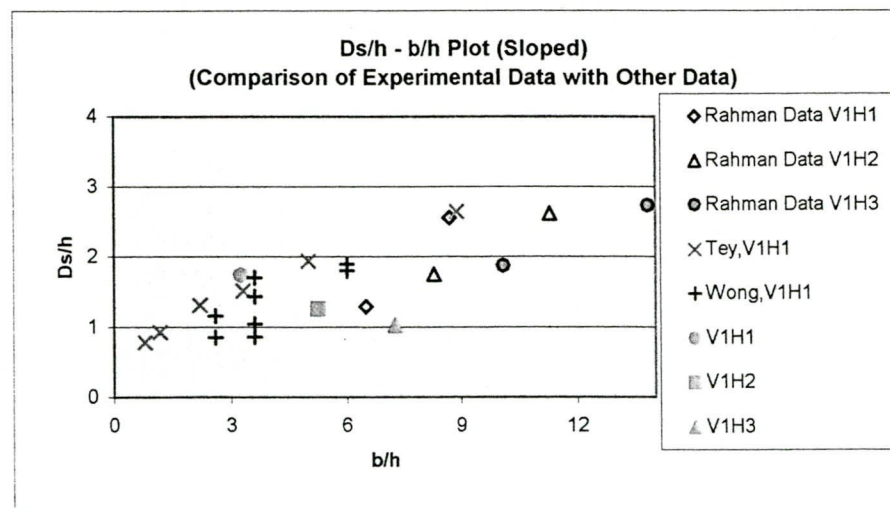
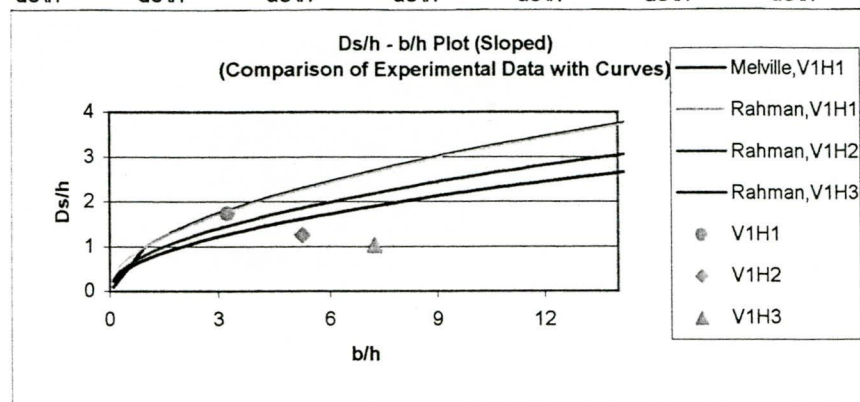
	V1H3	15.00	2.74						
	V1H3	20.00	3.16						
	V1H3	24.00	3.46						
	V1H3	25.00	3.54						
	V1H3	30.00	3.87						
Rahman Data	V1H1	6.50		1.29					
	V1H1	8.70		2.55					
	V1H2	8.30			1.75				
	V1H2	11.30			2.61				
	V1H3	10.10				1.87			
	V1H3	13.80				2.73			
Tey (1984)	V1H1	8.90					2.64		
	V1H1	5.00					1.94		
	V1H1	3.30					1.52		
	V1H1	2.20					1.31		
	V1H1	1.20					0.93		
	V1H1	0.80					0.78		
Wong (1982)	V1H1	3.60						0.86	
	V1H1	3.60						1.04	
	V1H1	3.60						1.43	
	V1H1	3.60						1.70	
	V1H1	6.00						1.80	
	V1H1	6.00						1.89	
	V1H1	2.60						0.85	
	V1H1	2.60						1.16	
Own	V1H1	3.25							1.74
	V1H2	5.25							1.26
	V1H3	7.25							

Table Discharge Through Scour

3 mm				4 mm			5 mm			Geobag			No apron		
Y	h	v (m/s)	q (cm ² /s)	h	v	q (cm ² /s)	h	v	q (cm ² /s)	h	v	q (cm ² /s)	h	v	q (cm ² /s)
0	8	0.137856	110.2845	8	0.110214	88.171088	3.7	0.237123	87.735378	8.4	0.150602	126.50559	8	0.125081	100.06447
10	8	0.024328	19.462312	8	0.036815	29.451905	4.98	0.010964	5.4601346	7.92	0.03394	26.880205	8	0.017209	13.767477
20	8	0.038999	31.19947	8	0.059958	47.966594	6.26	0.020351	12.739878	7.44	0.039976	29.742149	8	0.037359	29.887392
30	8	0.028417	22.733753	8	0.032954	26.363455	7.54	0.025916	19.540962	6.96	0.043882	30.54191	8	0.038049	30.438875
40	8	0.032249	25.799169	8	0.034826	27.860926	8.82	0.034636	30.548999	6.48	0.051742	33.528811	8	0.032689	26.151403
50	8	0.035438	28.350353	8	0.040638	32.510381	9.2	0.034944	32.148829	6	0.046085	27.650841	8	0.028563	22.850351
60	9.8	0.023842	23.365211	9.5	0.163757	155.56941	13.3	0.0369	49.076357	11.5	0.036552	42.035105	11.7	0.043294	50.654289
70	13.7	0.295969	405.47707	14.1	0.345005	486.45649	14.8	0.113657	168.21293	15.5	0.284959	441.68702	15.7	0.076336	119.84775
80	18.2	0.332742	605.59061	18	0.31558	568.04334	11.2	0.349061	390.9484	13.1	0.29956	392.42331	13.3	0.366832	487.88713
90	13	0.312764	406.59344	13.38	0.298721	399.68896	11.2	0.311194	348.53757	12.1	0.319133	386.15063	12.5	0.337436	421.79511
100	13.2	0.312552	412.56879	10	0.292953	292.95323	12.1	0.297811	360.35175	11.7	0.317118	371.02832	11.5	0.337939	388.62955
110	9.4	0.299542	281.56908	9.7	0.289853	281.15774	8.8	0.300551	264.48482	10.2	0.316123	322.44512	12.2	0.332755	405.96167
120	7.8	0.287744	224.4407	9.9	0.27302	270.29009	9.8	0.303377	297.3095	9.7	0.272824	264.63969	9.6	0.279479	268.29943

Scour Data for Sloped Structures ($\tau/\tau^*c > 0.8$)
(Data reference - Doctoral thesis of Munsur, 1998)

Source	V:H	b/h	ds/h	ds/h	ds/h	ds/h	ds/h	ds/h	ds/h	ds/h	ds/h	ds/h
Melville (1992)	V1H1	0.10	0.10									
	V1H1	0.20	0.20									
	V1H1	0.30	0.30									
	V1H1	0.50	0.50									
	V1H1	0.80	0.80									
	V1H1	0.90	0.90									
	V1H1	1.00	1.00									
	V1H1	1.50	1.22									
	V1H1	2.00	1.41									
	V1H1	3.00	1.73									
	V1H1	5.00	2.24									
	V1H1	8.00	2.83									
	V1H1	10.00	3.16									
	V1H1	15.00	3.87									
	V1H1	20.00	4.47									
	V1H1	24.00	4.90									
	V1H1	25.00	5.00									
	V1H1	30.00	5.00									
Rahman (1998)	V1H1	0.10		0.31								
	V1H1	0.20		0.44								
	V1H1	0.30		0.54								
	V1H1	0.50		0.70								
	V1H1	0.80		0.89								
	V1H1	0.90		0.94								
	V1H1	1.00		0.99								
	V1H1	1.50		1.22								
	V1H1	2.00		1.41								
	V1H1	3.00		1.72								
	V1H1	5.00		2.22								
	V1H1	8.00		2.81								



	3.70	1.00	
	5.90	4.03	
	6.00	4.00	
	5.20	3.90	
	4.60	3.95	
Rahman (1998)	7.00	3.22	
Data	10.50	4.20	
	14.00	5.03	
	6.10	3.56	
	7.70	4.17	
	9.20	4.66	
Experiment	3.13		2.27
	5.00		2.63
	7.50		2.87

h	ks	h/ks	$u/u^*=6+5.75\log(h/ks)$		
				u	u*
18	0.575	31.30	14.60	0.296	0.020274
16	0.575	27.83	14.31	0.275	0.019223
14	0.575	24.35	13.97	0.239	0.017105
12	0.575	20.87	13.59	0.19	0.013984
10	0.575	17.39	13.13	0.135	0.01028
8	0.575	13.91	12.57	0.149	0.011849
6	0.575	10.43	11.86	0.217	0.018303
4	0.575	6.96	10.84	0.235	0.021671
2	0.575	3.48	9.11	0.104	0.011412
18	0.575	31.30	14.60	0.299	0.02048
16	0.575	27.83	14.31	0.268	0.018734
14	0.575	24.35	13.97	0.216	0.015459
12	0.575	20.87	13.59	0.171	0.012585
10	0.575	17.39	13.13	0.12	0.009138
8	0.575	13.91	12.57	0.127	0.0101
6	0.575	10.43	11.86	0.173	0.014591
4	0.575	6.96	10.84	0.223	0.020565
2	0.575	3.48	9.11	0.135	0.014814
6	0.575	10.43	11.86	0.303	0.025556
5.5	0.575	9.57	11.64	0.293	0.025174
4	0.575	6.96	10.84	0.191	0.017614
2	0.575	3.48	9.11	0.122	0.013388
1	0.575	1.74	7.38	0.092	0.012463

ds = 27.8 cm, (t=1950 min)

$Q = 40 \text{ l/s}, \quad v(\text{local}) = 0.36 \text{ m/s},$

X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z				
450	0	-2.00	510	100	2.3	530	200	-1.90	560	90	-3.15	580	190	-0.60				
	10	-1.70		110	3.20		540	0		-27.40	100		-3.50	200	-3.60			
	20	-2.10		120	2.40			10		-25.90	110		-2.35	590	0	0.85		
	30	-2.30		130	1.5			20		-25.90	120		-0.50		10	6.10		
	40	-1.10		140	1.00			30		-25.90	130		1.30		20	4.20		
	50	-0.50		150	1.1			40		-24.40	140		1.15		30	-0.05		
	60	1.30		160	0.30			50		-20.40	150		1.30		40	-6.30		
	70	0.90		170	-0.40			60		-15.40	160		1.80		50	-9.70		
	80	1.50		180	-2.20			70		-10.00	170		0.00		60	-7.60		
	90	1.85		190	-1.70			80		-5.15	180		-1.90		70	-3.40		
	100	3.20		200	-0.90			90		-1.80	190		-2.40		80	-0.20		
	110	3.45		520	0			-17.60		100	-0.90		570		200	-2.90	90	-0.10
	120	2.20			10			-17.10		110	1.70				0	-0.50	100	-1.40
	130	2.90			20			-15.45		120	1.30				10	1.65	110	-2.75
	140	1.70			30			-15.10		130	2.20				20	0.30	120	-1.80
	150	0.90			40			-14.10		140	1.50				30	-5.40	130	-2.10
	160	-1.10			50			-12.60		150	0.80				40	-12.70	140	1.70
	170	0.50			60			-8.70		160	-0.65				50	-15.20	150	1.20
	180	-0.90			70			-4.90		170	-0.50				60	-13.20	160	-1.10
	190	-3.50			80			-1.50		180	1.20				70	-8.20	170	-0.50
200	-2.70	90	0.50		190	-2.80		80	-2.80	180	-2.00							
500	0	-4.80	100		0.80	550	200	-1.90	580	90	-2.00	600			190	-2.00		
	10	-4.50	110		2.50		0	-27.10		100	-3.20			200	-2.90			
	20	-5.00	120		0.70		10	-27.10		110	-4.80			0	1.30			
	30	-3.60	130		0.60		20	-27.10		120	-2.90			10	6.10			
	40	-2.50	140		1.10		30	-27.10		130	0.60			20	4.80			
	50	-0.50	150		1.10		40	-27.10		140	0.70			30	1.60			
	60	0.15	160		-1.40		50	-24.00		150	1.45			40	-4.70			
	70	1.60	170		0.40		60	-16.60		160	0.50			50	-7.05			
	80	1.75	180		-0.10		70	-11.20		170	-1.40			60	-5.40			
	90	2.75	190		-2.20		80	-5.30		180	-1.20			70	-1.85			
	100	3.00	200	-2.65	90		-3.40	190		-1.80	80		0.80					
	110	1.80	530	0	-23.30		100	-2.05		580	200		-1.00	90	-0.10			
	120	3.30		10	-21.70		110	-0.60			0		-0.50	100	-2.80			
	130	3.50		20	-20.80		120	0.70			10		4.20	110	-4.10			
	140	0.40		30	-20.50		130	1.50			20		1.30	120	-2.40			
	150	0.30		40	-19.30		140	0.24			30		-4.60	130	-1.85			
	160	0.10		50	-16.25		150	0.50			40		-9.05	140	-0.20			
	170	-1.40		60	-12.80		160	-1.00			50		-12.76	150	0.15			
	180	-1.90		70	-8.30		170	-2.20			60		-10.00	160	1.20			
	190	-0.90		80	-3.85		180	-0.2			70		-5.60	170	0.00			
200	-0.45	90		-0.70	190	-1.80	80	-1.30	180		-1.40							
510	0	-11.30		100	1.45	560	200	-0.40	620		90	-0.70	190	-0.90				
	10	-10.70		110	1.85		0	-20.80			100	-2.85	200	-1.40				
	20	-9.40		120	2.60		10	-20.80			110	-2.85	0	0.70				
	30	-9.40		130	2.40		20	-20.80			120	-4.10	10	4.70				
	40	-8.20		140	0.20		30	-20.80			130	-0.10	20	3.60				
	50	-6.40		150	-0.20		40	-20.80			140	0.10	30	2.80				
	60	-2.90		160	-2.00		50	-21.05			150	1.50	40	-0.20				
	70	-0.75		170	-1.20		60	-16.30			160	-1.00	50	-1.95				
	80	1.50		180	-0.80		70	-10.80			170	-1.20	60	-1.00				
	90	1.80		190	-2.30		80	-3.65			180	0.60	70	1.10				

X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z		X	Y	Z
620	80	0.00		700	0	-2.00		800	130	1.20								
	90	0.70			10	-0.20			140	-1.90								
	100	0.00			20	2.80			150	-1.95								
	110	-2.00			30	4.50			160	-2.60								
	120	-3.70			40	3.60			170	-2.55								
	130	-2.50			50	3.20			180	-1.70								
	140	-1.60			60	2.30			190	-4.90								
	150	-1.30			70	2.60			200	-3.70								
	160	-0.70			80	-1.15		850	0	2.40								
	170	-0.40			90	-0.30			10	1.25								
	180	-2.90			100	-2.85			20	0.70								
	190	-2.60			110	1.05			30	3.30								
	200	-2.10			120	-0.10			40	1.50								
640	0	0.30			130	-1.60			50	1.50								
	10	1.90			140	-1.70			60	3.95								
	20	4.40			150	-1.90			70	1.60								
	30	2.15			160	-4.90			80	1.15								
	40	2.25			170	-3.00			90	1.80								
	50	0.40			180	-2.50			100	-0.83								
	60	0.90			190	-0.10			110	0.40								
	70	1.85			200	-2.10			120	-1.15								
	80	2.40		750	0	0.90			130	-1.60								
	90	-0.30			10	-0.30			140	-2.00								
	100	-0.55			20	0.60			150	-2.30								
	110	-1.70			30	1.60			160	-3.40								
	120	-3.15			40	3.55			170	-2.80								
	130	-3.00			50	2.20			180	-3.10								
	140	-1.10			60	4.10			190	-3.20								
	150	-1.30			70	2.20			200	-3.90								
	160	-1.30			80	0.70		900	0	0.40								
	170	-2.80			90	1.30			10	2.50								
	180	-1.20			100	-0.95			20	4.20								
	190	-2.40			110	-0.70			30	1.95								
	200	-1.35			120	-2.10			40	2.30								
670	0	-0.40			130	-1.80			50	-0.20								
	10	2.60			140	-2.40			60	2.50								
	20	2.50			150	-0.90			70	1.95								
	30	3.90			160	-3.90			80	1.50								
	40	1.40			170	-4.30			90	0.20								
	50	2.20			180	-3.00			100	-0.10								
	60	0.40			190	-2.05			110	-0.5								
	70	1.60			200	-0.30			120	-0.10								
	80	1.10		800	0	-0.75			130	-2.30								
	90	-1.30			10	1.20			140	-5.05								
	100	0.60			20	1.00			150	-3.40								
	110	-1.10			30	1.60			160	-5.60								
	120	-2.00			40	1.90			170	-2.75								
	130	-2.65			50	1.75			180	-4.00								
	140	-3.10			60	2.10			190	-5.10								
	150	-1.10			70	2.20			200	-3.90								
	160	-1.70			80	1.60												
	170	-1.80			90	1.10												
	180	-1.25			100	-2.3												
	190	-2.7			110	-1.4												
	200	-1.8			120	-0.4												

