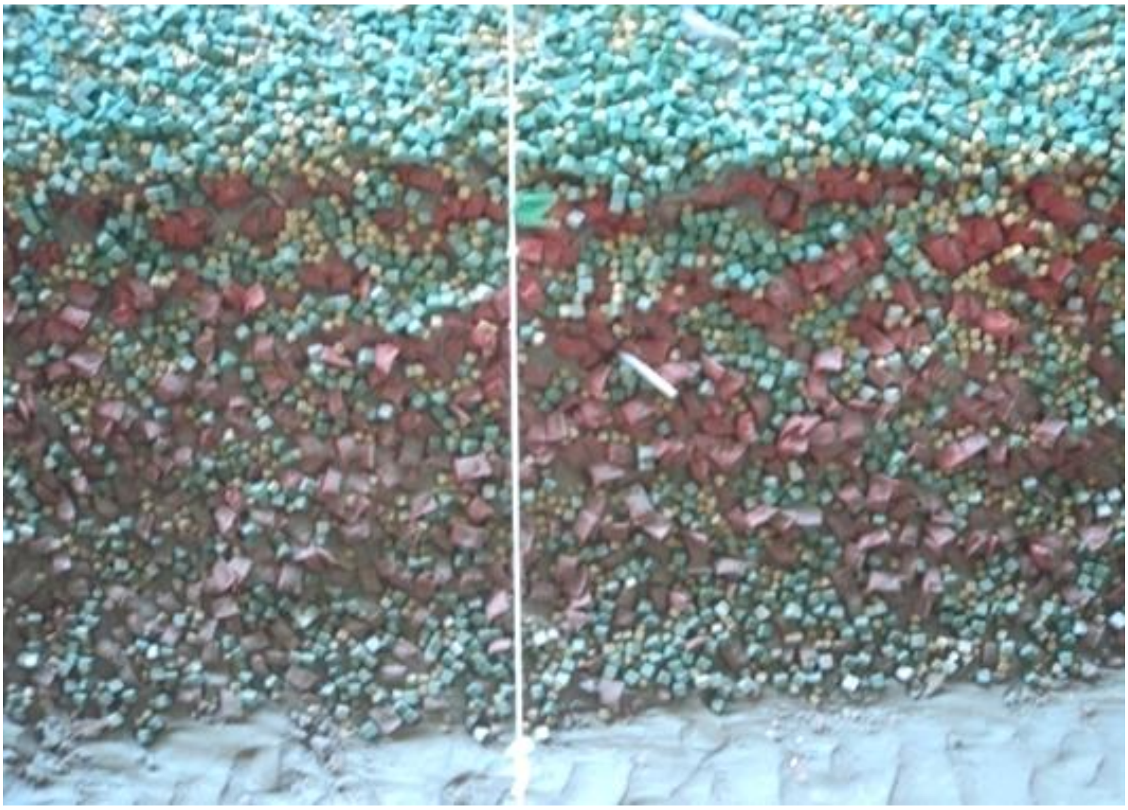
Investigation on launching characteristics of different materials to find out the cost-effective and sustainable solution for river bank protection



June 2017

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Government of the People's Republic of Bangladesh

1 INTRODUCTION

1.1 Scope of the Study

Bangladesh is a land of rivers having an agro based economy. From ancient time to the present days, rivers have been playing a dominant role in human activities. Rivers provide waterways to transport the agricultural and other commodities from one place to another, water for drinking, irrigation and act as reservoir for fish culture. They also help in the generation of electric power. But occasional heavy flood discharge has caused flooding of lands and caving of the banks, thereby causing heavy destruction to the cities and other important engineering constructions. The countries that have succeeded in controlling and harness the rivers have progressed very quickly. Examples of such success are found in many countries of the world starting from USA, through Europe to Asia.

During monsoon, rivers of Bangladesh carry huge amount of sediment along with water. They altogether cause significant change to geomorphic and other hydraulic characteristics of the rivers. Again during lean flows, there is heavy deposition of silts. Thus, throughout the year, there are changes in cross-section, slope, thalweg etc. of the river taking place. Again these parameters undergo great changes from year to year due to the change in water discharge and sediment discharge.

The first and foremost aim of river training is to stabilize and to train the river channel along certain alignment with certain cross-section. It has some objectives such as (i) To guide the approach flow through certain defined stretch to prevent the river from changing its course; (ii) To avoid outflanking of structures like bridges, weirs, aqueduct etc; (iii) To prevent flooding of the surrounding countries by providing a safe passage for the flood waters without overtopping the banks; (iv) To protect the river banks from erosion by deflecting the river away from the attacked banks; (v) To provide sufficient depth and good course for safe navigation; and (vi) To ensure effective disposal of suspended and bed load.

Protection of riverbanks from erosion is a part and parcel of river training works. A lot of important installation like towns, industries, different institutions, Hat-Bazar, agricultural lands etc. beside the river bank require effective bank protection or training works to save area from the bank erosion by flood flow even in lean flow. In this respect, RRI has taken a research work titled, “Investigation on launching characteristics of different materials to find out the cost-effective and sustainable solution for river bank protection”.

1.2 Objectives

- To investigate the launching behavior of stone chips, cement concrete (CC) blocks and geo-bags
- To observe the velocity and scour in the vicinity of bank protective structures
- To compare the performance of stone chips, CC blocks & geo-bags under oblique flow (60-degree) condition and
- To find out the cost-effective materials for launching apron to protect river bank.

1.3 Need and Justification

There is active bank erosion almost in all major rivers in the country causing damage to valuable land, properties and infrastructures from year to year. Because of high density of population along the river banks, a great numbers of people are displaced due to this continuous bank erosion process. These poor people migrated to nearby towns and cities and live a sub-human life in the slump areas. This has created a great natural and social problem in the country. Bank protection work is one of the prime necessities for poverty alleviation and national growth. The issue is the safety of lives, land & sustainability of the infrastructures against the forces acting in the rivers.

As Bangladesh is a lower riparian country, the large variation in discharge and huge amount of sediment load is very difficult to manage. So major emphasis should be given on the design parameters. Moreover, the design parameters such as design fl
ow velocity & design scour depth can be obtained through the present research work by physical modelling.

Launching Apron (LA) is an important part of river training structures. Without LA of appropriate launching materials, revetment and spurs cannot be stable and may collapse. Therefore, a research work has been undertaken at RRI to combat river bank erosion effectively. Through the research work, the performance of launching materials for river bank protection has been assessed to determine their efficacy and to find out the cost-effective material.

1.4 Methodology

The model is investigated on a mobile bed. The hydraulic similarity is established in the model to an undistorted scale. The model is a Froude model and is studied over a generalized bathymetry. The investigation of model is being carried out to investigate the local scour and velocity field at and around the revetments under different likely approach flow conditions. The model is constructed to an undistorted scale. The scale ratio is selected as 1:30. The model has been designed to fulfil both flow and sediment transport criterion simultaneously. It means the model velocity is higher than the critical flow velocity for the initiation of sediment motion. This is because for any velocity higher than the critical, the scour dimensions are only function of flow direction and structure geometry. The model will, therefore, reproduce the scour holes correctly.

A closed shed has selected for model development. It provides all kinds of facilities related to model study. Then preliminary layout of model is given by grid system. After setting reference grid points in the model, channel planform is given using these grid points and the bed & bank levels are fixed up by leveling instrument as per bathymetry using Rise & Fall method. This requires some cutting and filling of sand from the model.

In this physical model, various types of instrument and facilities are needed such as, a sharp-crested weir for measuring flow, point gauge for measuring water level, 3-D current meter for measuring velocity, high resolution camera for taking video and photographic view of model, stopwatch for taking instant time and plastic coloured balls for identifying flow path of flowing water.

In a physical model, the required discharge is measured using sharp-crested weir in the inflow section using Rebock's formula. Model velocity is quantified by 3D velocity meter. Water slope can be found by analyzing the water level measurements of different point gauges installed in the model. Flow lines of the stream can be identified by dropping color balls starting from calibration section and catching them at the end of the model. A stopwatch can be used to calculate surface velocity of the flow. In the physical model, model data requires to be analyzed for interpretation of test results.

1.5 Structure of the Report

This report presents the outcomes of the physical model investigation conducted at RRI. The Scope of the Study, Objectives, Need and Justification and Methodology are presented in ***Introduction*** chapter. ***Literature Review*** chapter describes the different structures constructed to protect the Ganges-Jamuna-Meghna and other river basin from severe erosion. Model Scale, Model Design, Characteristics Design Parameters and Model Set-up have been described in ***Model Design and Setup*** chapter. In ***Test Scenarios*** **c**hapter, the scenarios of the different test runs have been illustrated. The calibration as well as the application tests is described in ***Test Runs*** chapter. ***Results and Discussion*** chapter explains the justification of different test results from model study. The conclusions and recommendations of the model study are presented in ***Conclusion and Recommendation*** chapter.

2 Literature Review

2.1 Introduction

Bangladesh has a long history of combating riverbank erosion. Most of the people are living and housing beside the river strives to protect the banks against erosion from time immemorial. Various methods of bank protection have developed in the past with considerable local differences subject to available materials. Until the early sixties of previous century, bank protection works on main rivers were mainly limited to the upstream area of Hardinge Bridge on the river Ganges, where stabilization of banks were tried by means of brick revetments, Rajshahi brick groynes in the Ganges and Sirajganj Town Protection with brick mattress on the Jamuna. Brick mattress proved to be untenable due to damage of wire net and subsequent loss of bricks. Depending on morphology and bed configuration of the rivers, the location to be protected, space available etc., various types of direct bank protection measures such as revetment, groynes, spurs, retaining walls, porcupines or indirect measures such as cut-offs were executed in the past with more or less success. Side by side vastly developed engineering systems specifically designed for bank protection. Among these, revetments and groynes are more or less lasting measures; those have been used widely in the recent time.

The function of bank revetments and groynes is to prevent bank erosion that means they have to be designed to resist current & wave and to protect the riverbed & riverbank against changes. Their principal objective is to provide a stable riverbank. Experiences of selected bank protection works on major rivers of Bangladesh are given below:

1) Bhuapur Hard Point

Bhuapur Hard Point is a component of Bangabandhu Multipurpose Bridge along the left bank of Jamuna River, about 5 km upstream of the bridge corridor. It is designed to protect the banklines up to -20 m PWD. The length of this hard point (revetment) is about 1550 m long. The slope (1V:3.5H) was built with open stone asphalt and stone (10 kg to 60 kg) used as a launching material. The revetment has not yet subjected to any river attack, so no experience is available about the long-term stability.

2) Sirajganj Hard Point

Sirajganj Hard Point constructed with brick mattress to protect Sirajganj town in 1964, which washed away in 1969. During the seventies, more than 2.5 km revetment made of sand-cement blocks (CC cubes) was built but again destroyed during 1985 flood. It is noted here that this hard point had been considered as a right bank hard point for Bangabandhu Multipurpose Bridge. To fulfill the above-mentioned objective of the revetment that the Sirajganj hard point (revetment) reconstructed to increase safety factor against anticipated severe erosion hazard under River Bank Protection Project (RBPP) during the period of 1996-98. The falling apron was designed with two layers of CC cubes and the bank protection (1V:3.5H) techniques was taken to be 550 mm i.e.; one layer of CC blocks plus 350 mm of brick filter placed on top of the geo-textile. The hard point was severely damaged during the flood of 1998 and repair works were executed during the dry season 1998-99 by filling the eroded slope with a thick layer of cc blocks and overlapped by 2.5 layers of geotextile blankets. Main reasons for failure are the morphological changes creating unfavorable channel plan form with deep confluence scour and the characteristics of subsoil. In the month of July- August, 2005 again the hard point is under serious threat due to embayment and the measured scour depth was found to be -40 m PWD. The extremely deep scour -40.00 m PWD occurred not due to a high flood but mainly for change of planform.

3) Sarikandi and Mathurapara Hard Points

The Kalitola, Sarikandi and Mathurapara hard points were constructed to prevent Jamuna River from merging with the Bangali River that poses the risk of bypassing Bangabandhu Multipurpose Bridge. The three hard points constructed in a series were successfully in stopping shifting of Jamuna River towards the Bangali River for a short period. The construction of the hard point was carried out during 1996-1998. Total length of the protection work was 4.5 km, which protected about 6 km bank line of the river. The revetment had a slope of 1V:3.5H from top to apron level. After completion of construction, Mathurapara hard point experienced significant scouring in the upstream point and the falling apron started to develop. In the early 1999, CC blocks were damped to replenish the deployed apron close to the scour hole.

4) Revetment Works at Debdanga and Titporal

Following the construction of the hard points at Kalitola, Sariakandi and Mathurapara, some morphological changes of the Jamuna has occurred so that the point of attack has been shifted. This has again created the possibility of merging of Jamuna with Bangali River in Titporal at upstream and Debdanga at downstream of the above-mentioned hard points respectively. To avoid this situation and to prevent Kalitola and Mathurapara hard points from being outflanked, revetments have been constructed at Titporal and Debdanga along the right bank of Jamuna.

The length of revetments at Titporal and Debdanga are 2000 m and 1273 m respectively. The revetment works are constructed on a 1V:2H slope from LWL to embankment crest level. The toe protection (apron) has been achieved with 50 m^3 per meter of CC cubes placed on a 26 m wide apron from LWL to about 6 m PWD.

Immediately after construction of the revetment at Titporal and Debdanga, siltation on the apron has been observed. During the flood, 2007 erosion along the revetment occurred and partially damaged the revetment leading to additional maintenance requirements. After the construction, no damage was observed in Debdanga portion of the revetment work. However, in Titporal portion some failures in slopes were observed during 2007 and 2008.

5) Ghutail Revetment Structure

Ghutail revetment structure was constructed about 4 km south of Bahadurabad based on the experience gained from Bahadurabad Revetment. The structure was built in dry season of 1999-2000. The structure is 600 m long with two terminations and protecting about 530 m of bank line. Brick mattresses and CC cubes were used as a cover layer of the revetment slope 1V:3H (above berm) whereas RENO mattresses and CC cubes were implemented as launching and falling aprons, respectively. Scour occurred at downstream part of the structure in the next year of construction, when falling apron was deployed. Again, in 2003, scour occurred at upstream side and along the whole structure. The upstream part of the structure was damaged during 2004 flood due to embayment sand-filled geo-bags were dumped in apron and slope to stop failure of the structure. In early 2005 flood, there was also direct attack and damages of the revetment. After flood, the river has a tendency to shift its course away from the structure. A continuous monitoring and observation would be required to adopt the proper repair measure in due time.

6) Chandpur Town Protection

The Chandpur Town Protection work located on the left bank just downstream of the confluence of Upper Meghna River and Padma River, is an example of fighting nature with very limited resource.

Railway Department used to dump boulders in the past to protect its railway head at Natunbazar (Northen part of the town). The erosion intensity in the Chandpur area periodically becomes severe and measures were undertaken on emergency basis. Following serious erosion in 1970, large amount of boulders were dumped on the Puranbazar site and a 96 m long groyne was constructed in 1972-73 using about 80,000 m^3 boulders. In the next flood, a part of the head of groyne failed by material slides and due to lack of repairs, further damages and slides occurred in 1974 flood. The groyne was abandoned but the remaining submerged part created excessive local scours in the area. In the year of 1975, a comprehensive plan recommended a revetment work by dumping boulders in the area with total 540,000 m^3 boulders for 2408 m bank protection *i.e.* 224 m^3/m. Due to resources constraint only about 27% of boulders were dumped by 1988. The rate of dumping of boulders was slow, about 11,150 m^3/year and the amount of boulders was inadequate per meter length. After 1988, CC blocks were used instead of boulders with a slope of 1V:1.5H or even steeper at some locations. Since 1990, revetment works have been carried out with different sizes of cement concrete blocks over sand filled geotextile bags.

7) Rajshahi Town Protection

In Rajshahi Town Protection scheme almost all types of bank protection works have been practiced. In 1960, 6.5 km embankment was implemented with brick mattress encased two layers of galvanized iron wire net. In 1970, brick-filled gabions were used to save the flood protection embankment from flood damage and two spurs were constructed at GPO and Daragapara. During the period of 1971-1977, a series of brick-crate spurs and a T-groyne (groyne no. 1) was constructed that saved the downstream of police line but upstream reach faced serious erosion. Consequently, two groynes (groyne no. 2 and 5) and a brick-crate spur (No. 2B) were constructed by 1980 after conducting physical model study. These structures protected the Rajshahi town for several decades. Following the 1987 flood, 5.8 km revetment works and seven groynes or spurs were rehabilitated and constructed that was damaged considerably in 1998 flood. For slope protection, CC block (40cm x 40cm x 20cm) revetment over geo-textile filter with CC block as toe protection were used in these structure. A 70 m RCC spur having no earthen shank was built at Panchabati (Shasan ghat) area in 2000-2001. The bed protection was provided by 30 cm and 45 cm cube blocks and boulders. Brick mattresses were effective for long time with regular maintenance but didn’t sustain in large floods. The revetment work consisting of brick mattress proved to be unsustainable due to damage of wire net and consequent loss of bricks.

8) Bhola Town Protection and Protection in Tajumuddin

Bhola Town and its adjacent area, Tulatali Bazar, and severely affected bankline in Doulathan and Tajumuddin Upazila were provided protection through construction of revetment using CC blocks (40.32 m^3/m) in the trench along the bankline over a width of 28 m. The blocks launched with the advancing scour and arrested the erosion in the affected reach. Protection with sand-filled geo-bags has been provided in Tajumuddin Upazila for a length 2277 m in Lower Meghna River. The bankline above 0.00 m PWD to +3 m PWD were protected with 450 x 450 x 300 mm^3 CC blocks over a geotextile filter. Sand filled geo-bags were placed and dumped from 0 m PWD to -21 m PWD. Maximum scour anticipated in the design was up to -30 m PWD. Total volume of material (geo-bag) dumped per unit length of bank line is 50.00 m^3 per meter. Two different sizes of geo-bags weighing 175 kg and 126 kg were used. Another 887 m of river bank, just upstream of the above protection was constructed with 50 m^3 per meter of CC block from 0 m PWD to -21 m PWD. Two different sizes of CC blocks, 350 mm cube 50% and 400 mm cube 50% were dumped. The slope above low water level from 0 m PWD to +3 m PWD protected by one layer of 450 x 450 x 300 mm^3 CC block over a geotextile filter. The anticipated design scour in this case was also up to -30 m PWD.

9) Jamuna-Meghna River Erosion Mitigation Project (JMREMP)

The JMREMP was formulated to control riverbank erosion at two major Flood Control Drainage and Irrigation (FCDI) projects namely Pabna Irrigation and Rural Development Project (PIRDAP) and the Meghna-Donaghoda Irrigation Project (MDIP). Considering maximum expected scour (30 m for PIRDAP and 20 m for MDIP below low water level), suggested apron protection in PIRDAP and MDIP was 60.80 m^3 per meter and 40.66 m^3 per meter respectively. The amount of material was computed by estimating the maximum scour assuming a 1V:2H launching slope and 33.5 m length. In attempt to save Pechakhola and Mohongonj area from serious erosion in October 2004, a program was undertaken to provide protection in 600 m bankline, 200 m in Pechakhola and 400 m in Mohongonj by dumping geo-bags (20.16 m^3/m). Under this program, during the dry season of 2006-2007, 1200 m long filled mattress for wave protection has been built for pilot test purposes. Under the project in MDIP, 1250 m of bank from km 44.98 to km 48.23 was provided protection against erosion by fascine mattress ballast with geo-bags, falling apron and area coverage by geo-bags. Ekhlaspur hard point from km 48.230 to km 48.330 (100 m) has been rehabilitated by CC blocks in apron. 1.12 km of slope protection up to High Flood Level (HFL) in PIRDAP and 4.00 km in MDIP was built to first level protection by July 2004 and survived the flood season without any significant damage.

10) Kalitola Groyne

Kalitola Groyne was built by BWDB during mid 1980s at 117.5 km of the Brahmaputra Right Embankment in Bogra district and was completed in 1998. In September of the same year the scour level reached to -7 m PWD and the apron was deployed and in the next year 1500 no, 450 mm size CC blocks were dumped to replenish the deployed apron blocks just downstream of the nose. On 6th July the first damage of the spur-head occurred, which was countered by dumping cc blocks (650 mm size) and geo-bags. By mid-August further damages occurred and CC blocks on the revetment near the water surface were undermined on the upstream side of the nose. The scour bed level was found -14.50 m PWD in 2000 and more than 100,000 geotextile bags of different sizes were dumped. On September 4, 2007, 145 m of revetment at upstream face of shank and on October 23, 2007 another 125 m of bell mouth face was damaged creating a vertical face at the end, corresponding WL was 16.25 m and 13.84 m PWD. Again on November 27, 2007 another 75 m of upstream face of the bell mouth was damaged corresponding WL was 11.53 m PWD. The reason of failure of the groyne was mainly the rapid deep scouring with subsequent development of a sequence of flow slides. The falling apron was unable to react rapidly to the flow slide's penetration underneath the protection.

11) Sailabari Groyne

Sailabari groyne was constructed at Ziar Mohr, Sirajganj in 1978 along the right bank of Jamuna River that has recently been completely destroyed. The groyne can be described as an earthen dam with a slope protection like revetment. The side slopes and head of the groyne were protected with CC blocks. The groyne as constructed had 1.0 km long earthen shank with 60 m T-head. Revetment on slope of the shank, the T-head and toe protection required for the anticipated scour were provided based on existing and expected bathymetry and morphological condition. The groyne faced a major attack from the river in 1996 due to continuous shifting of the main channel towards the west bank at the upstream of the groyne. As a result, 20 m of the T-head was damaged. In addition to major repair of the T-head, 188 m long revetment work was constructed at upstream of the groyne. During 1998 flood, the T-head and a portion of the shank were severely attacked by flow and about 9000 m^3 CC blocks were dumped for protection. After 1998 flood, to support the groyne, 680m revetment was constructed at upstream side and 450 m^3 of CC blocks were stockpiled for emergency. On 28 June 2002, another 20 m out of remaining 40 m T-head part was washed away and on 26 July 2002, another 20 m of the shank also destroyed that detached the T-head from the shank. The damaged groyne was again reconstructed during 2002-2003. the groyne lost its function after 17 October, 2003 when it is almost totally washed away. The slope of scour hole in front of the groyne head during these high scour depths were steeper than 1H:2V. Even the gentlest observed slope of 1V:9H is steeper than the critical one of 1V:2H. As per satellite image of January 2006, the position of Sailabari groyne where it existed is now within the river, about 1 km from the west bank.

To protect the Ganges-Jamuna-Meghna and other river basin from severe erosion through the country different structures were constructed. Table 2.1 describes the features of the structures.

Table 2.1: Features of the structures

SI No	Name of Structure	Location	Material used in falling apron	Bank Slope (V:H)	Remarks
1	Bhuapur Hard Point	Bhuapur, Tangail	Boulders	1:3.5	No damage occurred.
2	Sirajganj Hard Point	Sirajganj	CC block	1:3.5	Falling apron do not work when rapid flow slides occur.
3	Sarikandi and Mathurapara Hard Points	Sirajganj	CC block	1:3.5	Adapting approach was deployed close to the scour hole.
4	Revetment Works at Debdanga and Titporal	Sirajganj	CC block	1:2	Adapting approach was required.
5	Ghutail Revetment Structure	Ghutail, Tangail	CC block	1:3	Damage due to incomplete upstream termination and under design of the falling apron.
6	Chandpur Town Protection	Chandpur	Boulders and CC block	1:1.5	Stable
7	Rajshahi Town Protection	Rajshahi	CC block	-	Unsustainable due to damage of wire net and consequent loss of bricks.
8	Bhola Town Protection and Protection in Tajumuddin	Bhola	Geo-bags	-	Stable
9	Jamuna-Meghna River Erosion Mitigation Project (JMREMP)	Pabna	Geo-bags	1:2	Survive without any significant change
10	Kalitola Groyne	Bogra	Geo-bags and CC blocks	1:1.35	Development of a sequence of flow slides.
11	Sailabari Groyne	Sirajganj	CC blocks	1:2	Fully damaged

Figure 2.1: Damaged revetment on the right bank of Padma river (d/s of Dholarmore, Tepakhola, Faridpur Sadar, Faridpur)

Figure 2.2: Bank caving of Padma river (at Hajiganj bazar, Charbhadrason upazila, Faridpur)

Figure 2.3: Bank erosion of Padma river (at Mawa site, Padma Multipurpose Bridge Project Area)

3 Model Design and Setup

3.1 Model Scale

Model scale is selected in such a way that it can reproduce all the hydraulic phenomena required for the study. The following salient points are normally considered for selection of model scale in the model study:

- The vertical scale should be selected in such a way that the measurement of depth and velocity can be carried out and the length scale should allow the model to be accommodated into the open air space of RRI.

- The discharge requirement should be within the RRI pumping capacity.

- The Reynolds number should be high enough to ensure rough turbulent flow in the model.

In the present study, the following scales are considered in the model.

Horizontal scale, L_r	=	1:30
Vertical scale, h_r	=	1:30
Velocity scale, v_r= sqrt (h_r)	=	1: 5.47
Discharge scale, $Q_r = h_r^{5/2}$	=	1:4930

3.2 Model Design

Model design is accomplished using Froud's model law and also considering model objectives and existing modelling facilities available at RRI.

<u>Froude's Model Law:</u>

$Fr_p = Fr_m$ i.e. $[v/(gh)^{0.5}]_{proto} = [v/(gh)^{0.5}]_{model}$

$\Rightarrow v_r = h_r^{0.5}$ (r=proto/model)

Where, v_r = velocity scale
h_r = vertical scale

The Froude condition should be fulfilled which holds when: $v_r = h_r^{0.5}$

The following criteria should be fulfilled by the Froud's model law:

- Sufficient water depth for precise measurement
- Turbulent flow confirmation in the model
- Ensuring sediment movement

<u>Sediment Transport Condition</u>

In the mobile bed model the following scale condition for sediment transport should be satisfied:
$v_m > v_{crm}$

Determination of Critical velocity (V_{cr}) and Sediment Transport

v_{cr} using Van Rijn Formula

$v_{cr} = 0.19(d_{50})^{0.1} \log(12h/ks)$ for $0.0001m \le d_{50} \le 0.0005m$
$v_{cr} = 8.50(d_{50})^{0.6} \log(12h/ks)$ for $0.0005m \le d_{50} \le 0.002m$

Here, ks = effective bed roughness of a flat bed (m) for sand and gravel material= $6*D_{50}$~$3*D_{90}$

v_{cr} using Shields Formula

$D_* = D_{50} [(\Delta g)/(\nu^2)]^{1/3}$
$\Theta_{cr} = 0.14D_*^{(-0.64)}$ for $4<D_*<=10$
$\Theta_{cr} = 0.24D_*^{(-1)}$ for $1<D_*<=4$
$v_{*cr} = \text{sqrt}(\Theta_{cr}\Delta g D_{50})$
$v_{cr} = v_{*cr}C/\text{sqrt}(g)$ or $\text{sqrt}(\Theta_{cr}C^2\Delta D_{50})$

Sediment Transport using Engelund-Hansen Formula

Sediment Transport by Engelund Hansen= $0.05v^5/(\Delta^2 \text{sqrt}(g) D_{50} C^3)$

Characteristics Design Parameters

An undistorted model is constructed considering horizontal and vertical scale of 1:30. The model is designed fulfilling the Froude's model law. The scour velocity in the model is such that sufficient sediment transport is ensured in the model and the model is expected to reach the dynamic equilibrium condition by running about 10-12 hours. The basic design parameters along with some derived parameters and the corresponding scales are shown in Table 3.1.

Table 3.1: Hydraulic and morphological parameters of the model

Parameters	Prototype	Model	Scale
Flume length, m		39.5	
Bottom width of the flume, m		4.3	
Velocity, m/s	2.5	0.456	5.47
Water depth, m	6	0.200	30
Water area, m^2		0.900	
Discharge, m^3/s	2025	0.411	4929.50
Scour discharge, m^3/s		0.492	
D_{50} of sand, m		0.000085	
Slope	0.00084	0.00084	1
Dimensionless particle diameter (D_*)		1.904	
Critical Shields parameter, Θ_{cr}		0.126	
Shields parameter, Θ		1.20	
Critical velocity by Shields, m/s		0.278	
Critical velocity by van Rijn, m/s		0.273	

Parameters	Prototype	Model	Scale
Froude number		0.326	
Shear velocity (v_*)		0.041	
Particle Reynolds number (Re_*)		0.933	
Sediment Transport by Enguland Hansen, m^3/s		0.0000203405	

3.3 Design of Launching Apron

(a) General calculations

Design data for the protection work is given below. The detail design has been done according to the standard design procedure (Volume-1, Standard Design Criteria, BWDB, 1993).

- Discharge for main channel: 2025 m^3/s
- Water depth: 6m
- Size of bed material, d_{50} : 0.085 mm
- Bottom width: 129m
- Average bed level: 4.5 mPWD
- Highest Flood Level, HFL: 10.5 mPWD
- Average velocity: 2.5 m/s

(b) Calculation for scour depth

Silt factor, f = $0.473\left(\frac{Q}{f}\right)^{\frac{1}{3}}$ = 0.513

As per Lacey's regime scour depth below HFL, R = $1.76\sqrt{d_{50}}\,, d_{50} is\ in\ mm$ = 7.47 m

(c) Determination of maximum scour depth below average bed level

Considering severe bend multiplying factor X = 1.75
Depth of scour = RX = 7.47*1.75 = 13.08 m (below HFL)
Maximum anticipated scouring bed level = (HFL-RX)
= (10.5-13.08) mPWD = -2.58 mPWD
Depth of anticipated scour, D = RX-y
= (13.08-6.0) m = 7.08 m (below avg. bed level)
Where, y = HFL – average bed level = (10.5-4.5) m = 6.0 m
Observed maximum scour depth = 12.0 m

(d) Determination of volume of launching apron (LA)

According to the Inglish formula, parameter, $T = 0.06Q^{1/3}$ m = 0.76 m
Thickness of slope pitching, t = 1.9T = 1.44 m
Considering a launching slope of 1:2, the volume of launching apron is calculated following the definition sketch
= sqrt(2^2+1^2)D*1.25t = 2.80tD = 2.8*1.44*12=48.38 m^3 = say 48 m^3

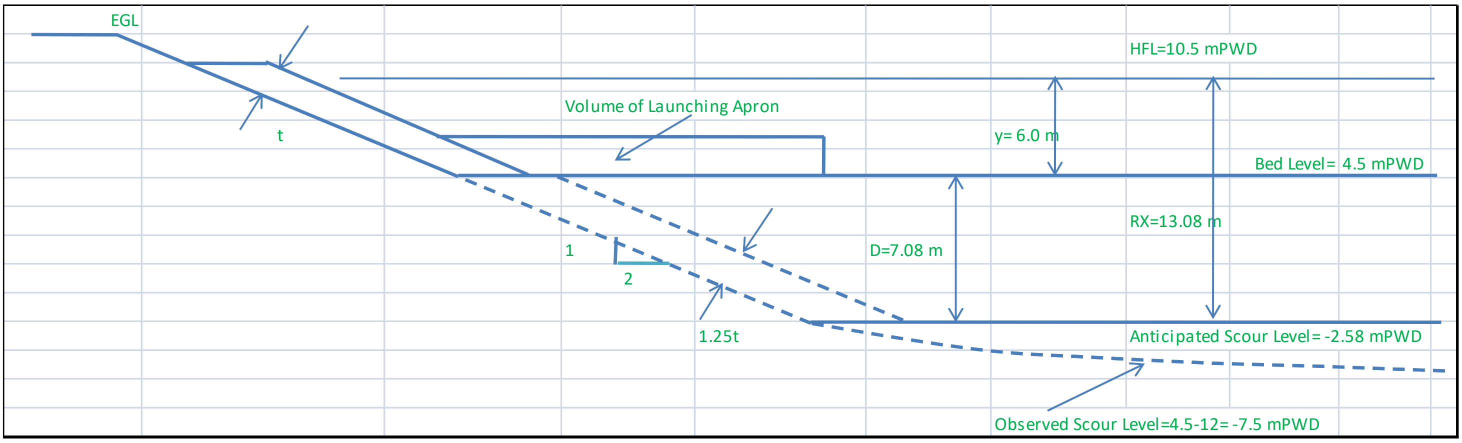

Figure 3.1: Definition sketch of design of bank protection work

(e) Determination of length and thickness of launching apron (LA)

The length of launching apron has been determined as per theory (L=1.5D). The thickness of launching apron =48/18 m=2.67 m

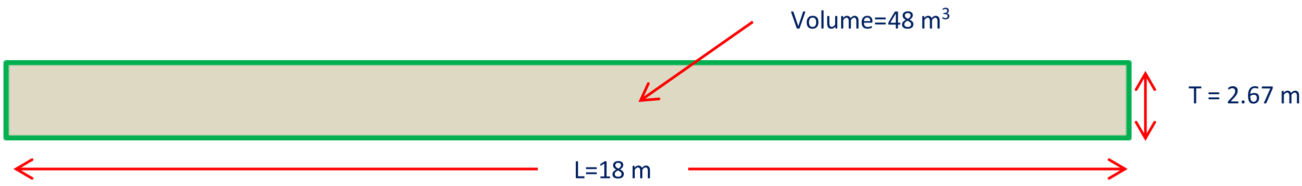

Figure 3.2: Thickness and length of launching apron

3.4 Model Set-up

The hydraulic scale model is set-up using the existing facilities of RRI. A closed shed of RRI having dimension of 84.25 m x 24.4 m has been used for setting up the model. The area reproduced in the model is about 1.20 km (channel length) and about 0.18 km (channel width). The layout of the model is shown in Figure 3.1. The model set-up includes model bed preparation, water circulation system, inflow weir, construction of stilling pond, outflow condition, Installment of point gauges and measurement of water level & velocity in the model are briefly described in the following section.

3.4.1 Model Bed Preparation

The generalized plain bathymetry is used in the bed for model testing. The model bed consists of fine sand (D_{50}=0.085 mm) in the movable portion and some portion of the bed is fixed by cement-plastering at the inflow and outflow section of the model. The prototype cross-sectional data of surveyed sections are converted to model to prepare the model bed.

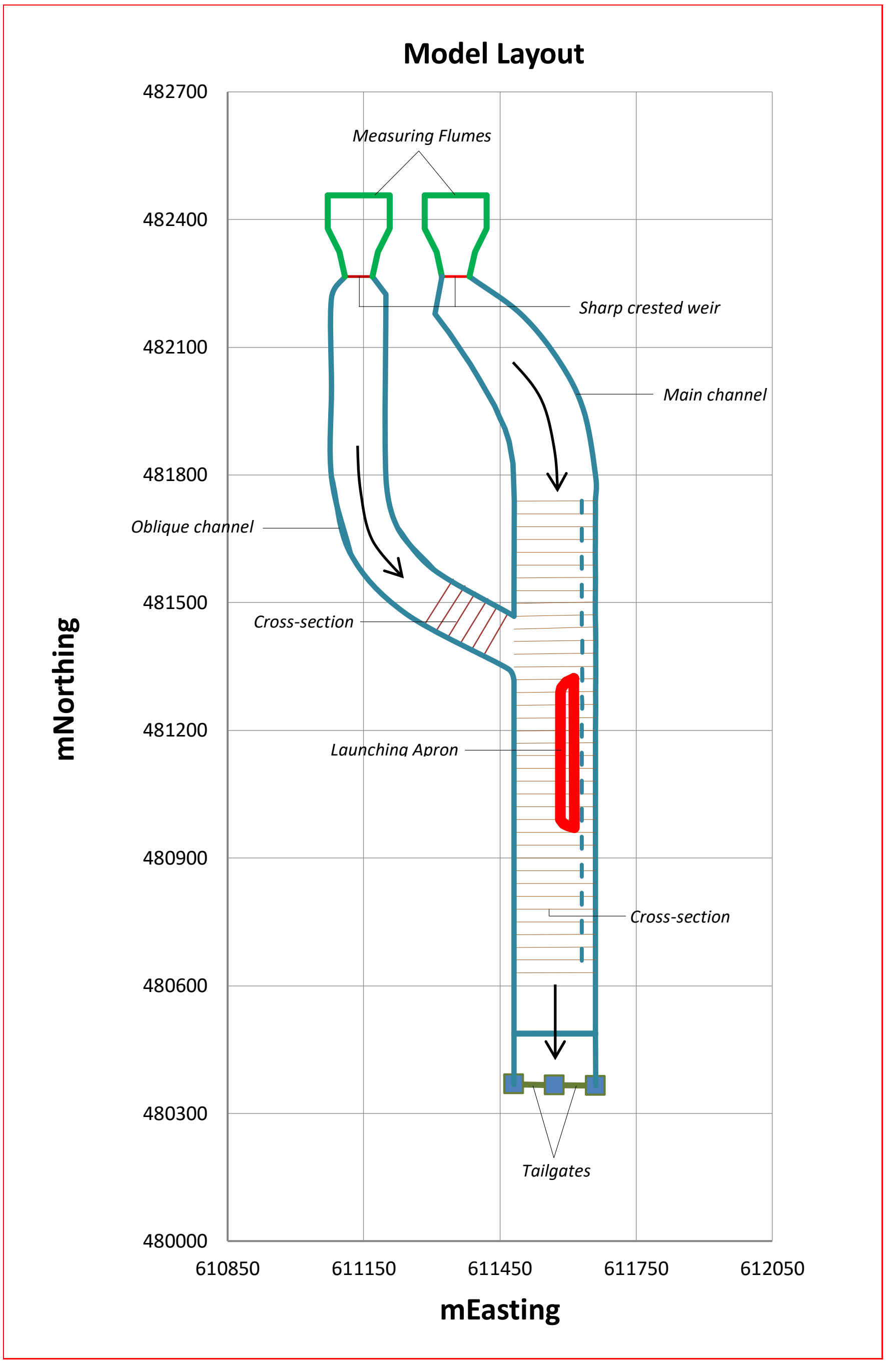

Figure 3.3: Layout of the model

3.4.2 Water Circulation System

Recirculation Tank

The channel network of the model area is a gravitational type. The available head difference between the supply and drainage sump is about 1.3 m. In the water circulation system, the supply sump is connected with the pump having capacity of 0.750 m^3/s. The supply sump and the measuring flume are interconnected by gate valves. The water enters into the model through these gate valves, flows over rectangular sharp crested weir and falls into the stilling pond where energy is dissipated for maintaining uniform flow at the upstream of the model boundary. At the downstream of the model area, a number of tailgates are provided to allow water for draining into the drainage sump. The drainage sump is linked with the suction reservoir of pump house.

3.4.3 Inflow Weir

The discharge is determined from the measured water level upstream of the sharp crested weir. The model discharge is measured with the sharp crested weir (Lengt=1.8 m and height =0.60 m) installed at the measuring flume, using Rehbock's formula as given below:

$$Q=(0.403 + 0.053h_w/p)(2g)^{0.5}b\,[(h_w + u_w^2/2g)^{1.5} - (u_w^2/2g)^{1.5}]$$

Where, Q	=	discharge in m^3/s
h_w	=	head over the weir in m
p	=	height of the crest of the weir in m
g	=	acceleration due to gravity in m/s^2
b	=	length of the weir in m
u_w	=	velocity of approach in m/s

3.4.4 Construction of Stilling Pond

At the upstream end of the model, a stilling pond is constructed in order to facilitate energy dissipation so that steady uniform flow is ensured.

3.4.5 Outflow Condition

In order to control the water level in the model two numbers of tailgate are installed at the end of the model. In all tests, desired water level is maintained by operating the tailgates.

3.4.6 Installment of Point Gauges

Two types of gauges are installed in the model (i) Discharge gauge (one no.) and (ii) Point gauge (three nos.). The function of discharge gauge is to measure discharge over the sharp crested weir using Rebock formula. The function of point gauge is to measure water level and water surface slope in the model.

3.4.7 Measurement of Water Level & Velocity

The water level for each of the tests is obtained from the point-gauge readings. The purpose of these gauges is to measure water surface level. Three numbers of point-gauge are located inside the model bed.

The flow velocities are measured with 3-D current meter. The average velocity is obtained by taking the velocity at 0.6 times the depth from the water surface. The surface velocity at shallow depths is measured using surface-floats and this velocity is multiplied by a factor 0.85 to obtain the average flow velocity.

3.5 Channel Section

Two types of channel are used for main channel and shoot channel. For main channel, one end is trapezoidal at left bank and the other end is the vertical. The shoot channel is the rectangular type. The channel sections for main channel and shoot channel are shown in Figure 3.4 & 3.5 respectively.

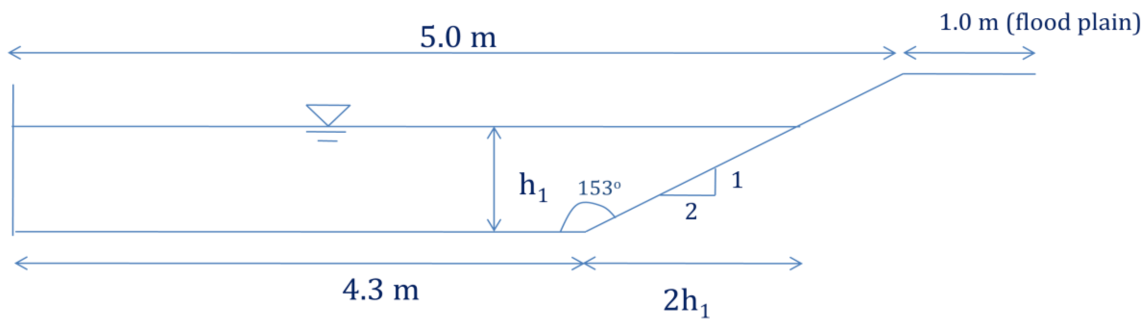

Figure 3.4: Section for main channel

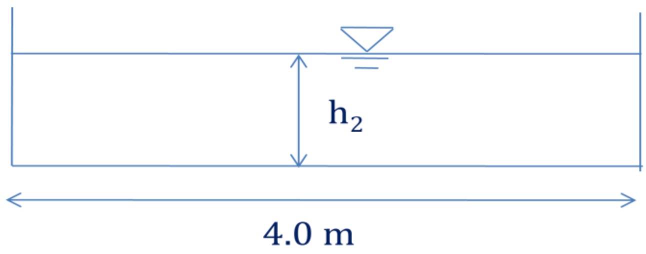

Figure 3.5: Section for shoot channel

4 TEST SCENARIOS

4.1 General

The calibration test plus 25 application test runs with structural intervention along left bankline have been conducted in the model. Test T0 contributed to the calibration of the model. The application tests T1 through T22 are carried out with a view to observe the performance of the bank protection structure (revetment) to prevent river bank erosion. Each application test was run with both Froude's discharge to determine flow velocity, flow lines etc and scour discharge to determine the scour depth. Scour discharge is run until equilibrium bed level has been reached in the model. The test scenarios of the model are described in Table 4.1.

Table 4.1 Test scenarios of the model

Test No.	Test	Test Scenarios	Angle between shoot channel & main channel	Discharge Condition	Test Objectives
1	T0	Calibration test. Plain bathymetry has been used	No oblique flow condition	Discharge in the main channel only. Q_{main}=2025m^3/s (q=450m^2/s)	Calibration of the model
2	T1	Test with geo-bags as launching materials (LM)			To determine the effectiveness of LA & design parameters
3	T2	Test with CC blocks as LM			To determine the effectiveness of LA & design parameters
4	T3	Test with stone chips as LM			To determine the effectiveness of LA & design parameters
5	T4.1	Test with stone chips as LM	60°	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m^3/s (q=250m^2/s) & Q_{shoot}=900m^3/s (q=225m^2/s)	To determine the effectiveness of LA & design parameters
6	T4.2			Q_{shoot}/Q_{main}= 1.00 Q_{main}=1012.5m^3/s (q=225m^2/s) & Q_{shoot}=1012.5m^3/s (q=253m^2/s)	To determine the effectiveness of LA & design parameters
7	T5.1	Test with geo-bags as LM	60°	Q_{shoot}/Q_{main}= 0.80	To determine the effectiveness of LA & design parameters
8	T5.2			Q_{shoot}/Q_{main}= 1.00	To determine the effectiveness of LA & design parameters
9	T6.1	Test with CC blocks as LM	60°	Q_{shoot}/Q_{main}= 0.80	To determine the effectiveness of LA & design parameters
10	T6.2			Q_{shoot}/Q_{main}= 1.00	To determine the effectiveness of LA & design parameters

Test No.	Test	Test Scenarios	Angle between shoot channel & main channel	Discharge Condition	Test Objectives
11	T7	Test with CC blocks as LM. The shoot channel feeds total discharge to the main channel.	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
12	T8	Test with stone chips as LM. The shoot channel feeds total discharge to the main channel.	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
13	T9	Test with geo-bags as LM. The shoot channel feeds total discharge to the main channel.	60°	Q_{shoot}=2025m^3/s = 411 l/s (model) (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
14	T10	Test with 3 spurs: Spur S1 (solid), Spur S2 (CC blocks) & Spur S3 (geo-bags)	60°	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m^3/s (q=250 m^2/s) & Qs_{hoot}=900m^3/s (q=225 m^2/s)	To observe the scour around spur S1 and effectiveness of LA around spurs S2 & S3
15	T11	Test as per design proposed by BWDB (LA consists of 50%CC block & 50%geo-bag and length 30m)	60°	Q_{shoot}/Q_{main}= 0.80	To determine the effectiveness of LA & design parameters
16	T12	Same as test T11 but the shoot channel feeds total discharge to the main channel	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
17	T13	Same as test T12 but length of LA=25m	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
18	T14	Same as test T13 but length of LA=35m	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
19	T15	Same as test T14 but LA consists of 40%CC block & 60%geo-bag and LA length=35m	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
20	T16	Same as test T14 but LA is shifted u/s by 60m at CS26-CS14.	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
21	T17	Test as per design proposed by BWDB. But CC block portion of LA consists of 45cm cube 50% and 35cm cube 50%. LA placed at CS26-CS14.	60°	Q_{shoot}=2025m^3/s (q=506m^2/s) Fully oblique flow	To determine the effectiveness of LA & design parameters

Test No.	Test	Test Scenarios	Angle between shoot channel & main channel	Discharge Condition	Test Objectives
22	T18	Same as test T17 but CC block portion of LA consists of 45cm cube 40% and 35cm cube 60%.	60^o	Q_{shoot}=2025m³/s (q=506m²/s) Fully oblique flow	To determine the effectiveness of LA & design parameters
23	T19	Test with 2 spurs S1 & S2 having shank length=30m and LA length=30m. The LA of S1 has two layers. Top layer consists of 45cm cube 40% & 35cm cube 60%. Bottom layer consists of 250kg geo-bag 50% & 175kg geo-bag 50%. The LA of spur S2 consists of 125kg geo-bag.	60^o	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m³/s (q=250m²/s) & Q_{shoot}=900m³/s (q=225m²/s)	To determine the effectiveness of LA & design parameters
24	T20	The u/s part of LA of spurs S1 & S2 is same as test T19.The d/s part of LA of spurs S1 & S2 consists of stone-chips only.	60^o	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m³/s (q=250m²/s) & Q_{shoot}=900m³/s (q=225m²/s)	To determine the effectiveness of LA & design parameters
25	T21	The u/s part of LA of spurs S1 & S2 is same as test T20. The d/s part of LA of spurs S1 & S2 consists of 60cm cube 60% and 45 cm cube 40%.	60^o	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m³/s (q=250m²/s) & Q_{shoot}=900m³/s (q=225m²/s)	To determine the effectiveness of LA & design parameters
26	T22	The u/s part of LA of spurs S1 & S2 is same as test T21.The d/s part of LA of spurs S1 & S2 consists of 60cm cube 60% & 45cm cube 40% at the top layer and 500kg geo-bags at the bottom layer.	60^o	Q_{shoot}/Q_{main}= 0.80 Q_{main}=1125m³/s (q=250m²/s) & Q_{shoot}=900m³/s (q=225m²/s)	To determine the effectiveness of LA & design parameters

5 Test Runs

5.1 Calibration Test (T0)

Test T0 is conducted to calibrate the model i.e., to simulate mainly velocity, discharge & water level in the model. An arbitrary plain bathymetry is reproduced in the model. The layout of the model for test T0 is shown in Figure 5.1.1.

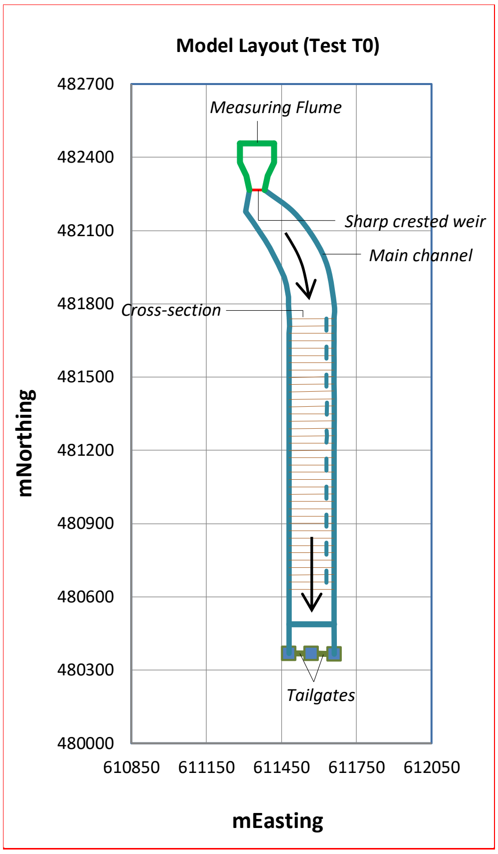

Figure 5.1.1: Layout of the model for test T0

Two things are important for calibration.

- Flow distribution
- Water level

In this test, the average velocity & scour depth were measured along the cross-sections and flow field was recorded by tracking floats from u/s to d/s as shown in Figure 5.1.3. The discharge 2025 m^3/s passes through the main channel only. Here, bed and bank both are movable.

5.1.1 Flow Distribution at Upstream

The velocity distribution at the upstream section is simulated at the upstream boundary of the model. The velocity distribution at the calibration section (CS-33) is measured and compared with the prototype value. A comparison between measured and prototype velocity is shown in Figure

5.1.2. From this figure it is evident that the measured values found in the model are very close to the prototype value.

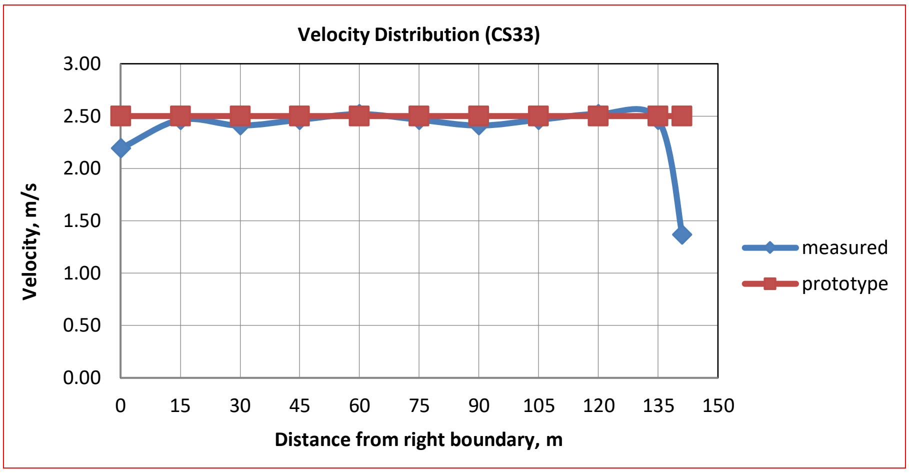

Figure 5.1.2 Comparison between prototype and model velocity at the calibration section in test T0

5.1.2 Water Level at Downstream

The water level of 10.33mPWD is maintained at the downstream of the model at CS1.

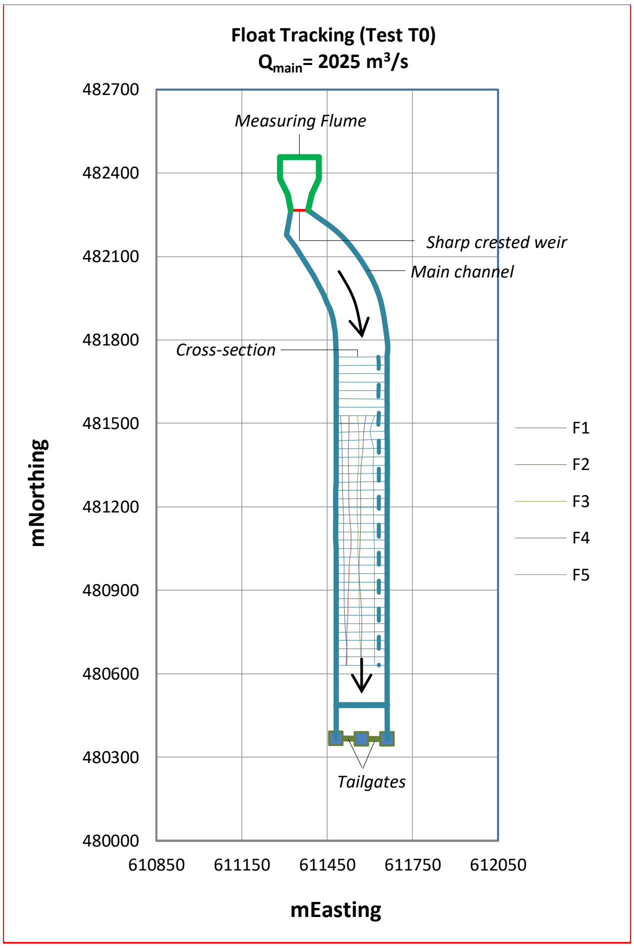

Figure 5.1.3: Flow field recorded by tracking floats from u/s to d/s in test T0

From the plot of flowlines, it can be seen that the flowlines are more or less parallel to the bankline.

Table 5.1.1: Flow velocity in test T0

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	2.14	2.41	2.25	2.13	2.09	2.06	2.28	2.21	2.30	2.10
2	CS31	2.23	2.30	2.30	2.28	2.23	2.04	2.28	2.21	2.1	2.00
3	CS30	2.02	2.01	1.97	1.99	2.07	2.09	2.13	2.06	2.24	2.23
4	CS29	1.84	1.94	1.87	1.82	2.04	2.00	2.05	2.22	2.24	2.12
5	CS28	2.18	1.95	2.06	1.95	1.82	1.97	2.12	2.00	2.28	2.14
6	CS27	2.15	2.23	2.07	2.13	2.02	1.76	2.16	2.12	2.19	2.05
7	CS26	2.35	2.02	1.93	2.10	2.10	1.98	2.10	2.02	2.13	2.07
8	CS25	2.33	2.21	2.07	2.17	2.13	2.06	2.10	2.23	1.60	2.10
9	CS24	2.15	2.11	2.11	2.18	1.97	1.78	2.32	2.24	1.25	2.09
10	CS23	2.42	2.33	2.22	2.21	2.02	1.98	2.50	2.45	1.79	2.14
11	CS22	2.17	2.30	2.46	2.17	2.08	1.80	2.20	2.37	2.10	1.32
12	CS21	2.32	2.35	2.47	2.36	2.39	2.13	2.41	2.41	1.63	1.74
13	CS20	2.23	2.33	2.11	2.27	1.98	1.86	2.11	2.40	1.32	1.41
14	CS19	2.02	2.40	2.14	2.27	2.18	1.94	2.25	2.27	1.11	1.44
15	CS18	2.14	2.20	2.08	2.09	2.36	1.90	2.20	2.03	1.32	1.28
16	CS17	2.09	2.30	2.07	2.21	1.75	2.13	2.46	2.05	1.37	2.02
17	CS16	2.32	2.35	2.14	2.27	1.82	2.03	2.18	2.25	0.93	1.40
18	CS15	2.01	2.43	2.34	2.36	1.96	1.94	2.22	2.17	1.45	2.01
19	CS14	2.14	2.33	2.24	2.44	1.49	1.85	2.30	2.45	1.20	2.22
20	CS13	2.00	2.25	2.23	2.37	1.89	1.93	2.31	2.14	1.66	1.43
21	CS12	2.10	2.35	2.27	2.19	1.79	1.71	2.30	2.09	1.79	1.62
22	CS11	2.02	2.02	2.41	2.26	2.23	1.93	1.76	2.09	2.15	1.64
23	CS10	2.15	2.25	2.24	2.14	1.78	1.83	2.09	1.86	1.95	2.21
24	C9	1.67	2.19	1.98	2.23	1.94	1.89	2.10	2.13	2.17	2.00
25	CS8	2.00	2.26	2.38	2.15	1.94	1.74	2.25	1.97	1.97	1.56
26	CS7	2.02	2.20	2.16	2.31	2.00	1.88	2.14	1.89	1.89	2.03
27	CS6	2.09	2.19	2.19	2.20	1.90	1.76	2.16	2.08	2.08	2.08
28	CS5	2.07	2.28	2.17	2.42	1.68	1.80	2.11	2.29	2.29	2.00
29	CS4	2.11	2.19	2.34	2.37	1.94	1.82	2.09	2.10	2.10	2.15
30	CS3	2.01	2.47	1.98	2.09	1.49	1.79	2.12	2.31	2.31	1.55
31	CS2	1.98	2.16	2.07	2.06	1.70	1.93	2.17	2.18	2.18	2.16
32	CS1	1.93	2.26	2.18	2.14	1.87	1.85	2.27	2.33	2.33	2.25

From the above table, it can be seen that the maximum velocity 2.5 m/s which is 90m away from the right bank at CS24.

Table 5.1.2: Scour/deposition in test T0

Sl No.	CS No.	Scour /deposition (m)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45	60.0	75	90.0	105.0	120.0	127.5
1	CS30	-1.6	-2.7	-2.4	-1.0	-0.9	-1.6	-11.6	-0.5	-0.6	-0.7
2	CS29	-1.8	-3.8	-2.1	-2.3	-1.2	-1.4	-7.8	-0.4	-0.5	-0.3
3	CS28	-1.3	-2.6	-2.4	-3.2	-1.5	-0.1	-4.8	-8.2	-0.3	-0.5
4	CS27	-0.9	-2.0	-1.6	-2.5	-1.4	-0.2	-3.4	-8.4	-0.5	-0.6
5	CS26	-0.6	-1.8	-1.3	-1.7	-1.1	-0.5	-9.9	-8.9	-0.6	-0.4

Sl No.	CS No.	Scour /deposition (m)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45	60.0	75	90.0	105.0	120.0	127.5
6	CS25	-0.2	-1.0	-1.3	-1.2	-1.4	-0.9	-8.0	-9.0	0	-0.9
7	CS24	0.1	0.0	-0.9	-0.2	-0.5	-0.4	-5.5	-9.7	-8.6	-0.4
8	CS23	0.2	0.1	-0.3	-0.5	-0.9	-0.3	-3.2	-9.6	-9.1	-0.3
9	CS22	0.3	-0.2	-0.1	-0.5	-0.6	-0.4	-9.0	-10.2	-8.8	-0.4
10	CS21	4.9	4.1	4.5	4.3	4.1	4.0	4.5	4.9	5.1	4.0
11	CS20	0.8	0.4	-0.1	-0.1	0.1	0.4	-4.8	-10.4	-10.1	-9.3
12	CS19	0.6	0.2	0.7	0.6	0.2	0.4	-2.9	-10.5	-10.0	-9.9
13	CS18	0.3	1.4	1.6	1.2	1.7	1.4	-3.6	-10.5	-10.0	-9.8
14	CS17	-0.9	0.1	0.4	1.3	0.5	-0.3	-2.9	-10.1	-9.8	-9.6
15	CS16	-1.0	0.0	0.7	0.8	1.1	0.9	-2.9	-10.4	-11.4	-9.8
16	CS15	-0.3	0.2	0.8	1.5	1.2	0.8	-3.3	-10.4	-10.2	-10.6
17	CS14	-0.6	0.1	-0.3	1.2	1.6	0.9	-2.4	-9.5	-9.4	-10.2
18	CS13	-0.5	0.3	0.0	1.1	1.4	0.4	-3.3	-10.2	-10.7	-1.3
19	CS12	-0.5	-0.1	0.8	0.6	1.1	0.6	-2.9	-10.6	-10.6	-10.8
20	CS11	0	0.6	0.9	1.1	1.5	1.4	-2.5	-9.4	-9.8	-10.5
21	CS10	0.4	0.4	0.4	0.7	0.9	1.0	-3.8	-10.7	-10.9	-10.2
22	C9	0.0	0.3	0.3	0.8	0.8	0.3	-4.0	-10.7	-10.9	-10.1
23	CS8	0.0	0.4	0.3	0.8	0.8	0.7	-3.3	-10.3	-10.7	-10.6
24	CS7	0.4	0.0	0.0	0.1	0.1	0.5	-3.4	-10.7	-10.8	-0.6
25	CS6	0.6	0.1	0.5	0.7	1.0	0.2	-2.4	-10.4	-10.7	-10.1
26	CS5	-1.1	-1.0	-1.1	-0.9	-0.7	-0.8	-4.2	-11.4	-11.7	-10.7
27	CS4	0.9	0.5	0.2	1.0	0.8	0.6	-3.7	-10.6	-10.9	-10.8
28	CS3	0.6	0.4	0.8	0.5	0.4	0.2	-3.3	-10.5	-11.3	-10.8
29	CS2	0.7	0.2	0.2	1.0	0.5	0.5	-3.4	-11.0	-11.3	-10.1
30	CS1	0.7	0.6	0.5	0.6	0.8	0.3	-3.3	-10.9	-11.1	-5.0

NB: negative values indicates scour and positive values indicates deposition.

From the above table, it can be seen that the maximum scour 11.7m which is 120m away from the right bank at CS5.

Figure 5.1.4: Calibration test (T0)

5.1.3 Findings

Scour occurred along the left bank as the bank is moveable in this test. The maximum scour depth measured as 11.7 m which is 120 m away from the right boundary (near the end of the slope) at CS5. The maximum velocity measured as 2.5 m/s which is 90m away from the right boundary at CS24.

5.2 Test T1

Test T1 is conducted with geo-bags as launching material. This is the first application test. The area to be protected is around 360 m. Here, the total volume of launching apron 48 m^3/m. The percentage of geo-bag: 100% (125 kg). The length of the launching material is 18 m considering maximum scour depth 12 m for revetment. The thickness of the launching apron is 2.67 m as shown in section 3.4 of this report. Here the discharge 2025 m^3/s passes through the main channel only. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of geo-bags was tested in this run. Here the slope pitching of revetment was kept fixed but the bed was movable. The layout of the model for this test is shown in Figure 5.2.1.

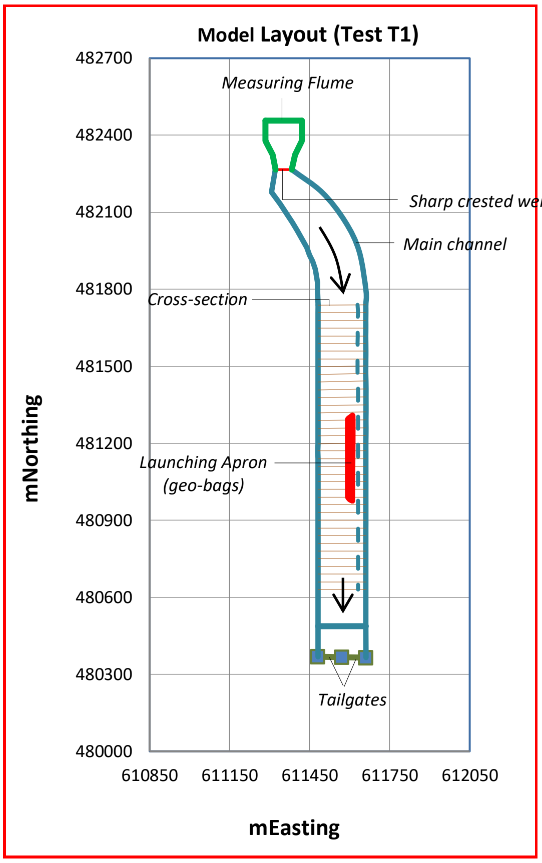

Figure 5.2.1: Layout of the model for test T1

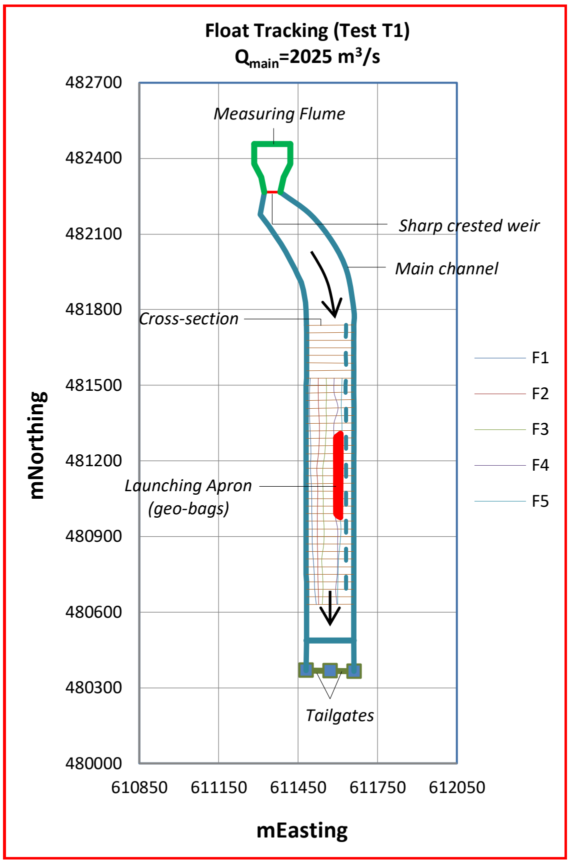

Figure 5.2.2: Flow field recorded by tracking floats from u/s to d/s in test T1

Table 5.2.1: Flow velocity in test T1

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	2.14	2.41	2.25	2.13	2.09	2.06	2.28	2.21	2.30	2.00
2	CS31	2.23	2.30	2.30	2.28	2.23	2.04	2.28	2.21	2.00	2.10
3	CS30	2.02	2.01	1.97	1.99	2.07	2.09	2.13	2.06	2.24	2.23
4	CS29	1.84	1.94	1.87	1.82	2.04	2.00	2.05	2.22	2.24	1.12
5	CS28	2.18	1.95	2.06	1.95	1.82	1.97	2.12	2.00	2.28	1.14
6	CS27	2.15	2.23	2.07	2.13	2.02	1.76	2.16	2.12	2.19	1.05
7	CS26	2.35	2.02	1.93	2.10	2.10	1.98	2.10	2.02	2.13	1.07
8	CS25	2.33	2.21	2.07	2.17	2.13	2.06	2.10	2.23	1.60	1.10
9	CS24	2.15	2.11	2.11	2.18	1.97	1.78	2.32	2.24	1.25	1.09
10	CS23	2.42	2.33	2.22	2.21	2.02	1.98	2.50	2.45	1.79	2.14
11	CS22	2.17	2.30	2.46	2.17	2.08	1.80	2.20	2.37	2.10	1.32
12	CS21	2.32	2.35	2.47	2.36	2.39	2.13	2.41	2.41	1.63	1.74
13	CS20	2.23	2.33	2.11	2.27	1.98	1.86	2.11	2.40	1.32	1.41
14	CS19	2.02	2.40	2.14	2.27	2.18	1.94	2.25	2.27	1.11	1.44
15	CS18	2.14	2.20	2.08	2.09	2.36	1.90	2.20	2.03	1.32	1.28
16	CS17	2.09	2.30	2.07	2.21	1.75	2.13	2.46	2.05	1.37	1.02
17	CS16	2.32	2.35	2.14	2.27	1.82	2.03	2.18	2.25	0.93	1.40
18	CS15	2.01	2.43	2.34	2.36	1.96	1.94	2.22	2.17	1.45	1.01
19	CS14	2.14	2.33	2.24	2.44	1.49	1.85	2.30	2.45	1.20	1.22
20	CS13	2.00	2.25	2.23	2.37	1.89	1.93	2.31	2.14	1.66	1.43

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
21	CS12	2.10	2.35	2.27	2.19	1.79	1.71	2.30	2.09	1.79	1.62
22	CS11	2.02	2.02	2.41	2.26	2.23	1.93	1.76	2.09	2.15	1.64
23	CS10	2.15	2.25	2.24	2.14	1.78	1.83	2.09	1.86	1.95	1.21
24	C9	1.67	2.19	1.98	2.23	1.94	1.89	2.10	2.13	2.17	2.00
25	CS8	2.00	2.26	2.38	2.15	1.94	1.74	2.25	1.97	1.97	1.56
26	CS7	2.02	2.20	2.16	2.31	2.00	1.88	2.14	1.89	1.89	1.03
27	CS6	2.09	2.19	2.19	2.20	1.90	1.76	2.16	2.08	2.08	1.08
28	CS5	2.07	2.28	2.17	2.42	1.68	1.80	2.11	2.29	2.29	2.00
29	CS4	2.11	2.19	2.34	2.37	1.94	1.82	2.09	2.10	2.10	1.15
30	CS3	2.01	2.47	1.98	2.09	1.49	1.79	2.12	2.31	2.31	1.55
31	CS2	1.98	2.16	2.07	2.06	1.70	1.93	2.17	2.18	2.18	1.16
32	CS1	1.93	2.26	2.18	2.14	1.87	1.85	2.27	2.33	2.33	1.25

Table 5.2.2: Flow velocity in test T1 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	Start of LA	2.10
2	Between start of LA & CS23	2.18
3	CS23	2.48
4	CS22	2.69
5	CS21	2.81
6	CS20	2.95
7	CS19	2.66
8	CS18	**3.09**
9	CS17	2.91
10	CS16	2.87
11	CS15	3.09
12	CS14	2.83
13	CS13	2.73
14	Between CS13 & end of LA	2.55
15	End of LA	2.27

From the above table, it can be seen that the maximum velocity 3.09 m/s at CS18 along the end of the launching apron.

Table 5.2.3: Scour in test T1 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-1.20
2	CS22	-0.81
3	CS21	-0.93
4	CS20	-1.32
5	CS19	-1.11
6	CS18	-1.20
7	CS17	-1.14
8	CS16	-0.87
9	CS15	-1.26
10	CS14	-1.44
11	CS13	-0.87

From the above table, it can be seen that the maximum scour 1.44 m at CS14 along the end of the launching apron.

Figure 5.2.3: Launching pattern after test run (T1)

5.2.1 Findings

Along the end of the launching apron, no significant scour as the flow is parallel to the bankline (no oblique flow). Maximum velocity along the end of launching apron is found around 3.09 m/s (CS18). Maximum scour along the end of launching apron is found around 1.44m (CS14). Due to parallel flow, no significant launching of geo-bags occurs along the end of the launching apron.

5.3 Test T2

Test T2 is same as test T1 but in this case, CC blocks were introduced as launching material instead of geo-bags. The percentage of CC-block: 60% (50cm cube) and 40% (40cm cube). Here the discharge 2025 m^3/s passes through the main channel only as in test T1. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of CC blocks was tested here. The layout of the model for test T0 is shown in Figure 5.3.1.

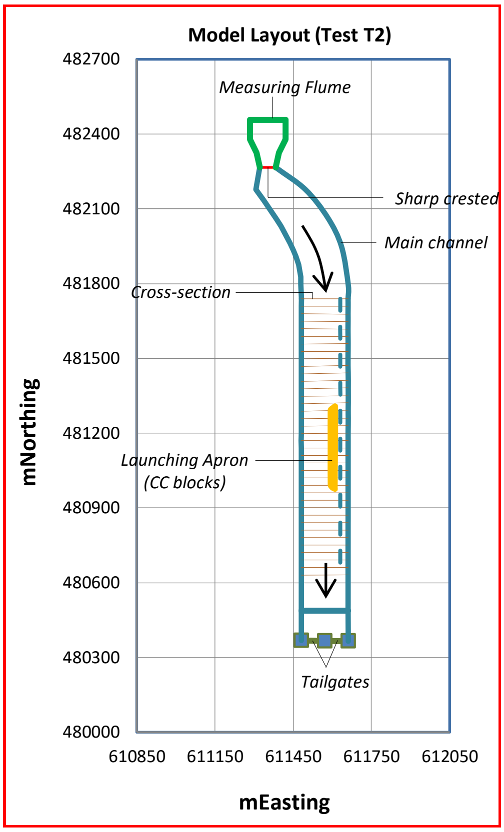

Figure 5.3.1: Layout of the model for test T2

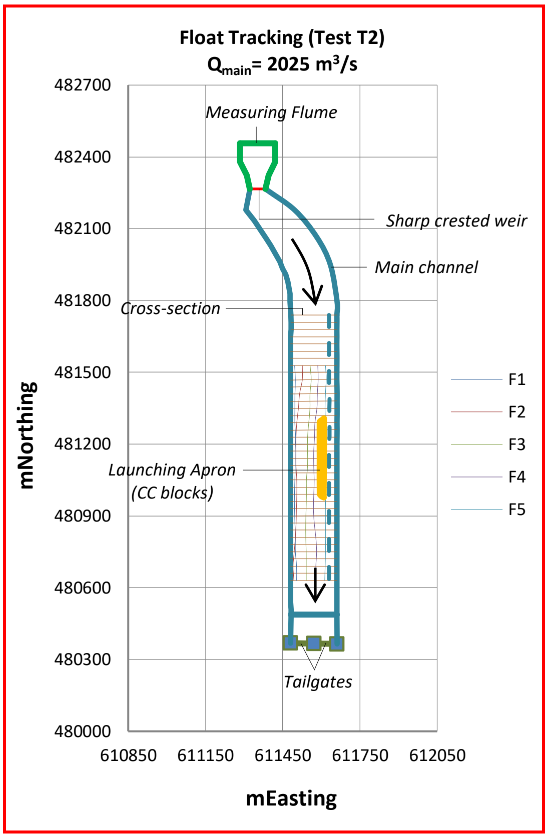

Figure 5.3.2: Flow field recorded by tracking floats from u/s to d/s in test T2

Table 5.3.1: Flow velocity in test T2

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	2.19	2.36	2.32	2.24	2.21	2.39	2.43	2.33	2.40	2.03
2	CS31	2.12	2.26	2.22	2.18	1.73	2.25	2.39	2.66	2.52	1.10
3	CS30	1.69	1.32	1.76	1.27	1.22	1.90	1.61	2.28	1.66	1.05
4	CS29	1.44	1.71	1.83	1.46	1.52	1.85	2.25	2.02	1.94	1.15
5	CS28	1.72	1.64	1.69	1.80	1.63	1.56	1.42	2.10	1.91	2.08
6	CS27	1.66	1.78	1.74	1.52	1.53	2.00	2.07	2.04	2.12	1.79
7	CS26	1.79	1.89	1.80	1.85	1.88	1.92	1.87	2.17	2.10	1.85
8	CS25	1.96	1.79	1.96	1.73	1.64	2.08	1.89	2.01	2.14	1.73
9	CS24	1.83	1.85	1.88	2.07	1.96	1.99	2.09	2.14	1.70	1.93
10	CS23	1.73	1.73	1.71	1.83	1.74	2.03	2.23	2.23	1.80	1.87
11	CS22	1.69	1.93	1.94	2.17	1.82	1.90	2.03	2.22	1.89	1.90
12	CS21	1.86	1.87	1.83	1.94	1.85	1.85	2.09	2.22	1.46	2.01
13	CS20	1.85	1.90	2.01	2.00	1.70	1.90	2.12	2.09	1.78	1.97
14	CS19	1.96	2.01	1.91	1.96	1.80	2.04	2.15	2.16	1.61	2.09
15	CS18	1.90	1.97	1.92	2.10	1.89	2.10	2.08	2.19	1.90	2.06
16	CS17	1.99	2.09	2.13	1.94	1.46	1.92	2.09	2.10	1.61	1.81
17	CS16	1.92	2.06	2.10	1.99	1.78	1.96	2.07	2.08	1.81	1.87
18	CS15	1.53	1.81	1.98	2.01	1.61	1.79	1.89	2.21	1.78	2.01
19	CS14	1.91	1.87	2.04	1.86	1.90	2.05	2.00	1.48	1.91	1.94
20	CS13	1.85	2.01	1.71	2.04	1.61	1.98	2.16	2.36	1.63	1.99
21	CS12	1.96	2.00	2.19	2.17	1.81	1.75	1.96	1.96	1.28	2.01
22	CS11	1.87	1.94	1.82	2.10	1.78	1.91	2.10	1.84	1.61	1.45
23	CS10	1.88	2.04	1.92	2.07	1.39	1.63	2.15	1.88	1.71	0.25
24	C9	1.83	1.90	2.11	2.10	1.45	1.63	2.13	1.72	1.50	0.07
25	CS8	1.86	2.02	1.99	2.16	2.08	1.82	1.70	1.61	2.07	1.66
26	CS7	1.66	1.98	1.83	2.13	1.55	1.70	2.00	2.02	1.79	0.09
27	CS6	1.98	1.96	2.13	2.08	1.20	1.72	2.07	1.86	1.95	0.16
28	CS5	1.94	2.13	2.16	1.97	1.36	1.50	2.02	1.97	1.84	2.0
29	CS4	1.83	1.97	1.99	1.87	1.38	1.56	1.91	1.81	2.07	1.94
30	CS3	1.89	1.93	1.93	2.09	1.35	1.66	1.93	1.99	2.06	2.08
31	CS2	1.89	1.78	2.04	1.97	1.35	1.59	1.82	1.56	2.07	1.59
32	CS1	1.80	1.97	2.31	1.98	1.83	2.13	1.55	1.50	1.60	1.70

Table 5.3.2: Flow velocity in test T2 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	2.29
2	Between CS24 & CS23	2.22
3	CS23	2.32
4	CS22	2.24
5	CS21	2.17
6	CS20	2.06
7	CS19	2.01
8	CS18	2.21
9	CS17	2.02

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
10	CS16	1.95
11	CS15	1.88
12	CS14	2.08
13	CS13	2.11
14	Between CS13 & CS12	1.88
15	End of LA (CS12)	1.91

From the above table, it can be seen that the maximum velocity 2.32 m/s at CS23 along the end of the launching apron.

Table 5.3.3: Scour in test T2 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-1.86
2	CS22	-1.35
3	CS21	-1.71
4	CS20	-1.35
5	CS19	-1.71
6	CS18	-1.68
7	CS17	-1.50
8	CS16	-1.95
9	CS15	-1.80
10	CS14	-1.20
11	CS13	-1.32

From the above table, it can be seen that the maximum scour 1.95 m at CS16 along the end of the launching apron.

Figure 5.3.3: Launching pattern after test run (T2)

5.3.1 Findings

No significant scour as the flow is parallel to the bankline (no oblique flow) along the end of the launching apron. Maximum velocity along the end of launching apron is found around 2.32 m/s (CS23). Maximum scour along the end of launching apron is found around 1.95 m (CS16). Also there is no significant launching of CC block occurs along the end of the launching apron due to parallel flow.

5.4 Test T3

Test T3 is same as test T2 with the introduction of stone chips instead of CC blocks as launching material. Stone chips passing through 3/4" (1.905 cm) sieve and retained on 1/2" (1.27 cm) sieve were used after scaled down in this research. The discharge passes 2025 m^3/s through the main channel only. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of stone chips was tested here. The layout of the model for test T0 is shown in Figure 5.4.1.

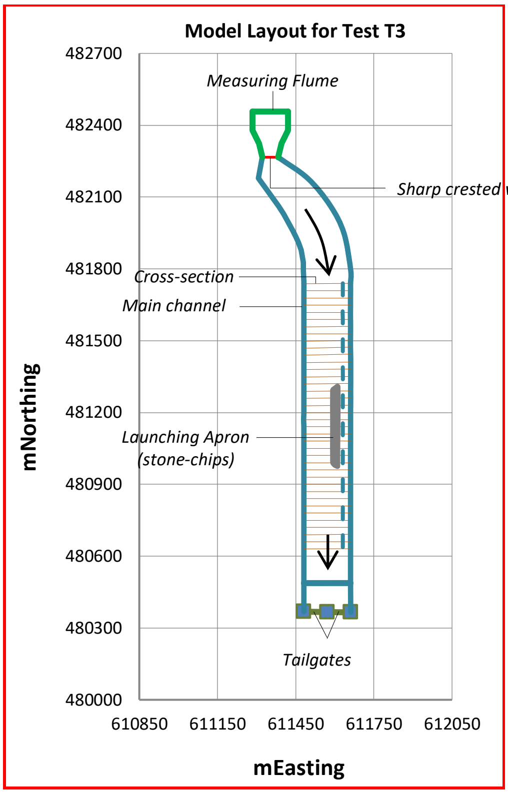

Figure 5.4.1: Layout of the model for test T2

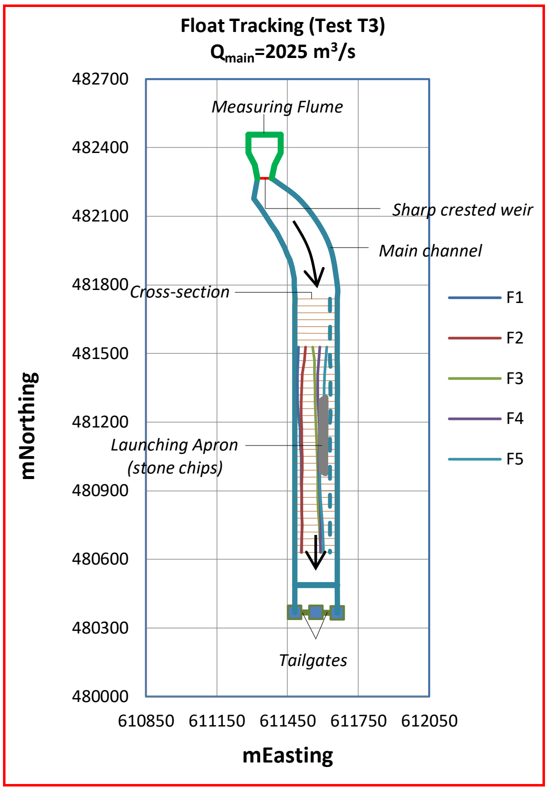

Figure 5.4.2: Flow field recorded by tracking floats from u/s to d/s in test T3

Table 5.4.1: Flow velocity in test T3

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	2.35	2.27	2.54	2.28	2.48	2.50	2.54	2.63	2.48	0.18
2	CS31	2.08	2.24	2.01	2.12	1.70	1.83	2.17	2.27	2.29	2.04
3	CS30	1.97	1.83	2.09	1.81	2.07	1.85	2.50	2.16	2.33	2.05
4	CS29	1.97	2.09	2.10	1.81	0.00	2.18	1.83	2.51	2.15	1.78
5	CS28	1.50	2.04	1.62	1.54	1.86	1.97	2.20	2.49	2.41	1.70
6	CS27	2.10	2.02	2.25	1.92	1.67	1.93	2.13	2.28	2.58	0.30
7	CS26	2.20	2.15	1.93	1.93	1.81	2.28	2.31	2.31	2.66	1.92
8	CS25	2.46	1.98	2.04	2.12	2.15	1.92	2.33	2.09	2.04	0.50
9	CS24	2.09	1.89	1.88	2.43	2.02	2.30	2.36	2.57	2.76	2.18
10	CS23	2.18	2.07	2.26	2.26	1.91	2.17	2.30	2.32	2.37	2.40
11	CS22	2.23	2.16	2.23	2.22	1.64	2.63	2.41	2.60	2.39	2.44
12	CS21	1.93	1.97	2.03	1.81	1.53	2.34	2.49	2.41	2.14	2.29
13	CS20	1.94	2.23	2.62	2.32	1.97	2.43	2.41	2.52	2.31	2.14
14	CS19	2.08	2.13	2.24	2.25	2.21	2.35	2.37	2.19	2.14	2.44
15	CS18	1.67	2.13	2.23	2.06	2.04	2.74	2.64	2.36	2.21	2.30
16	CS17	2.12	2.10	2.26	2.24	1.56	2.02	2.49	2.40	1.93	2.10
17	CS16	2.16	2.03	1.89	2.17	1.62	2.43	2.47	1.96	2.10	2.08
18	CS15	2.00	2.28	1.98	2.22	1.70	2.05	2.47	2.39	0.20	2.28
19	CS14	2.01	1.92	2.03	2.01	2.23	1.53	1.99	2.56	1.84	2.38
20	CS13	2.10	2.01	2.15	2.20	1.57	2.00	2.44	2.60	0.00	2.10
21	CS12	2.07	2.13	2.19	2.09	1.95	1.98	2.40	2.60	1.68	2.08

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
22	CS11	2.23	2.15	2.29	2.10	1.77	1.76	2.16	2.33	1.68	1.70
23	CS10	1.88	2.25	2.18	2.35	1.61	2.08	2.64	2.31	1.89	1.90
24	C9	2.25	2.26	2.33	2.24	1.98	1.93	2.13	2.26	2.23	2.10
25	CS8	2.02	1.89	1.93	2.09	1.89	1.95	2.33	2.25	1.77	2.15
26	CS7	2.05	2.17	0.00	0.00	1.79	2.00	2.26	2.37	1.68	2.02
27	CS6	2.11	2.36	2.08	2.23	1.84	1.86	2.07	2.41	2.00	1.91
28	CS5	2.07	2.15	2.27	2.37	1.61	2.06	2.18	2.46	0.03	1.64
29	CS4	2.25	2.22	2.32	2.15	1.53	1.93	2.19	2.54	0.13	1.53
30	CS3	2.16	2.29	2.12	2.41	1.34	1.62	2.15	2.19	0.08	1.97
31	CS2	2.14	2.30	2.01	2.08	1.57	2.08	2.16	1.87	1.74	2.21

Table 5.4.2: Flow velocity in test T3 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	2.18
2	Between CS24 & CS23	2.25
3	CS23	2.43
4	CS22	**2.58**
5	CS21	2.37
6	CS20	2.33
7	CS19	2.29
8	CS18	2.24
9	CS17	2.19
10	CS16	1.95
11	CS15	2.03
12	CS14	2.15
13	CS13	1.89
14	Between CS13 & CS12	1.54
15	CS12 (End of LA)	1.61

From the above table, it can be seen that the maximum velocity 2.58 m/s at CS22 along the end of the launching apron.

Table 5.4.3: Scour in test T3 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-1.56
2	CS22	-1.23
3	CS21	-0.78
4	CS20	-1.65
5	CS19	-1.32
6	CS18	-1.56
7	CS17	-1.56
8	CS16	-1.47
9	CS15	-1.59
10	CS14	-1.32
11	CS13	-1.35

From the above table, it can be seen that the maximum scour 1.65 m at CS20 along the end of the launching apron.

Figure 5.4.3: Launching pattern after test run (T3)

5.4.1 Findings

Along the end of the launching apron, no significant scour as the flow is parallel to the bankline (no oblique flow). Maximum velocity along the end of launching apron is found around 2.58 m/s (CS22). Maximum scour along the end of launching apron is found around 1.65 m (CS20). Due to parallel flow, no significant launching of stone chips occurs along the end of the launching apron.

5.5 Test T4.1

Test T4.1 is conducted with stone chips as launching material. Here, the total volume of launching material is 48 m^3/m, length of launching apron is 18 m and its thickness is 2.67 m (same as previous tests). Stone chips passing through 3/4" (1.905 cm) sieve and retained on 1/2" (1.27 cm) sieve were used after scaled down in this research. There is a shoot (oblique) channel connected to the main channel. The shoot channel makes an angle of 60^o with the main channel. The discharge 2025 m^3/s is distributed in such a way that the discharge ratio of main channel to shoot channel is 0.80. The discharge in the main and shoot channel is 1125 m^3/s and 900 m^3/s respectively. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of stone chips was tested in this test.

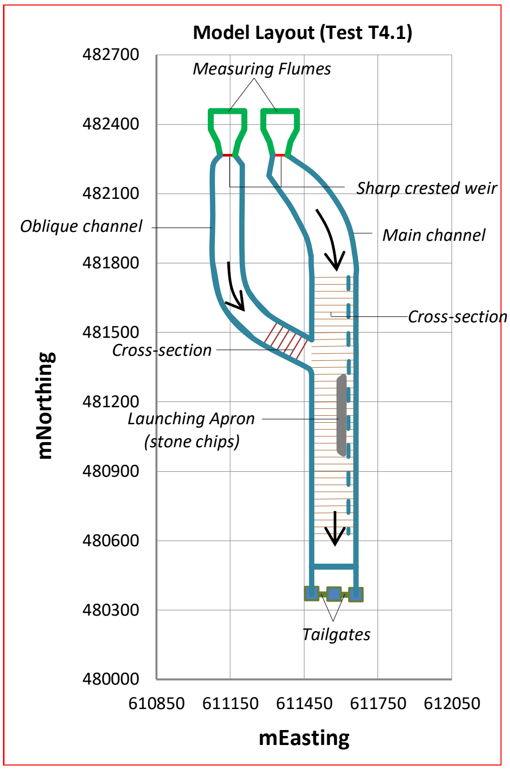

Figure 5.5.1: Layout of the model for test T4.1

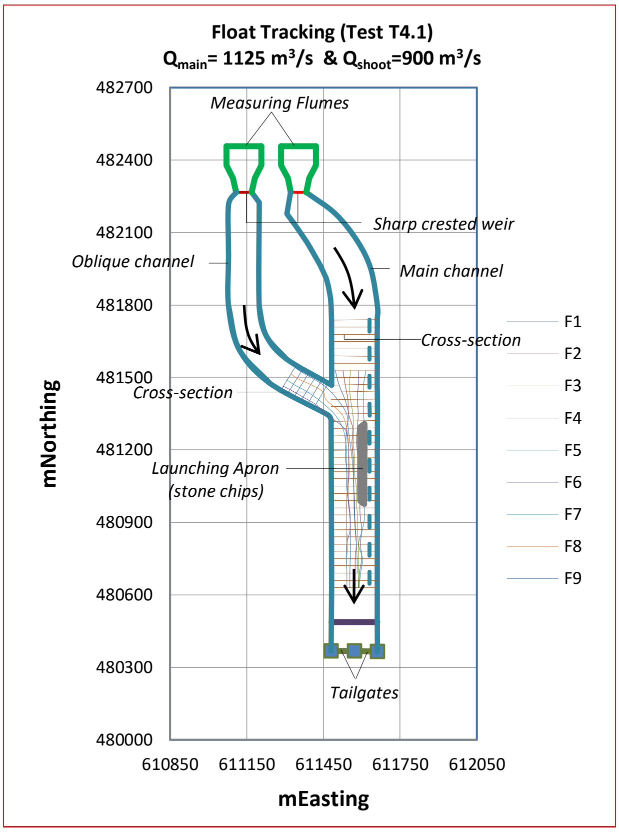

Figure 5.5.2: Flow field recorded by tracking floats from u/s to d/s in test T4.1

Table 5.5.1: Flow velocity in test T4.1 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.42	1.81	1.70	1.82	1.71	1.79	1.83	1.94	1.54	1.72
2	CS31	1.74	1.86	1.82	1.70	1.63	1.82	1.99	2.04	1.99	2.39
3	CS30	0.94	1.14	1.22	1.20	1.31	1.35	1.74	1.58	1.49	2.02
4	CS29	0.83	1.25	1.17	1.26	1.52	1.41	1.53	1.80	1.02	1.38
5	CS28	1.01	1.17	1.30	1.41	1.46	1.52	1.59	1.77	1.90	1.14
6	CS27	1.04	1.15	1.37	1.62	1.45	1.70	1.64	1.78	2.12	1.03
7	CS26	0.93	1.15	1.41	1.65	1.66	1.79	1.64	1.70	2.08	1.34
8	CS25	1.07	1.44	1.64	1.67	1.73	1.63	1.89	1.79	2.03	1.16
9	CS24	-0.63	-0.17	0.79	1.99	1.94	1.52	1.95	1.91	1.80	1.35
10	CS23	-0.75	0.29	1.21	1.83	1.92	1.79	1.78	1.92	0.93	2.15
11	CS22	0.08	0.04	0.41	1.80	2.12	2.09	2.18	2.12	1.27	1.56
12	CS21	0.98	1.08	1.79	2.16	1.94	2.32	2.36	2.08	1.30	1.13
13	CS20	1.12	1.24	1.86	2.21	2.10	2.04	2.38	1.74	1.06	1.11
14	CS19	1.53	1.36	2.04	1.89	2.30	1.86	2.38	2.62	0.17	1.12
15	CS18	1.75	1.65	1.90	2.01	2.03	2.35	2.61	2.01	0.00	1.34
16	CS17	1.93	1.87	1.99	2.31	2.07	2.35	2.45	2.11	0.17	1.19
17	CS16	2.02	1.57	2.11	1.79	1.90	2.28	2.52	2.77	0.13	1.34
18	CS15	1.70	1.60	1.97	2.15	2.35	2.67	2.63	2.48	0.06	1.10
19	CS14	1.98	1.84	1.91	2.37	1.53	2.36	2.46	0.97	1.04	1.13
20	CS13	1.85	2.03	1.68	1.85	2.11	2.28	2.60	0.24	0.74	1.00
21	CS12	1.95	2.10	2.01	2.27	2.16	2.40	2.66	2.59	1.26	1.17
22	CS11	1.93	2.05	2.18	2.13	1.96	2.16	2.51	2.57	1.43	1.08
23	CS10	1.89	2.06	2.03	2.00	1.52	2.17	2.58	2.60	1.56	1.47
24	C9	1.89	2.22	1.95	2.12	1.82	2.27	2.59	2.43	1.37	1.19
25	CS8	2.05	1.95	1.78	2.02	1.55	1.94	2.47	2.61	2.15	1.34
26	CS7	1.86	1.65	1.77	1.48	1.83	1.90	2.51	2.56	2.44	1.62
27	CS6	1.87	1.78	1.77	1.90	1.75	1.53	2.06	2.49	2.24	1.42
28	CS5	1.74	1.70	1.67	2.04	1.02	1.79	2.40	2.55	2.28	1.19
29	CS4	1.77	1.91	1.69	1.51	1.66	1.98	2.46	2.64	2.46	1.76
30	CS3	1.76	1.83	1.71	1.95	1.38	1.86	2.27	2.60	2.50	1.63
31	CS2	2.00	1.52	2.17	2.58	2.60	1.56	1.47	0.97	1.04	1.13
32	CS1	1.89	2.06	2.03	2.00	1.52	1.94	2.47	2.61	1.76	1.50

Table 5.5.2: Flow velocity in test T4.1 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.79	1.90	1.48	2.39	1.80	2.21	1.59	1.98	2.00
2	CS3	1.83	1.94	2.31	1.97	1.87	1.84	1.65	1.54	1.90
3	CS1	1.67	1.96	1.73	1.62	1.67	1.98	1.58	1.86	2.05

Table 5.5.3: Flow velocity in test T4.1 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	1.88
2	Between CS24 & CS23	1.89
3	CS23	1.99
4	CS22	2.28
5	CS21	2.36
6	CS20	2.38
7	CS19	2.45
8	CS18	2.61
9	CS17	2.73
10	CS16	2.67
11	CS15	2.80
12	CS14	2.58
13	CS13	2.65
14	Between CS13 & CS12	2.31
15	End of LA (CS12)	2.14

From the above table, it can be seen that the maximum velocity 2.80 m/s at CS15 along the end of the launching apron.

Table 5.5.4: Scour in test T4.1 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-6.81
2	CS22	**-7.71**
3	CS21	-7.29
4	CS20	-6.99
5	CS19	-6.96
6	CS18	-4.80
7	CS17	-6.12
8	CS16	-5.25
9	CS15	-5.76
10	CS14	-4.89
11	CS13	-4.20

From the above table, it can be seen that the maximum scour 7.71 m at CS22 along the end of the launching apron.

Figure 5.5.3: Launching pattern after test run (T4.1)

5.5.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 2.8 m/s (CS15). Maximum scour along the end of launching apron is found around 7.71 m (CS22). Due to the combination of straight and oblique flow, launching of stone chips occurs. Here stone chips cover the developed slope completely and there are no bare spaces.

5.6 Test T4.2

Test T4.2 is same as test T4.1 but here the discharge ratio of main channel to shoot channel is 1.0 instead of 0.8. The discharge through the main and shoot channel is 1012.5 m^3/s individually. Here the length of the launching apron is extended by 60m upstream to produce more severe condition (as per suggestion made by Additional Chief Engineer, BWDB. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The effectiveness of stone chips as launching materials was tested in this test.

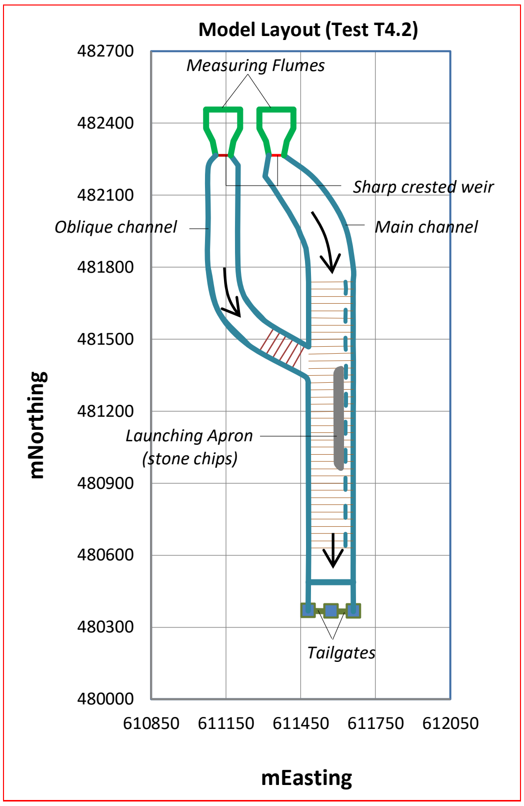

Figure 5.6.1: Layout of the model for test T4.2

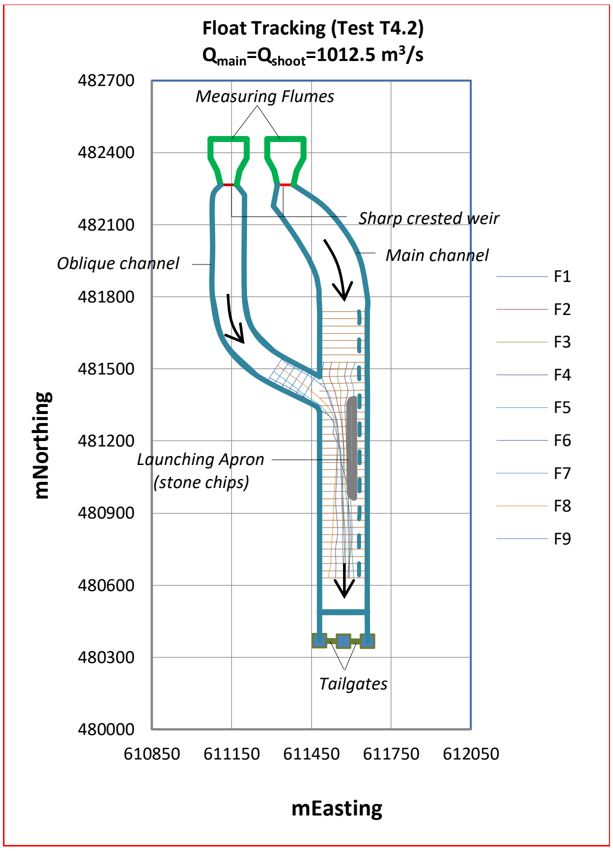

Figure 5.6.2: Flow field recorded by tracking floats from u/s to d/s in test T4.2

Table 5.6.1: Flow velocity in test T4.2 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.15	1.04	1.64	1.53	1.42	1.20	1.31	1.42	1.75	1.42
2	CS31	0.82	0.88	0.99	0.71	0.88	1.48	1.42	1.70	1.53	1.37
3	CS30	1.26	1.37	1.42	1.37	1.37	1.59	1.53	1.64	1.81	1.48
4	CS29	0.66	1.37	1.26	1.42	1.31	1.53	1.64	1.48	1.75	1.10
5	CS28	1.15	1.31	1.26	1.37	1.37	1.59	1.64	1.70	1.59	1.37
6	CS27	1.53	1.75	1.75	1.70	1.37	1.53	1.59	1.64	1.86	1.26
7	CS26	1.53	1.59	1.37	1.64	1.70	1.64	1.86	1.70	1.75	1.53
8	CS25	2.41	2.68	2.36	2.08	1.70	1.70	1.59	1.81	2.19	2.08
9	CS24	-0.44	0.55	2.41	2.30	1.86	1.75	2.08	1.97	2.08	2.14
10	CS23	0.16	-0.22	0.44	1.97	2.46	1.92	1.70	1.70	1.59	1.70
11	CS22	0.00	0.00	0.88	1.59	2.36	1.59	1.70	2.08	1.86	1.75
12	CS21	0.44	0.33	0.82	0.55	1.20	2.08	1.81	1.53	1.15	0.60
13	CS20	0.55	0.93	1.92	1.70	2.19	2.68	2.25	2.19	1.75	1.97
14	CS19	0.82	0.55	1.10	1.59	1.64	2.63	2.36	1.86	1.64	1.70
15	CS18	1.20	1.92	2.41	2.30	2.25	2.41	2.30	2.19	1.86	2.14
16	CS17	1.20	1.04	1.10	1.64	1.37	1.31	0.99	2.03	1.31	1.53
17	CS16	1.37	1.97	2.30	2.25	2.08	1.81	2.30	2.19	1.81	1.81
18	CS15	1.20	1.20	1.15	1.10	1.20	2.19	2.36	1.10	1.64	1.75
19	CS14	1.53	1.97	2.25	2.46	2.08	1.75	2.68	2.19	1.75	1.75
20	CS13	2.19	2.08	2.41	2.63	1.97	2.74	2.74	2.74	1.75	1.97
21	CS12	1.97	1.97	1.31	1.86	2.08	2.08	2.96	2.85	1.59	1.64
22	CS11	1.81	2.14	2.03	2.46	2.08	1.75	2.85	2.85	1.42	1.59
23	CS10	1.86	1.86	1.75	1.70	1.59	2.25	2.74	2.79	1.53	1.42
24	C9	1.53	1.86	2.08	1.86	1.59	2.14	2.41	2.63	1.97	1.42
25	CS8	2.08	2.08	1.97	2.25	1.64	1.75	2.36	2.30	1.53	1.48
26	CS7	1.37	2.03	1.92	2.08	1.31	1.42	2.63	1.75	1.20	1.37
27	CS6	1.75	1.86	1.59	2.08	1.37	2.30	2.25	2.63	2.08	1.75
28	CS5	1.70	1.97	2.25	2.14	1.59	1.64	2.52	2.63	2.41	2.08
29	CS4	1.91	1.92	1.88	1.77	1.49	1.42	1.70	1.42	1.20	1.99
30	CS3	1.42	1.81	1.70	2.08	1.86	2.08	2.25	2.74	2.14	1.64
31	CS2	1.64	1.75	1.53	1.42	0.66	0.88	1.48	1.20	1.31	1.04
32	CS1	1.64	1.86	2.14	2.19	1.97	1.97	2.74	2.52	2.19	2.36

Table 5.6.2: Flow velocity in test T4.2 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.86	1.97	2.19	1.92	2.08	1.92	1.64	1.97	1.81
2	CS3	1.97	1.64	1.53	1.59	1.94	1.75	1.86	1.86	1.90
3	CS1	2.03	1.75	1.70	1.97	1.98	1.91	1.98	1.77	1.96

Table 5.6.3: Flow velocity in test T4.2 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	1.64
2	Between CS26 & CS25	1.81
3	CS25	1.31
4	CS24	1.75
5	CS23	2.14
6	CS22	2.14
7	CS21	1.70
8	CS20	2.30
9	CS19	2.36
10	CS18	2.68
11	CS17	2.74
12	CS16	2.52
13	CS15	2.63
14	CS14	**3.07**
15	CS13	2.74
16	Between CS13 & CS12	2.63
17	CS12(End of LA)	0.99

From the above table, it can be seen that the maximum velocity 3.07 m/s at CS14 along the end of the launching apron.

Table 5.6.4: Scour in test T4.2 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS25	-1.68
2	CS24	-1.50
3	CS23	-2.13
4	CS22	-2.16
5	CS21	-2.67
6	CS20	-4.59
7	CS19	-6.21
8	CS18	-6.30
9	CS17	-6.12
10	CS16	-5.85
11	CS15	-5.61
12	CS14	-5.01
13	CS13	-4.20

From the above table, it can be seen that the maximum scour 6.30 m at CS18 along the end of the launching apron.

Figure 5.6.3: Launching pattern after test run (T4.2)

5.6.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 3.07 m/s (CS14). Maximum scour along the end of launching apron is found around 6.3 m (CS18). Due to the combination of straight and oblique flow, launching of stone chips occurs. There are no bare spaces on the developed slope and stone chips cover the launching slope completely.

5.7 Test T5.1

Test T5.1 is same as T4.1 with the introduction of geo-bags as launching material instead of stone chips. The percentage of geo-bag is 100% (125 kg). The discharge through the main and shoot channel is 1125 m^3/s and 900 m^3/s respectively. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of geo-bags was tested here.

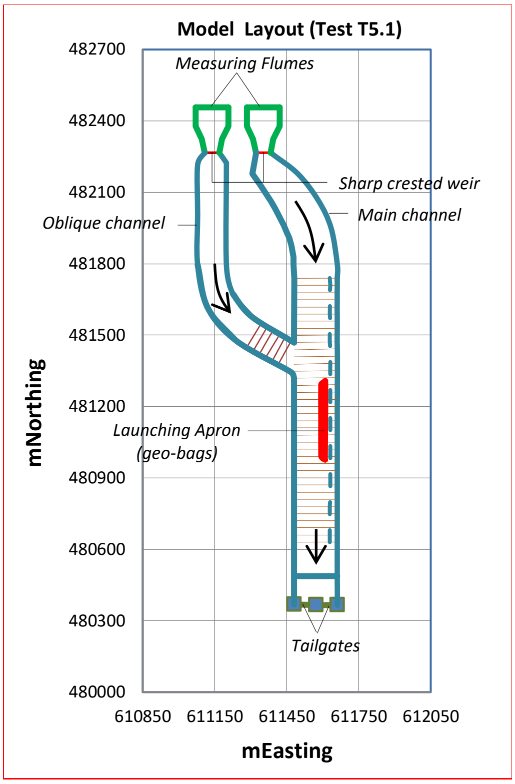

Figure 5.7.1: Layout of the model for test T5.1

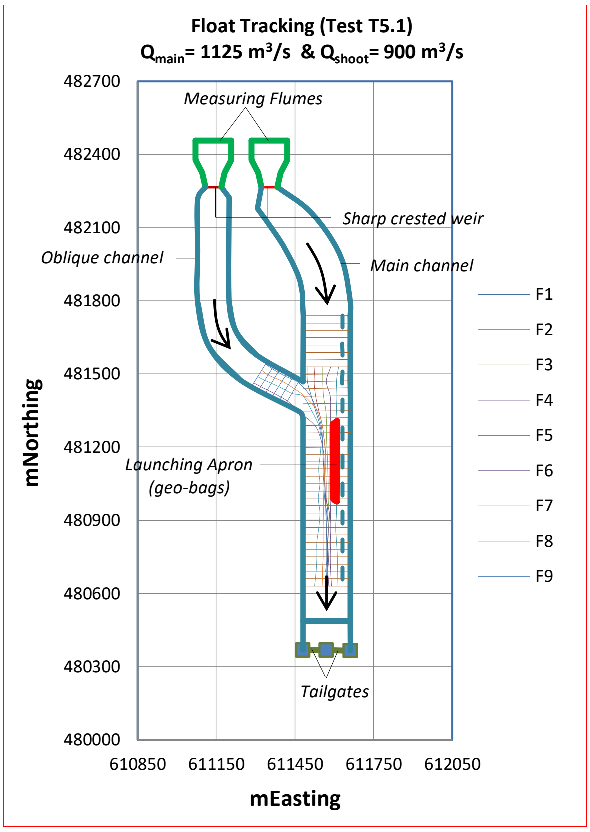

Figure 5.7.2: Flow field recorded by tracking floats from u/s to d/s in test T5.1

Table 5.7.1: Flow velocity in test T5.1 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.71	1.69	1.74	1.69	1.64	1.67	1.62	1.77	1.65	1.63
2	CS31	1.20	1.29	1.60	1.51	1.31	1.85	1.81	1.89	2.13	1.42
3	CS30	1.21	1.20	1.30	1.05	1.36	1.66	1.57	1.46	1.95	1.74
4	CS29	0.66	0.90	1.01	1.02	1.33	1.48	1.41	1.43	1.49	1.20
5	CS28	0.98	1.48	1.18	1.31	1.21	1.38	1.45	1.67	1.43	1.56
6	CS27	1.21	1.52	1.29	1.43	1.53	1.77	1.58	1.54	1.54	1.67
7	CS26	1.06	1.45	1.72	1.73	1.75	1.56	1.64	1.56	1.71	1.78
8	CS25	1.86	2.30	2.03	1.97	1.80	1.26	1.63	1.68	1.54	1.10
9	CS24	1.18	1.70	2.00	2.22	1.68	1.93	1.69	1.67	1.84	1.69
10	CS23	-0.28	0.62	1.47	2.20	2.20	1.97	2.06	1.79	2.11	1.01
11	CS22	0.85	0.19	0.61	1.80	2.24	2.41	2.35	2.35	2.41	1.04
12	CS21	0.95	1.25	1.51	2.12	2.33	2.17	2.38	2.26	0.03	1.23
13	CS20	1.08	1.35	2.09	2.58	2.30	2.50	2.46	2.45	0.96	1.59
14	CS19	1.33	1.22	2.08	1.87	2.39	2.37	2.35	2.65	2.45	1.88
15	CS18	1.48	1.64	2.21	2.60	2.48	2.70	2.89	2.62	2.02	1.03
16	CS17	1.51	1.76	2.19	2.54	1.81	2.59	2.63	2.87	1.66	1.07
17	CS16	1.41	1.34	2.16	2.39	2.43	2.78	2.81	2.71	0.02	1.05
18	CS15	1.38	1.63	1.95	2.47	2.39	2.83	2.77	2.95	1.43	1.01
19	CS14	1.70	1.65	2.18	2.78	2.11	2.60	2.84	2.05	1.06	1.21
20	CS13	1.68	1.82	2.25	2.41	2.20	2.84	2.89	2.55	1.57	1.03
21	CS12	1.13	1.52	1.61	2.27	1.92	2.20	2.48	2.63	1.43	1.84
22	CS11	1.65	1.86	2.05	1.71	1.82	2.22	2.61	2.10	1.57	1.87
23	CS10	1.99	1.80	1.76	2.04	1.60	2.16	2.58	2.67	1.52	1.07
24	C9	1.81	1.94	1.99	1.75	1.98	2.49	2.59	2.71	1.44	1.05
25	CS8	1.74	1.62	2.09	1.87	1.40	1.71	2.23	2.55	1.99	1.04
26	CS7	1.98	1.72	1.96	2.04	1.76	1.83	2.63	2.71	2.18	1.02
27	CS6	1.90	1.79	1.96	1.91	1.44	1.95	2.71	2.58	2.04	1.53
28	CS5	2.02	1.58	1.89	1.74	1.44	1.93	2.51	2.38	2.13	1.17
29	CS4	2.10	1.83	1.62	1.84	1.49	2.06	2.59	1.39	1.71	1.10
30	CS3	2.30	1.70	1.98	1.94	1.77	2.31	2.44	1.73	1.77	1.83
31	CS2	2.10	2.00	1.97	2.05	2.10	1.83	1.62	1.84	1.49	2.06
32	CS1	2.59	2.21	1.99	1.99	1.48	2.28	2.63	2.46	1.93	1.13

Table 5.7.2: Flow velocity in test T5.1 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.69	1.61	1.96	1.91	1.80	2.05	1.54	1.59	2.00
2	CS3	1.94	1.98	1.99	1.90	1.88	1.95	1.81	1.73	1.75
3	CS1	2.11	1.95	1.81	2.25	1.64	1.91	1.94	1.93	1.97

Table 5.7.3: Flow velocity in test T5.1 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	2.40
2	Between CS24 & CS23	2.33
3	CS23	2.15
4	CS22	2.65
5	CS21	2.62
6	CS20	2.86
7	CS19	3.06
8	CS18	3.14
9	CS17	2.10
10	CS16	0.95
11	CS15	1.42
12	CS14	1.16
13	CS13	1.94
14	Between CS13 & CS12	1.28
15	CS12 (End of LA)	0.93

From the above table, it can be seen that the maximum velocity 3.14 m/s at CS18 along the end of the launching apron.

Table 5.7.4: Scour in test T5.1 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-6.39
2	CS22	-8.46
3	CS21	**-8.91**
4	CS20	-8.28
5	CS19	-7.56
6	CS18	-6.81
7	CS17	-6.63
8	CS16	-6.42
9	CS15	-5.52
10	CS14	-5.04
11	CS13	-4.50

From the above table, it can be seen that the maximum scour 8.91 m at CS21 along the end of the launching apron.

Figure 5.7.3: Launching pattern after test run (T5.1)

5.7.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 3.14 m/s (CS18). Maximum scour along the end of launching apron is found around 8.91 m (CS21). Due to oblique flow, launching of geo-bags occurs along the end of the launching apron but there are some bare spaces and mass failure of geo-bags occurs.

5.8 Test T5.2

Test T5.2 is same as T5.1 but here the discharge 2025 m^3/s is distributed in such a way that the discharge ratio of main channel to shoot channel is 1. The discharge through the main channel is same as that of shoot channel and it is 1012.5 m^3/s. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of geo-bags was tested here.

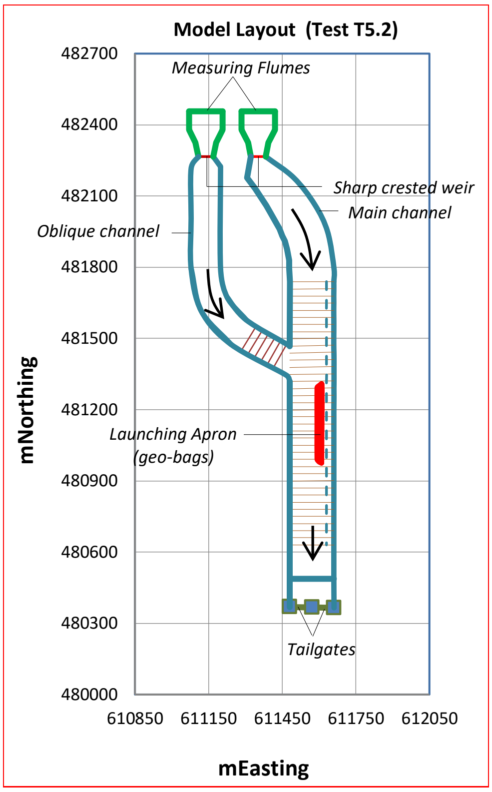

Figure 5.8.1: Layout of the model for test T5.2

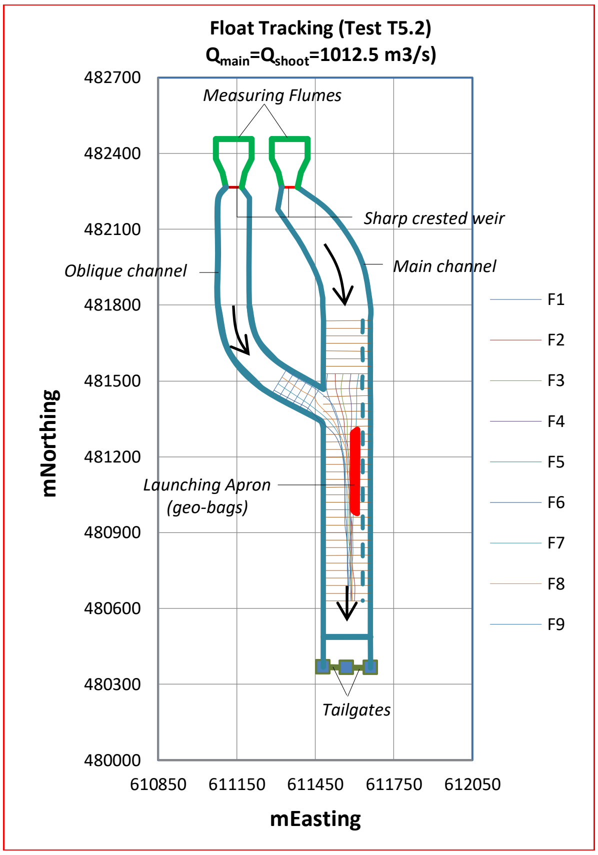

Figure 5.8.2: Flow field recorded by tracking floats from u/s to d/s in test T5.2

Table 5.8.1: Flow velocity in test T5.2 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.13	1.18	1.24	1.29	1.03	1.20	1.15	1.11	1.65	0.00
2	CS31	1.17	1.41	1.62	1.41	1.32	1.42	1.35	1.55	1.53	1.65
3	CS30	0.98	1.25	1.16	1.08	1.21	1.33	1.40	1.44	1.30	1.60
4	CS29	0.56	1.05	1.25	1.14	0.96	1.56	1.37	1.58	2.03	2.00
5	CS28	0.79	1.20	1.23	1.34	1.26	1.61	1.42	1.27	1.61	1.71
6	CS27	0.99	1.01	1.50	1.38	1.33	1.51	1.43	1.41	1.63	1,65
7	CS26	1.52	1.38	1.66	1.78	1.59	1.76	1.67	1.60	1.89	1.40
8	CS25	0.06	1.77	1.64	1.66	1.56	1.74	1.64	1.62	1.54	1.58
9	CS24	-0.60	1.91	0.83	-1.31	1.61	1.74	1.75	1.34	1.95	1.88
10	CS23	0.07	0.34	1.76	0.80	1.67	1.94	1.80	1.99	0.99	1.13
11	CS22	-0.03	0.87	1.91	0.00	1.49	1.72	1.89	2.21	1.57	1.69
12	CS21	0.81	1.16	1.37	0.31	1.48	2.09	2.12	2.27	0.77	1.14
13	CS20	0.99	0.54	1.53	1.89	1.80	2.01	2.19	1.87	1.04	1.24
14	CS19	0.99	0.91	1.45	1.86	1.75	2.50	1.18	2.76	1.98	1.94
15	CS18	1.05	1.19	1.55	1.78	1.96	2.34	2.44	2.84	1.11	1.20
16	CS17	1.17	1.22	1.51	1.71	2.22	2.82	2.38	2.75	0.82	1.02
17	CS16	1.10	1.09	1.27	2.09	2.07	2.50	2.48	2.81	1.29	1.87
18	CS15	1.10	1.40	1.63	2.43	2.20	2.86	2.62	2.29	1.51	1.11
19	CS14	1.19	1.33	1.51	2.20	1.55	2.75	2.73	2.79	2.38	1.65
20	CS13	1.25	1.53	1.82	1.30	1.96	1.98	2.14	1.86	0.24	1.11
21	CS12	1.26	1.45	1.66	1.58	1.37	2.45	2.55	2.23	0.03	1.50
22	CS11	1.32	1.34	1.77	1.35	1.32	2.36	2.30	2.26	0.86	1.72
23	CS10	1.59	1.37	1.52	1.26	1.66	2.06	2.16	2.44	1.20	1.93
24	C9	1.48	1.37	1.35	1.55	1.54	2.22	2.40	2.41	1.15	1.05
25	CS8	1.69	1.43	1.65	1.77	1.70	2.43	2.29	1.69	2.04	2.00
26	CS7	1.39	1.10	1.58	0.99	1.70	1.88	2.39	2.33	1.87	2.10
27	CS6	1.34	1.46	1.54	1.16	1.25	1.94	2.42	2.36	2.27	1.48
28	CS5	1.41	1.44	1.39	1.07	1.31	1.75	2.25	2.28	1.64	1.09
29	CS4	1.32	1.68	1.45	1.53	1.84	1.88	2.31	2.42	2.34	1.52
30	CS3	1.88	1.75	1.49	1.45	1.19	1.82	2.44	2.54	2.29	1.38
31	CS2	1.64	1.43	1.29	1.63	1.37	1.87	2.33	2.46	2.29	1.70

Table 5.8.2: Flow velocity in test T5.2 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.72	1.89	1.59	1.49	1.59	1.76	1.49	1.55	1.60
2	CS3	2.05	1.65	1.81	1.73	1.47	1.36	1.16	1.95	1.80
3	CS1	2.12	2.23	2.12	1.79	1.69	2.08	2.09	1.81	1.98

Table 5.8.3: Flow velocity in test T5.2 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	2.10
2	Between CS24 & CS23	1.74
3	CS23	2.27
4	CS22	1.72
5	CS21	1.48
6	CS20	1.68
7	CS19	1.99
8	CS18	2.22
9	CS17	2.16
10	CS16	2.05
11	CS15	1.59
12	CS14	2.38
13	CS13	2.36
14	Between CS13 & CS12	2.37
15	CS12(End of LA)	1.65

From the above table, it can be seen that the maximum velocity 2.38 m/s at CS14 along the end of the launching apron.

Table 5.8.4 Scour in test T5.2 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-4.68
2	CS22	-4.29
3	CS21	-3.93
4	CS20	-4.92
5	CS19	-7.02
6	CS18	-6.93
7	CS17	-6.42
8	CS16	-5.97
9	CS15	-5.82
10	CS14	-4.98
11	CS13	-4.50

From the above table, it can be seen that the maximum scour 7.02 m at CS19 along the end of the launching apron.

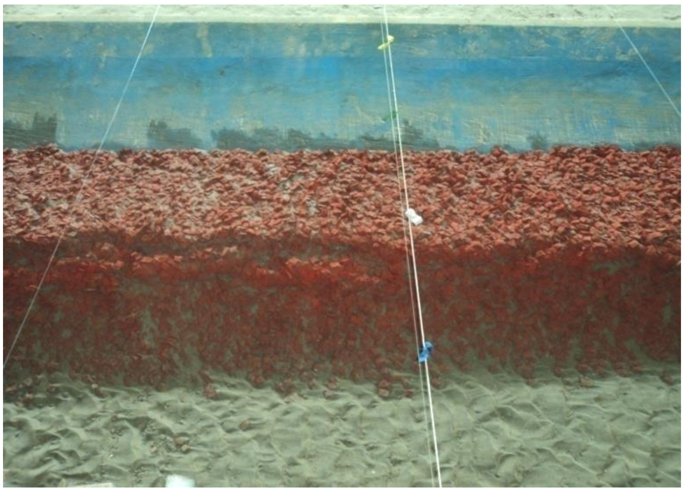

Figure 5.8.3: Launching pattern after test run (T5.2)

5.8.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 2.38 m/s (CS14). Maximum scour along the end of launching apron is found around 7.02 m (CS19). Due to oblique flow, launching of geo-bags occurs but mass failure occurs and there are some bare spaces on the developed slope.

5.9 Test T6.1

Test T6.1 is same as test 5.1 but here CC blocks are used as launching material Instead of geo-bags. The percentage of CC blocks: 60% (50 cm cube) and 40% (40 cm cube). The discharge ratio of main channel to shoot channel is 0.80. The discharge through the main and shoot channel is 1125 m^3/s and 900 m^3/s respectively. The average velocity & scour depth were measured along the cross-sections and flow field was recorded in this test. The performance of CC blocks was tested here.

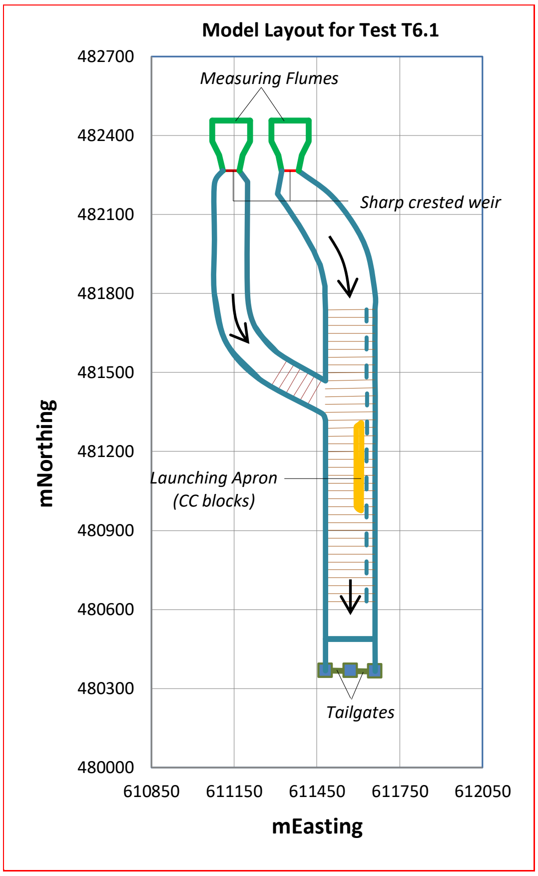

Figure 5.9.1: Layout of the model for test T6.1

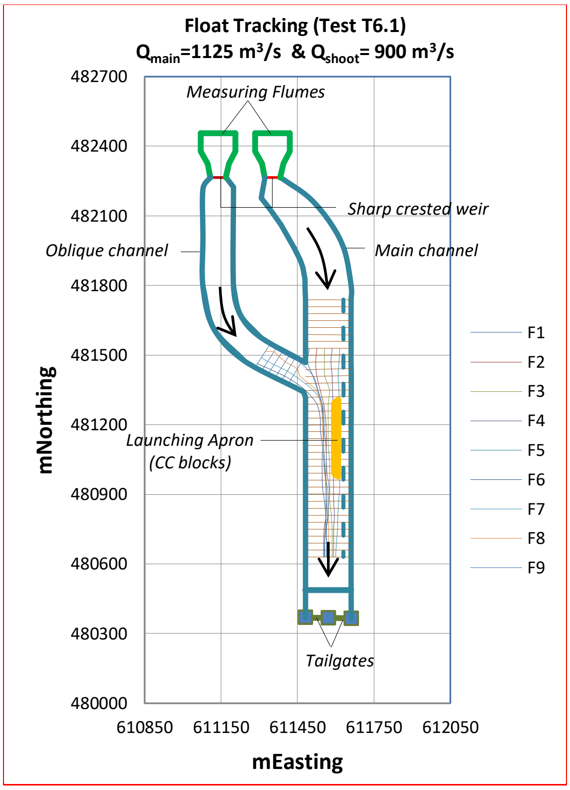

Figure 5.9.2: Flow field recorded by tracking floats from u/s to d/s in test T6.1

Table 5.9.1: Flow velocity in test T6.1 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.76	1.73	1.63	1.71	1.34	1.79	1.66	1.70	1.85	1.42
2	CS31	1.43	1.33	1.35	1.33	0.99	1.40	1.26	1.23	1.61	1.75
3	CS30	1.21	1.25	1.29	1.22	1.05	1.27	1.28	1.33	1.67	1.01
4	CS29	0.99	1.29	1.27	1.34	1.24	1.61	1.51	1.52	1.77	1.07
5	CS28	0.93	1.45	1.14	1.43	1.29	1.60	1.42	1.49	1.52	1.20
6	CS27	0.99	1.32	1.61	1.36	1.43	1.27	1.36	1.41	1.40	1.19
7	CS26	1.15	1.19	1.50	1.60	1.50	1.52	1.50	1.32	1.57	1.17
8	CS25	1.18	1.74	1.89	1.99	1.53	1.77	1.54	1.68	1.79	1.32
9	CS24	1.22	1.45	1.73	1.93	1.76	0.13	1.07	1.66	1.61	1.65
10	CS23	1.05	1.12	1.56	2.07	1.94	1.73	1.71	1.98	1.06	1.01
11	CS22	1.01	1.23	1.29	1.91	2.35	1.74	1.86	2.07	1.24	1.07
12	CS21	1.86	1.98	1.79	1.94	2.02	0.76	0.94	0.47	1.46	1.00
13	CS20	1.13	1.12	1.47	1.10	2.01	1.97	1.26	2.13	1.24	1.06
14	CS19	1.39	1.30	1.89	1.29	0.53	1.62	1.74	1.48	1.04	1.01
15	CS18	1.48	1.59	1.60	1.17	1.05	1.27	2.00	1.99	1.53	1.12
16	CS17	1.83	1.68	1.98	2.30	2.34	2.75	2.80	1.88	1.02	1.03
17	CS16	1.72	1.69	1.89	1.68	2.06	3.01	2.30	1.03	1.00	1.03
18	CS15	1.90	1.68	2.25	2.26	2.47	2.72	2.70	2.34	1.04	1.33
19	CS14	1.92	1.42	1.77	2.60	1.81	2.71	2.47	2.83	1.09	1.02
20	CS13	1.75	1.82	2.21	2.34	2.10	2.50	2.65	2.28	1.05	1.00
21	CS12	1.72	1.86	1.92	2.32	1.53	1.57	2.45	2.45	0.93	1.00
22	CS11	1.75	1.64	2.06	2.30	2.02	2.19	2.32	2.51	1.19	1.21
23	CS10	1.82	1.69	2.08	2.29	2.54	2.04	2.30	2.28	1.56	1.30
24	C9	1.90	1.86	1.86	2.23	1.80	2.06	2.48	2.44	1.50	1.59
25	CS8	1.74	1.74	1.85	2.33	1.77	1.67	2.12	2.54	1.92	1.56
26	CS7	1.73	2.05	2.12	2.08	1.72	2.03	2.08	2.21	2.05	1.30
27	CS6	1.53	1.83	1.75	1.91	1.27	1.11	2.02	2.69	2.27	1.70
28	CS5	1.69	1.78	2.01	2.14	1.78	2.12	2.63	2.68	2.02	1.57
29	CS4	1.77	1.75	1.97	2.09	2.08	2.18	2.40	2.66	2.50	1.73
30	CS3	2.04	1.73	2.02	1.98	1.56	1.79	2.42	2.27	2.27	0.90
31	CS2	1.84	1.96	2.09	1.37	0.90	1.36	2.10	2.22	2.24	1.64
32	CS1	2.08	2.10	2.13	2.15	1.39	1.84	2.22	2.70	2.38	2.71

Table 5.9.2: Flow velocity in test T6.1 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.86	1.95	1.92	1.99	1.96	1.86	1.96	1.93	1.81
2	CS5	1.91	1.96	1.94	1.72	1.94	1.92	1.78	1.98	1.97
3	CS4	1.79	1.91	1.90	1.93	1.61	1.90	1.95	1.95	1.98
2	CS3	1.90	1.96	1.90	1.96	1.75	1.97	1.82	1.71	1.91
3	CS2	1.76	1.99	1.95	1.83	1.93	1.83	1.82	1.94	1.92

Table 5.9.3: Flow velocity in test T6.1 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	1.10
2	CS24 & CS23	1.18
3	CS23	1.93
4	CS22	1.98
5	CS21	1.99
6	CS20	2.23
7	CS19	2.19
8	CS18	2.19
9	CS17	2.45
10	CS16	2.57
11	CS15	2.44
12	CS14	2.67
13	CS13	2.57
14	Between CS13 & CS12	2.19
15	CS12 (End of LA)	1.15

From the above table, it can be seen that the maximum velocity 2.67 m/s at CS14 along the end of the launching apron.

Table 5.9.4: Scour in test T6.1 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS23	-7.1
2	CS22	-7.9
3	CS21	**-8.7**
4	CS20	-7.3
5	CS19	-6.4
6	CS18	-6.7
7	CS17	-6.5
8	CS16	-5.7
9	CS15	-4.8
10	CS14	-4.9
11	CS13	-4.4

From the above table, it can be seen that the maximum scour 8.7 m at CS21 along the end of the launching apron.

Figure 5.9.3: Launching pattern after test run (T6.1)

5.9.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 2.67 m/s (CS14). Maximum scour along the end of launching apron is found around 8.7m (CS21). Due to the combination of straight and oblique flow, launching of CC blocks occurs. Here CC blocks cannot cover the launching slope completely and there are bare spaces on the developed slope.

5.10 Test T6.2

Test T6.2 is same as Test 6.1 but here the discharge ratio of main channel to shoot channel is 1.0 and the length of the launching apron has been extended in the upstream direction up to CS26 as per suggestion made by Additional Chief Engineer, BWDB. The average velocity & scour depth were measured and flow field was recorded in this test. The performance of CC blocks was tested here.

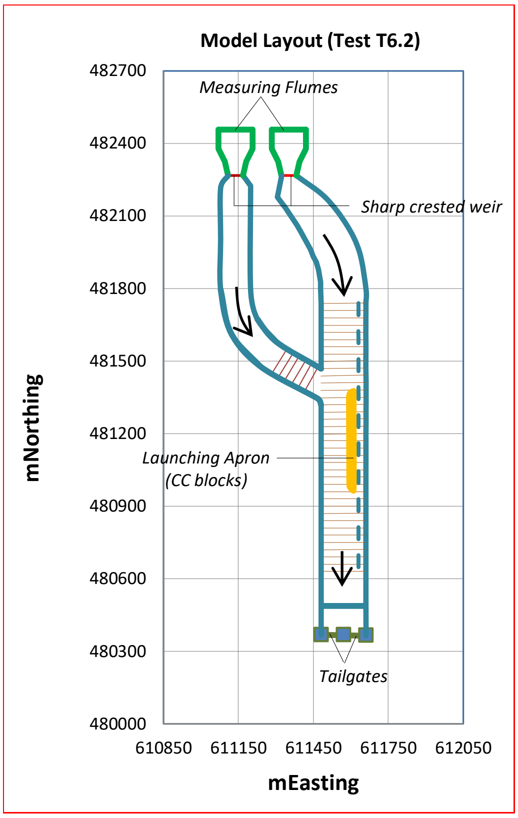

Figure 5.10.1: Layout of the model for test T6.2

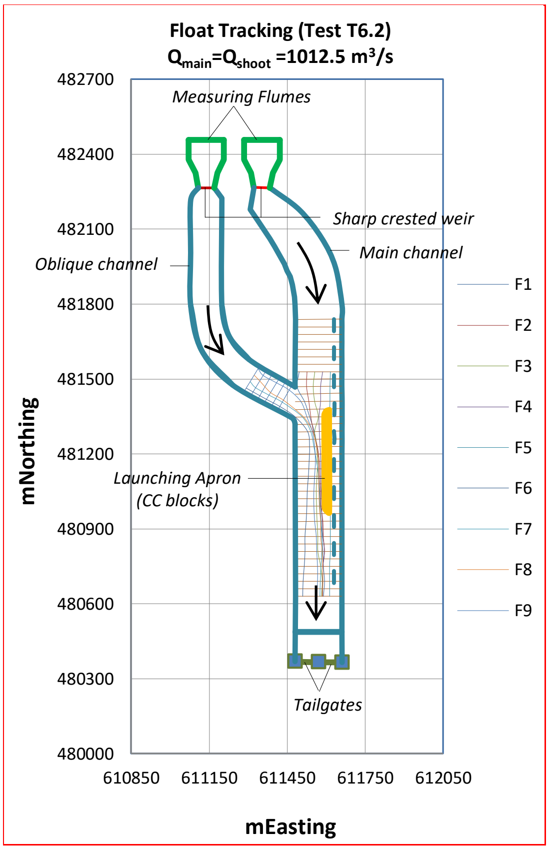

Figure 5.10.2: Flow field recorded by tracking floats from u/s to d/s in test T6.2

Table 5.10.1: Flow velocity in test T6.2 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS33	1.91	1.81	1.90	1.20	1.10	1.20	1.10	0.99	1.90	1.53
2	CS32	1.99	1.80	1.91	1.73	1.64	1.53	1.92	1.91	1.90	1.70
3	CS31	0.99	1.70	1.42	1.31	1.90	1.80	1.42	1.53	1.64	1.42
4	CS30	0.99	1.88	1.42	1.53	1.31	1.53	1.53	1.64	1.42	1.53
5	CS29	1.77	1.80	1.91	1.62	1.91	1.72	1.53	1.53	1.75	1.64
6	CS28	1.20	1.42	1.42	1.80	1.42	1.31	1.20	1.31	1.20	1.64
7	CS27	1.90	1.91	1.53	1.53	1.64	1.64	1.75	1.75	1.64	1.75
8	CS26	0.99	1.20	1.31	1.53	1.64	1.53	1.42	1.31	1.10	1.20
9	CS25	0.88	2.19	2.08	1.86	1.86	1.64	1.86	1.86	2.03	1.97
10	CS24	1.44	1.11	2.08	2.19	2.08	1.86	1.75	1.97	1.75	1.31
11	CS23	1.74	1.77	1.42	1.53	1.31	1.20	0.66	0.99	1.20	1.53
12	CS22	1.44	1.97	2.08	2.41	2.52	2.63	2.41	2.52	1.86	2.19
13	CS21	1.31	1.64	2.19	2.63	2.63	2.63	1.75	2.30	1.97	2.19
14	CS20	1.64	1.75	1.97	2.30	2.52	2.41	2.19	1.64	1.64	1.53
15	CS19	1.64	1.53	1.97	2.19	2.52	2.63	2.52	1.75	1.86	1.53
16	CS18	1.42	1.53	2.19	1.86	2.08	2.08	2.63	2.68	1.86	1.97
17	CS17	1.53	1.75	2.08	2.41	1.97	2.52	2.74	2.74	1.97	2.08
18	CS16	1.64	1.64	1.86	2.52	2.30	2.52	2.63	2.41	1.86	2.08
19	CS15	1.64	1.75	1.86	1.97	2.08	2.52	2.74	2.52	1.75	1.86
20	CS14	1.53	1.86	1.86	2.08	2.08	2.63	2.74	2.41	1.97	1.97
21	CS13	1.31	1.75	2.19	2.08	2.08	2.74	2.74	2.74	2.08	2.08
22	CS12	1.48	1.42	1.92	2.08	1.86	2.74	2.74	2.74	0.99	1.70
23	CS11	1.64	1.64	2.14	2.19	2.25	2.68	2.74	2.74	1.64	1.97
24	CS10	1.64	1.64	1.81	2.25	1.75	2.25	2.74	2.74	1.75	1.53
25	C9	1.97	1.53	1.85	1.10	1.59	1.20	1.97	1.75	1.70	1.77
26	CS8	1.53	1.75	2.08	2.03	1.64	2.19	2.74	2.74	2.36	1.75
27	CS7	1.53	1.53	1.42	1.75	1.75	1.92	2.41	2.74	2.30	1.42
28	CS6	1.64	2.08	1.92	2.25	2.08	1.70	2.74	2.74	2.63	1.75
29	CS5	1.75	2.08	2.30	2.41	2.03	2.52	2.68	2.74	2.46	1.86
30	CS4	1.59	1.53	2.08	2.19	1.81	2.68	2.52	2.68	2.41	1.81
31	CS3	1.04	1.64	1.75	1.86	1.53	2.08	2.57	2.63	2.57	1.97
32	CS2	1.86	1.97	1.86	2.08	1.64	2.68	2.46	1.10	1.75	2.19
33	CS1	1.75	2.19	1.64	1.64	1.86	1.53	2.14	2.19	2.57	1.75

Table 5.10.2 Flow velocity in test T6.2 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	2.19	1.91	1.53	1.64	1.75	1.53	1.92	1.92	1.90
2	CS4	1.64	1.75	2.19	1.86	1.70	1.90	1.75	1.70	1.55
3	CS2	1.53	1.75	1.86	2.19	1.86	1.53	1.64	1.75	1.53

Table 5.10.3: Flow velocity in test T6.2 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	1.20
2	Between CS26 & CS25	1.26
3	CS25	1.42
4	CS24	2.14
5	CS23	2.14
6	CS22	2.19
7	CS21	1.75
8	CS20	2.52
9	CS19	2.19
10	CS18	2.74
11	CS17	2.57
12	CS16	2.63
13	CS15	2.85
14	CS14	3.01
15	CS13	2.68
16	Between CS13 & CS12	2.57
17	End of LA	0.66

From the above table, it can be seen that the maximum velocity 3.01 m/s at CS14 along the end of the launching apron.

Table 5.10.4: Scour in test T6.2 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS25	2.49
2	CS24	2.22
3	CS23	2.49
4	CS22	2.49
5	CS21	3.27
6	CS20	4.65
7	CS19	5.19
8	CS18	5.94
9	CS17	5.76
10	CS16	5.67
11	CS15	5.55
12	CS14	5.37
13	CS13	4.65

From the above table, it can be seen that the maximum scour 5.94 m at CS18 along the end of the launching apron.

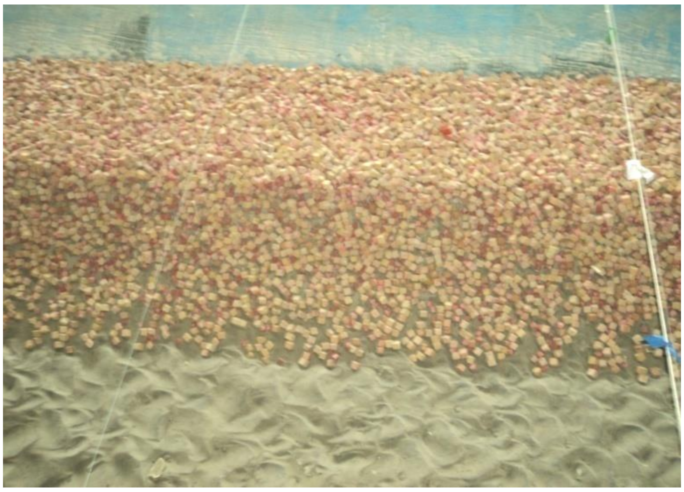

Figure 5.10.3: Launching pattern after test run (T6.2)

5.10.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 3.01 m/s (CS14). Maximum scour along the end of launching apron is found around 5.94m (CS18). Here launching of CC blocks occurs due to the combination of straight and oblique flow. There are bare spaces on the developed slope and CC blocks cannot cover the launching slope completely.

5.11 Test T7

In this test, the main channel was closed at CS38 (1st upstream cross-section). The shoot channel feeds the total discharge (2025 m^3/s) to the main channel. Here this test is conducted with the CC block as launching material placed in the main channel. Here, the total volume of launching material is 48 m^3/m, length of launching apron is 18 m and its thickness is 2.67 m (same as previous tests). The percentage of CC blocks: 60% (50 cm cube) and 40% (40 cm cube). The objective of this test is to observe the effectiveness of lunching apron under severe flow attack by fully oblique flow. The average velocity & scour depth were measured and flow field was recorded in this test.

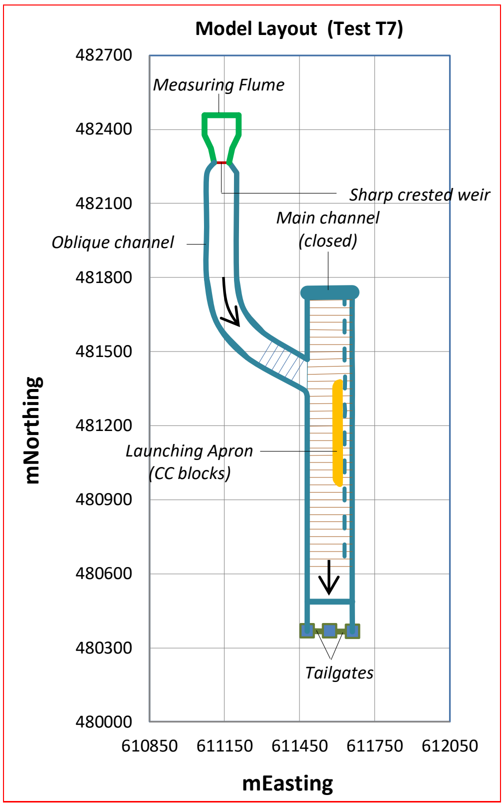

Figure 5.11.1: Layout of the model for test T7

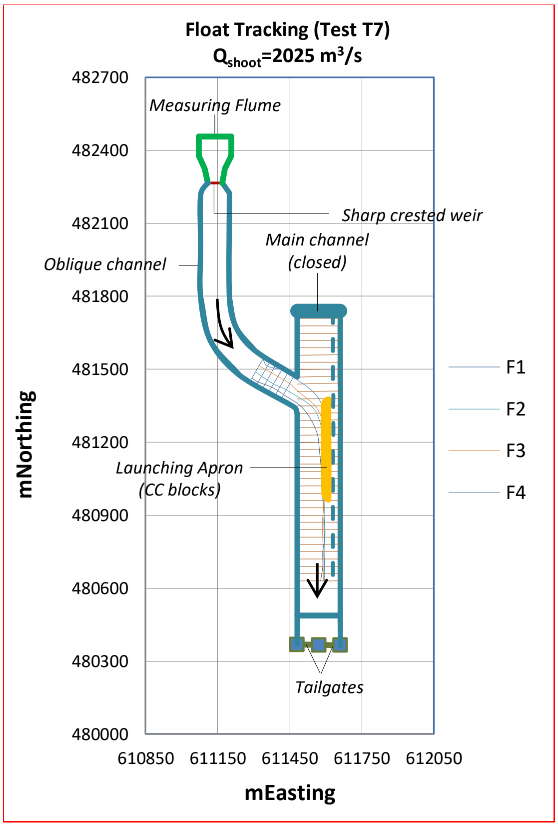

Figure 5.11.2: Flow field recorded by tracking floats from u/s to d/s in test T7

Table 5.11.1: Flow velocity in test T7 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS26	0.71	0.60	0.93	1.10	0.88	0.99	0.93	0.82	0.66	1.33
2	CS25	0.66	1.10	1.31	1.20	1.31	1.75	1.42	1.42	1.20	1.04
3	CS24	-0.55	0.77	1.75	1.75	2.19	1.64	2.14	2.14	1.64	1.75
4	CS23	-	-	0.88	1.75	1.53	1.86	1.97	1.92	1.59	1.48
5	CS22	-	-	1.59	2.14	2.36	2.57	2.57	2.03	1.26	1.48
6	CS21	-	-	-	1.48	1.97	2.14	2.52	2.46	2.14	1.59
7	CS20	-	-	-	2.19	2.30	2.52	2.52	3.01	2.19	2.41
8	CS19	-	-	-	1.10	1.97	2.30	2.08	2.30	1.48	1.15
9	CS18	-	-	1.53	2.25	2.30	2.85	1.92	1.26	0.88	1.44
10	CS17	1.00	1.04	1.75	2.14	2.63	2.85	2.68	2.74	2.19	1.64
11	CS16	0.82	1.81	2.30	2.63	2.68	2.68	2.68	2.74	2.14	1.92
12	CS15	0.99	1.64	2.19	2.30	2.52	2.74	2.85	3.01	1.64	2.19
13	CS14	1.04	1.42	2.19	2.30	2.85	2.46	2.63	2.30	2.63	2.68
14	CS13	1.37	1.59	1.92	2.14	2.36	2.63	2.85	2.74	2.19	2.08
15	CS12	1.37	1.64	2.19	2.30	1.92	1.81	1.92	1.92	1.20	1.37
16	CS11	1.20	1.20	1.75	1.92	2.63	2.63	2.74	2.68	1.64	1.53
17	CS10	1.37	1.42	1.64	1.75	1.64	2.19	2.46	2.74	1.64	1.37
18	C9	1.53	1.64	2.25	2.19	2.19	2.46	2.25	2.19	1.75	1.48
19	CS8	1.37	1.64	1.97	2.19	2.03	2.52	2.46	2.25	2.46	1.70
20	CS7	1.20	1.70	1.92	2.19	2.19	2.30	2.74	2.74	2.30	1.64
21	CS6	1.64	1.92	1.92	2.19	2.08	2.25	2.46	2.74	2.30	2.19
22	CS5	1.53	1.97	2.08	2.14	1.92	2.46	2.63	2.74	2.68	2.14
23	CS4	1.64	1.75	2.19	2.19	2.19	2.46	2.30	2.74	2.46	1.97
24	CS3	1.20	1.70	1.97	2.19	1.64	2.19	2.46	2.68	2.46	2.19
25	CS2	1.64	1.75	2.08	2.19	2.14	2.46	2.74	2.74	2.63	2.46
26	CS1	1.92	1.75	1.64	1.20	1.15	1.92	1.37	1.64	1.64	1.15

Table 5.11.2 Flow velocity in test T7 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	2.01	2.01	2.29	2.01	2.03	2.56	2.05	2.15	2.34
2	CS3	2.19	1.92	2.19	1.64	1.86	1.92	1.90	2.10	1.64
3	CS1	1.90	1.53	1.97	2.15	2.10	1.99	1.88	1.99	1.85

Table 5.11.3: Flow velocity in test T7 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.55
2	Between CS26 & CS25	0.99
3	CS25	1.31
4	CS24	1.75
5	CS23	1.70
6	CS22	2.25
7	CS21	2.03
8	CS20	2.03
9	CS19	1.04
10	CS18	1.75
11	CS17	3.01
12	CS16	2.19
13	CS15	2.96
14	CS14	3.29
15	CS13	3.01
16	Between CS13 & CS12	2.08
17	CS12 (End of LA)	1.64

From the above table, it can be seen that the maximum velocity 3.29 m/s at CS14 along the end of the launching apron.

Table 5.11.4: Scour in test T7 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS25	-2.28
2	CS24	-5.67
3	CS23	-8.64
4	CS22	-12.84
5	CS21	-14.37
6	CS20	-11.61
7	CS19	-11.7
8	CS18	-7.47
9	CS17	-7.08
10	CS16	-7.26
11	CS15	-6.30
12	CS14	-5.25
13	CS13	-4.92

From the above table, it can be seen that the maximum scour 14.37 m at CS21 along the end of the launching apron.

Figure 5.11.3: Launching pattern after test run (T7)

5.11.1 Findings

Along the end of the launching apron, scour occurred as the launching apron in the main channel is subjected to fully oblique flow. Maximum velocity along the end of launching apron is found around 3.29 m/s (CS14). Maximum scour along the end of launching apron is found around 14.37 m (CS21). Due to fully oblique flow, launching of CC blocks occurs. But here CC blocks cannot cover the launching slope completely and at some places there are some bare spaces on launching slope.

5.12 Test T8

This test is same as test T7 but here stone chips are used as launching material instead of CC blocks as in test T7. Stone chips passing through 3/4" (1.905 cm) sieve and retained on 1/2" (1.27 cm) sieve were used after scaled down in this research. In this test, the average velocity & scour depth were measured along the cross-sections and flow field was recorded. The test is done to see the performance of stone chips as lunching apron under severe flow attack by fully oblique flow.

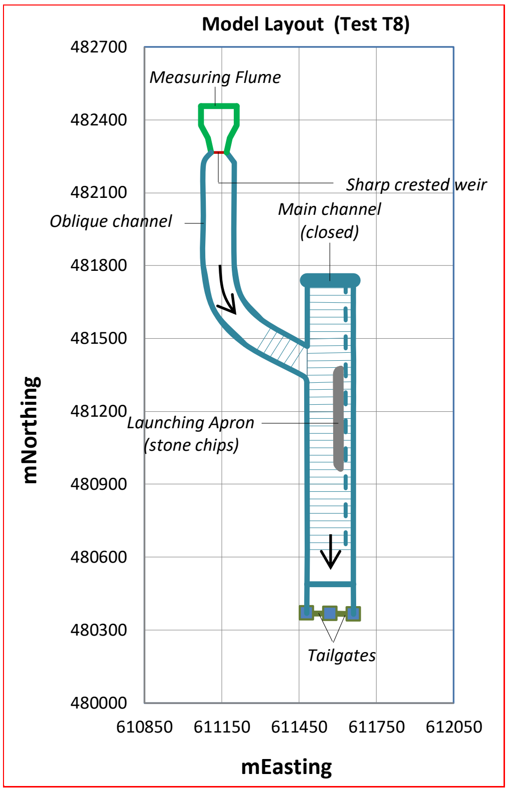

Figure 5.12.1: Layout of the model for test T8

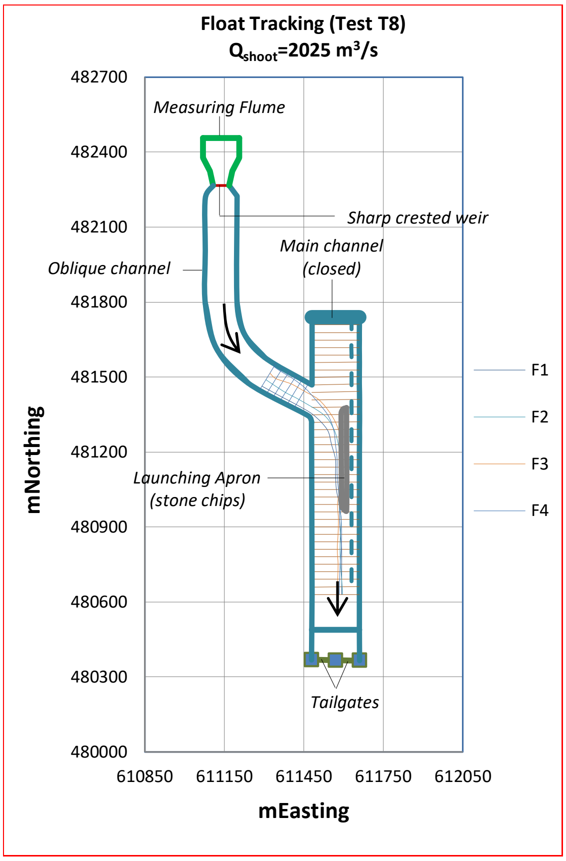

Figure 5.12.2: Flow field recorded by tracking floats from u/s to d/s in test T8

Table 5.12.1: Flow velocity in test T8 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	**15.0**	**30.0**	**45.0**	**60.0**	**75.0**	**90.0**	**105.0**	**120.0**	**130.5**
1	CS26	1.31	1.37	1.26	1.48	1.53	1.53	1.42	1.26	1.77	1.71
2	CS25	2.03	1.31	2.19	2.19	2.14	1.70	1.53	1.10	1.04	1.04
3	CS24	-0.55	2.08	2.36	2.36	2.41	2.19	2.08	2.03	1.53	1.48
4	CS23	-	-	1.20	3.01	2.96	2.46	2.19	2.25	1.64	1.37
5	CS22	-	-	1.75	2.74	2.68	2.79	2.41	2.36	1.97	1.92
6	CS21	-	-	1.92	2.63	2.85	2.74	2.68	2.63	1.92	2.25
7	CS20	-	-	2.08	2.52	2.74	2.85	2.74	2.52	2.19	2.30
8	CS19	0.66	-	0.60	1.31	2.14	2.14	2.79	3.01	1.97	1.97
9	CS18	0.66	0.71	1.31	2.08	2.19	2.57	2.57	2.85	2.41	2.46
10	CS17	0.88	0.99	1.92	2.52	2.63	2.63	2.74	2.74	2.08	2.25
11	CS16	0.77	1.31	2.03	2.08	2.36	2.57	2.74	2.85	2.30	2.08
12	CS15	0.93	1.26	1.97	2.14	2.74	2.30	2.68	2.36	2.03	2.36
13	CS14	0.71	1.48	1.75	2.14	2.14	2.25	2.90	2.68	2.08	2.57
14	CS13	1.37	1.59	2.14	2.36	2.68	2.63	3.01	2.90	2.08	2.19
15	CS12	1.26	1.15	2.03	2.19	2.30	2.25	2.85	2.52	1.20	1.81
16	CS11	1.53	1.92	2.36	2.52	2.85	2.96	3.12	2.85	1.75	1.53
17	CS10	1.75	2.08	2.52	2.36	2.46	2.85	3.18	3.29	2.14	1.64
18	C9	1.53	1.64	1.59	1.75	1.81	3.07	2.68	3.01	1.92	1.53
19	CS8	1.92	2.19	2.30	2.41	2.30	2.85	2.68	3.01	2.46	1.92
20	CS7	2.14	2.19	2.52	2.41	2.36	2.85	2.57	2.96	3.01	2.19
21	CS6	1.97	2.08	2.36	2.41	1.81	2.03	2.74	3.01	2.57	2.19
22	CS5	1.64	1.92	1.59	1.64	1.64	2.14	2.30	2.46	2.30	1.92
23	CS4	1.75	2.03	1.64	1.92	1.92	2.19	2.63	2.74	2.30	2.19
24	CS3	1.64	1.92	2.14	1.92	1.75	2.46	2.19	2.63	2.46	2.19
25	CS2	1.75	2.08	1.92	2.08	2.08	2.19	2.63	2.74	2.46	2.19
26	CS1	2.08	2.19	1.92	1.92	1.64	2.19	2.19	1.92	1.92	1.70

Table 5.12.2 Flow velocity in test T8 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	**15.0**	**30.0**	**45.0**	**60.0**	**75.0**	**90.0**	**105.0**	**120.0**
1	CS6	2.19	2.36	2.34	2.79	2.18	2.12	1.97	2.36	2.08
2	CS3	1.99	1.70	2.08	2.08	1.86	1.92	1.81	1.97	1.53
3	CS1	1.92	1.86	1.97	2.25	2.10	1.90	1.95	1.64	2.00

Table 5.12.3: Flow velocity in test T8 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.16
2	Between CS26 & CS25	0.93
3	CS25	1.37
4	CS24	1.64
5	CS23	1.97
6	CS22	1.92
7	CS21	2.19
8	CS20	2.46
9	CS19	2.74
10	CS18	2.63
11	CS17	2.74
12	CS16	3.29
13	CS15	3.12
14	CS14	2.85
15	CS13	3.56
16	Between CS13 & CS12	3.18
17	CS12 (End of LA)	2.03

From the above table, it can be seen that the maximum velocity 3.56 m/s at CS13 along the end of the launching apron.

Table 5.12.4: Scour in test T8 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS25	-1.98
2	CS24	-4.8
3	CS23	-7.86
4	CS22	-9.39
5	CS21	-10.59
6	CS20	-12.33
7	CS19	-11.04
8	CS18	-9.78
9	CS17	-9.09
10	CS16	-7.86
11	CS15	-6.96
12	CS14	-6.03
13	CS13	-5.16

From the above table, it can be seen that the maximum scour 12.33 m at CS20 along the end of the launching apron.

Figure 5.12.3: Launching pattern after test run (T8)

5.12.1 Findings

Along the end of the launching apron, scour occurred as the launching apron in the main channel is subjected to fully oblique flow. Maximum velocity along the end of launching apron is found around 3.56m/s (CS13). Maximum scour along the end of launching apron is found around 12.33m (CS20). Due to fully oblique flow, launching of stone chips occurs and stone chips cover the launching slope completely. There is no bare space on the launching slope.

5.13 Test T9

This test is same as test T8 but here geo-bags are used as launching material instead of stone chips as in test T8. The percentage of geo-bag is 100% (125 kg). The average velocity & scour depth were measured in this test and flow field was recorded. The test is done to see the performance of geo-bags as lunching apron under severe flow attack by fully oblique flow.

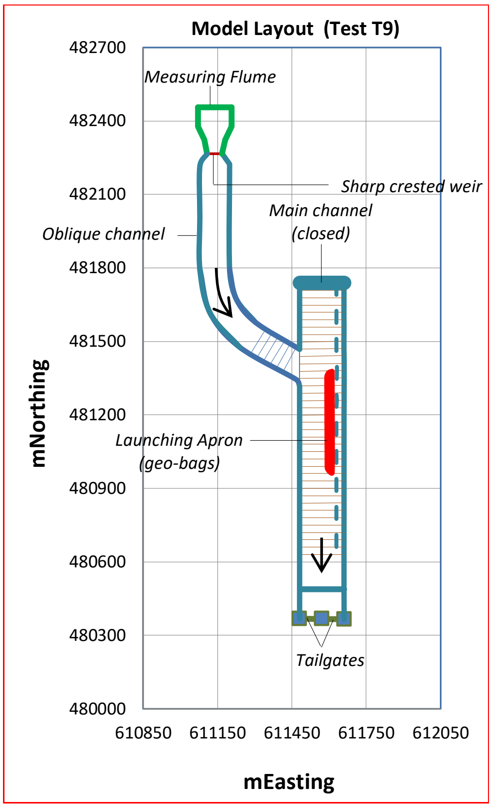

Figure 5.13.1: Layout of the model for test T9

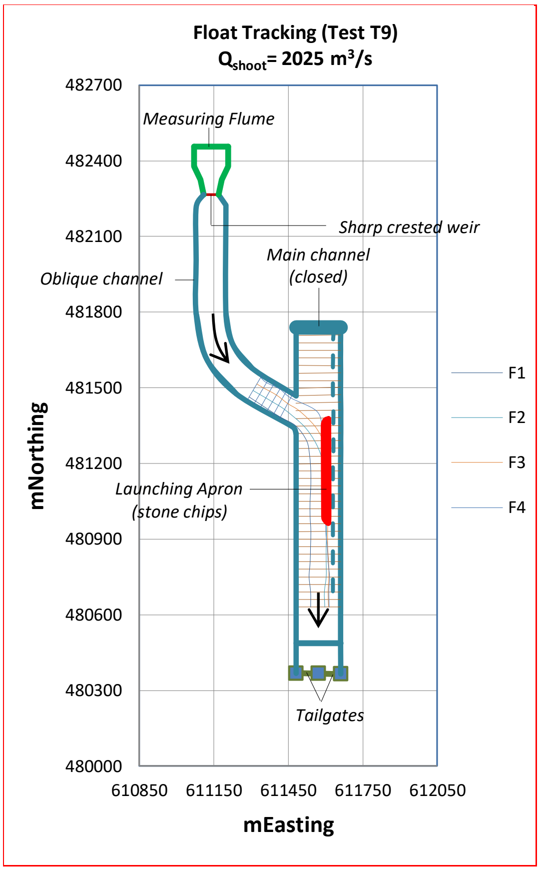

Figure 5.13.2: Flow field recorded by tracking floats from u/s to d/s in test T9

Table 5.13.1: Flow velocity in test T9 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS26	1.26	0.88	1.26	1.20	1.04	1.26	1.20	1.20	1.04	0.82
2	CS25	1.97	0.77	0.66	0.88	1.15	1.26	1.42	1.26	1.04	0.88
3	CS24	-	0.27	1.86	1.97	1.92	1.92	1.86	1.75	1.42	1.37
4	CS23	-	-	1.20	1.26	0.77	1.20	1.31	1.42	1.59	1.10
5	CS22	-	-	1.64	2.30	2.36	2.19	2.08	2.03	1.70	1.75
6	CS21	-	-	1.48	1.92	2.25	2.14	1.75	1.48	1.20	1.10
7	CS20	-	-	1.92	2.03	2.14	2.46	2.63	2.74	2.19	2.08
8	CS19	-	-	1.86	2.41	2.52	2.57	2.57	2.79	2.25	2.30
9	CS18	0.44	0.82	1.70	2.08	1.75	1.64	2.19	2.46	2.30	2.08
10	CS17	0.93	1.31	1.75	2.30	2.36	2.30	2.74	3.29	2.41	2.25
11	CS16	1.04	1.53	1.86	2.46	2.52	2.74	2.96	3.01	1.97	2.08
12	CS15	1.10	1.37	2.08	2.63	2.68	2.85	2.74	2.30	1.64	1.75
13	CS14	1.37	1.75	2.63	2.74	2.46	3.12	3.01	2.68	1.86	1.86
14	CS13	1.53	1.64	2.41	2.41	2.46	3.01	3.01	2.96	1.92	1.86
15	CS12	1.64	2.08	2.08	2.63	2.46	3.18	3.01	2.85	1.10	1.75
16	CS11	1.31	1.64	2.08	1.97	2.41	2.63	2.52	2.68	1.20	1.10
17	CS10	1.75	1.97	2.08	1.97	2.30	2.63	2.52	2.52	1.53	1.10
18	C9	1.75	1.86	2.19	2.52	2.30	2.74	2.85	2.74	1.97	1.53
19	CS8	1.75	1.97	2.08	2.14	2.19	2.74	2.74	2.52	1.92	1.37
20	CS7	1.97	2.08	2.52	2.41	2.30	2.63	3.01	3.01	2.85	1.75
21	CS6	1.86	2.08	2.41	2.30	1.97	2.30	2.74	3.01	2.74	1.86
22	CS5	1.97	1.97	2.19	2.52	2.08	2.52	2.74	2.96	3.01	2.08
23	CS4	1.64	2.08	2.41	2.19	2.19	2.74	3.01	3.01	3.01	0.99
24	CS3	2.08	2.19	2.30	2.19	2.46	1.86	2.74	2.74	2.96	2.08
25	CS2	2.08	1.97	2.41	2.46	2.08	2.19	2.74	3.01	2.57	1.92
26	CS1	1.86	1.92	2.19	2.30	2.30	2.68	2.96	3.12	3.01	2.63

Table 5.13.2 Flow velocity in test T9 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	2.63	2.08	2.57	2.36	2.68	3.29	3.01	2.36	1.59
2	CS3	1.92	1.92	1.53	1.59	1.64	0.88	2.63	1.48	1.53
3	CS1	1.59	1.48	1.97	1.75	2.08	1.37	0.88	0.71	0.55

Table 5.13.3: Flow velocity in test T9 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.49
2	Between CS26 & CS25	0.93
3	CS25	0.93
4	CS24	1.97
5	CS23	1.75
6	CS22	1.92
7	CS21	1.42
8	CS20	2.08
9	CS19	2.41
10	CS18	2.08
11	CS17	2.63
12	CS16	3.01
13	CS15	3.18
14	CS14	2.68
15	CS13	3.01
16	Between CS13 & CS12	1.75
17	CS12 (End of LA)	1.42

From the above table, it can be seen that the maximum velocity 3.18 m/s at CS15 along the end of the launching apron.

Table 5.13.4: Scour in test T9 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS25	-0.6
2	CS24	-3.27
3	CS23	-6.06
4	CS22	-9.39
5	CS21	-10.98
6	CS20	-11.94
7	CS19	-11.16
8	CS18	-9.93
9	CS17	-8.82
10	CS16	-7.71
11	CS15	-7.14
12	CS14	-6.39
13	CS13	-5.4

From the above table, it can be seen that the maximum scour 11.94 m at CS20 along the end of the launching apron.

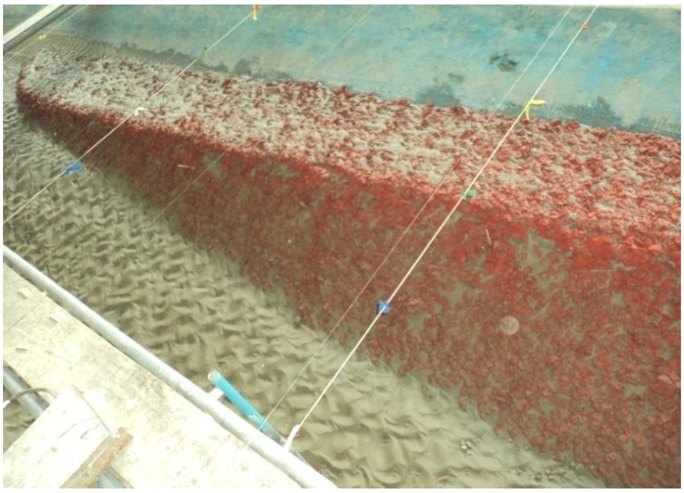

Figure 5.13.3: Launching pattern after test run (T9)

5.13.1 Findings

Along the end of the launching apron, scour occurred as the launching apron in the main channel is subjected to fully oblique flow. Maximum velocity along the end of launching apron is found around 3.18 m/s (CS15). Maximum scour along the end of launching apron is found around 11.94 m (CS20). Due to fully oblique flow, launching of geo-bags occurs. But mass failure is occurred and geo-bags can not cover the launching slope fully. At some places, there are some bare spaces and geo-bag slides down.

5.14 Test T10

Test T10 is conducted with 3 spurs (S1, S2 & S3). S1 is a solid spur fixed by cement plastering and there is no launching apron around this spur. S2 is an earthen spur, protected by CC blocks and its launching apron consists of CC blocks (as launching materials). S3 is an earthen spur, protected by geo-bags and in this case, geo-bags are used as launching materials in the launching apron.

The discharge 2025 m^3/s is distributed in such a way that the discharge ratio of main channel to shoot channel is 0.80. The discharge through the main and shoot channel is 1125m^3/s and 900 m^3/s respectively. The average velocity & scour depth were measured and flow field was recorded in this test. Here the absolute maximum scour around spur S1 was measured. In addition, scour values around the launching apron of spurs S2 & S3 have been measured. Also the performance of CC blocks & geo-bags as launching materials was tested here.

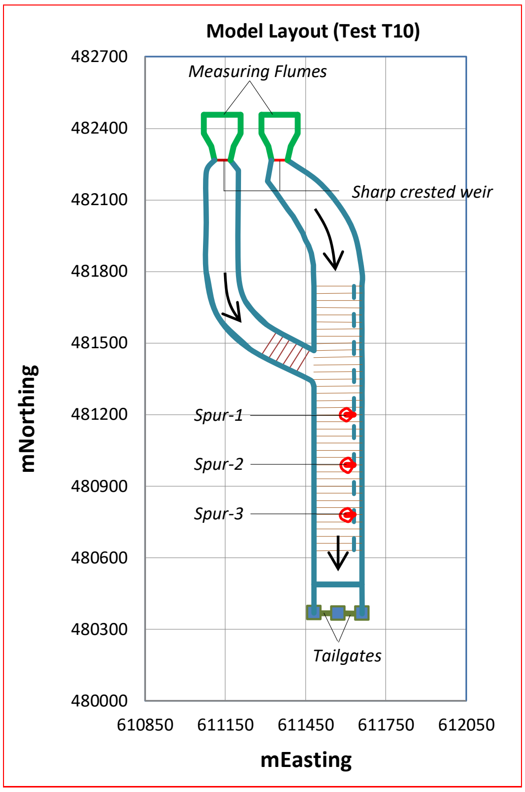

Figure 5.14.1: Layout of the model for test T0

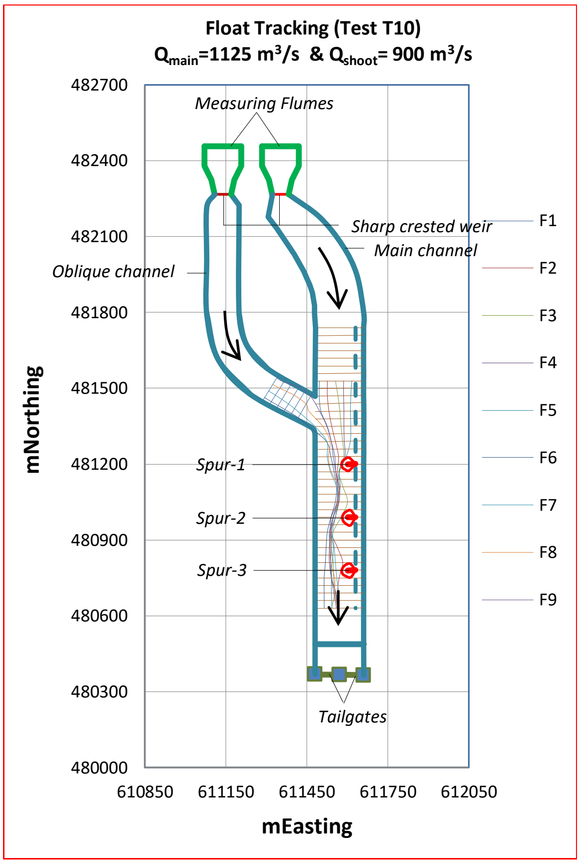

Figure 5.14.2: Flow field recorded by tracking floats from u/s to d/s in test T10

Table 5.14.1: Flow velocities at the cross-sections u/s, d/s and along the spurs S1, S2 & S3 in test T10

Sl. No.	CS No.	Velocity (m/s)										
		Distance from right boundary (m)										
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	135	150
10	CS23	0.11	0.33	1.64	2.19	2.41	2.14	1.97	2.08	2.36	1.75	-
12	CS21	1.10	1.53	1.64	1.92	1.64	2.46	1.53	1.64	0.66	0.00	-
13	**CS20**	1.37	1.20	1.64	2.46	2.30	2.30	1.37	1.92	-	-	-
14	CS19	1.42	1.75	1.92	1.92	1.64	2.30	1.37	0.00	0.00	0.00	-
19	CS14	2.08	2.63	3.01	2.74	2.19	2.85	2.74	1.92	1.86	1.20	
20	**CS13**	2.08	2.30	2.19	2.30	2.74	1.37	1.53	-	-	-	-
21	CS12	2.30	2.74	3.01	2.85	3.29	2.19	0.27	0.00	0.00	0.00	
26	CS7	2.63	3.01	3.01	3.01	2.74	2.46	2.08	1.20	0.66	0.27	
27	**CS6**	2.46	2.74	3.01	3.01	3.01	2.74	2.46	-	-	-	-
28	CS5	3.01	2.85	3.01	3.01	3.01	2.85	0.27	0.00	0.00	0.00	-

Table 5.14.2: Flow velocity around spurs at different points from upstream in test T10

Sl. No.	Flow velocity around the spurs (m/s)		
	Spur S1	Spur S2	Spur S3
1	1.64	1.53	0.66
2	2.19	1.20	0.82
3	2.08	1.97	1.31
4	2.19	2.46	2.41
5	0.55	2.85	2.74
6	-0.55	2.96	2.85
7	-0.82	1.53	3.01
8		0.66	2.19
9		-0.55	-0.27
10		-0.66	-0.55
11		-0.44	-0.44

From the above table, it can be seen that the maximum velocity around spurs S1, S2 & S3 is 2.19, 2.96 & 3.01 m/s respectively.

Table 5.14.3: Scour around spurs at different points from upstream in test T10

Sl. No.	Scour around the spurs (m/s)		
	Spur S1	Spur S2	Spur S3
1	-10.35	0.27	2.10
2	-11.82	-3.09	-0.57
3	-13.38	-5.55	-2.91
4	-13.23	-6.99	-4.47
5	-15.69	-7.14	-4.80
6	-19.62	-6.54	-5.19
7	-15.45	-6.75	-2.61
8	-7.50	-8.94	-8.13
9	-10.35	-12.72	-4.71
10	-11.82	-6.21	1.95
11	-13.38	-8.01	2.0

From the above table, it can be seen that the maximum scour around spurs S1, S2 & S3 is 19.62, 12.72 & 8.13 m.

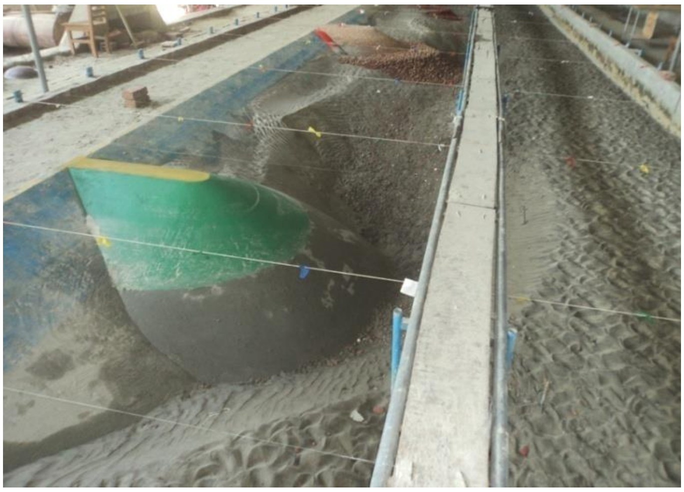

Figure 5.14.3: Launching pattern around spur S1 after test run (T10)

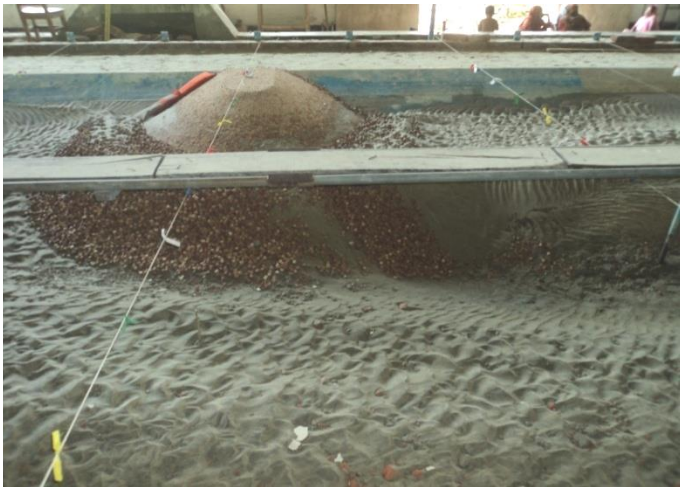

Figure 5.14.4: Launching pattern around spur S2 after test run (T10)

Figure 5.14.5: Launching pattern around spur S3 after test run (T10)

5.14.1 Findings

The spurs in this test are subjected to oblique flow. Maximum velocity around the spurs is found 2.19, 2.96 & 3.01 m/s respectively. Maximum scour around the spurs is measured as 19.62, 12.72 & 8.13 m respectively. In this test, CC blocks & geo-bags were displaced from the launching slope of spurs S2 & S3 respectively due to the development of scour hole & back flow.

5.15 Test T11

This test is done as per design suggested by Design Circle-VI, BWDB, Dhaka. Here the launching apron has two layers. Top layer consists of CC blocks & bottom layer consists of geo-bags. The total volume of launching materials (geo-bags + CC blocks) is 60 m^3/m. The CC block has two sizes: 45 cm cube & 35 cm cube. The percentage of CC block: 60% (45cm cube) and 40% (35cm cube). The geo-bag has two sizes: 1300 mm X 2100 mm (250 kg) and 1075 mm X 850 mm (175 kg). The percentage of geo-bag: 175 kg bag- 50% and 250 kg bag- 50%. The length of the launching apron is 30 m and its thickness is 2 m. The design of launching apron suggested by BWDB is shown in Figure 5.15.1.

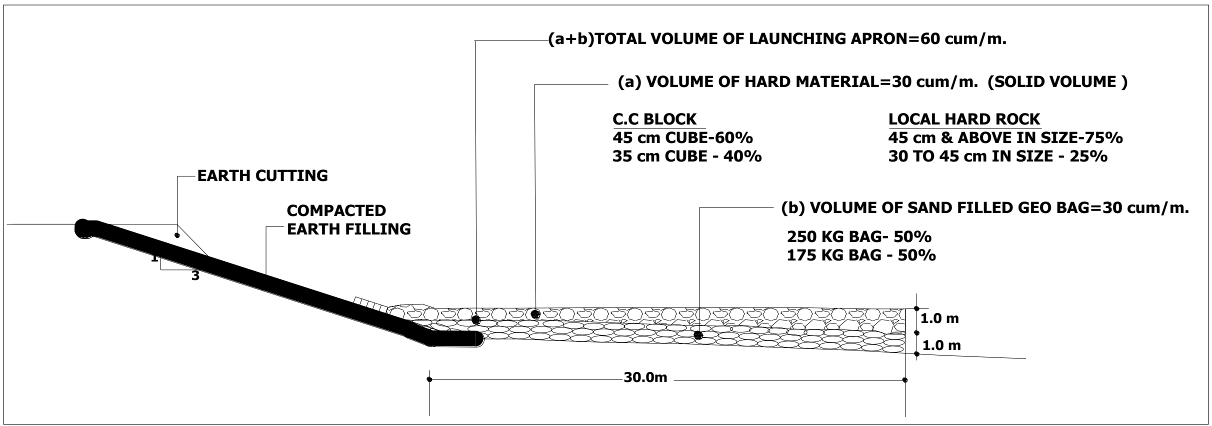

Figure 5.15.1: Design of launching apron suggested by Design Circle-VI of BWDB, Dhaka.

The discharge 2025 m^3/s is distributed in such a way that the discharge ratio of main channel to shoot channel is 0.80. The discharge through the main and shoot channel is 1125 m^3/s and 900 m^3/s respectively. The average velocity & scour depths were measured along the cross-sections and flow field was recorded in this test. The performance of composite launching apron (CC blocks + Geo-bags) was tested here.

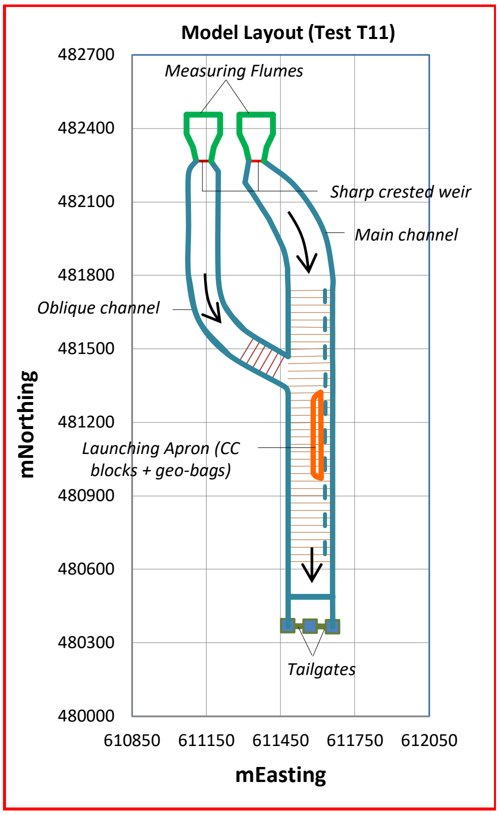

Figure 5.15.2: Layout of the model for test T11

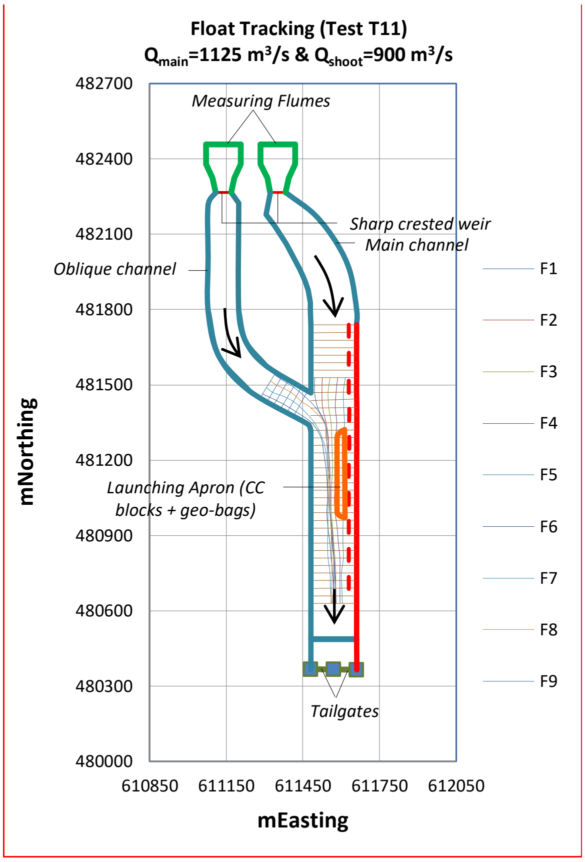

Figure 5.15.3: Flow field recorded by tracking floats from u/s to d/s in test T11

Table 5.15.1: Flow velocity in test T11 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	1.97	2.08	2.19	2.41	1.92	2.25	1.86	2.03	2.08	2.03
2	CS24	-0.11	1.37	1.48	1.10	1.64	2.08	1.20	0.77	1.31	1.20
3	CS23	-	0.66	2.30	2.63	2.41	2.08	2.30	2.36	2.30	2.41
4	CS22	-	0.55	1.20	1.64	2.41	2.08	2.08	2.03	2.08	2.08
5	CS21	0.77	0.88	2.30	2.46	2.52	2.41	2.41	2.30	2.14	2.19
6	CS20	1.37	1.48	1.97	2.19	2.46	1.97	2.30	1.97	1.75	1.97
7	CS19	1.31	1.20	1.64	1.97	2.08	2.30	2.52	1.42	1.20	1.53
8	CS18	1.48	1.75	2.30	2.63	2.36	1.92	2.46	1.75	1.86	2.08
9	CS17	1.20	1.31	1.53	2.36	2.30	1.37	1.75	1.59	1.59	2.19
10	CS16	1.64	2.19	2.41	2.46	2.52	2.41	2.46	2.08	2.08	2.08
11	CS15	1.10	1.04	1.75	1.86	1.75	2.08	1.86	2.03	1.59	1.64
12	CS14	1.75	2.36	2.57	2.68	2.63	2.63	2.30	1.70	1.86	2.03
13	CS13	1.10	1.75	1.70	2.19	1.81	2.25	2.52	1.64	1.53	2.36
14	CS12	1.70	2.36	2.63	2.68	2.25	2.85	3.18	1.26	1.15	1.48
15	CS11	1.26	1.37	1.53	1.97	1.97	2.08	2.41	1.64	1.10	1.31
16	CS10	1.59	1.75	2.14	2.19	2.14	2.30	2.41	2.03	1.31	1.10
17	C9	1.31	1.53	1.64	2.08	1.75	1.75	2.19	2.41	1.48	1.48
18	CS8	1.59	1.64	1.64	1.86	1.70	1.81	2.08	2.19	1.31	1.26
19	CS7	1.31	1.42	1.53	1.81	1.53	1.92	2.25	2.41	2.03	1.81
20	CS6	1.42	1.59	1.86	1.92	1.97	1.86	2.41	2.30	1.70	1.59
21	CS5	1.53	1.86	2.08	2.41	2.08	2.46	2.30	2.36	2.08	1.75
22	CS4	1.59	1.64	1.75	2.08	1.97	2.19	2.25	2.14	1.97	1.81
23	CS3	1.42	1.75	1.81	1.97	1.86	2.14	2.19	2.41	1.86	1.86
24	CS2	1.64	1.70	1.64	1.92	1.97	2.08	2.19	2.36	2.03	1.70
25	CS1	1.75	1.53	1.75	1.86	2.08	2.14	2.30	2.46	2.36	1.86

Table 5.15.2: Flow velocity in test T11 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.75	1.86	1.75	1.59	1.64	1.64	2.08	1.80	1.97
2	CS3	1.94	1.88	1.77	1.90	1.99	1.91	1.90	1.71	1.79
3	CS1	1.82	1.88	1.94	1.80	1.89	1.94	1.82	1.88	1.27

Table 5.15.3: Flow velocity in test T11 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	1.10
2	Between CS24 & CS23	0.99
3	CS23	2.30
4	CS22	1.75
5	CS21	2.41
6	CS20	2.74
7	CS19	1.86

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
8	CS18	2.41
9	CS17	1.20
10	CS16	2.74
11	CS15	1.81
12	CS14	2.68
13	CS13	2.68
14	Between CS13 & CS12	1.59
15	CS12 (End of LA)	1.64

From the above table, it can be seen that the maximum velocity 2.74 m/s at CS20/CS16 along the end of the launching apron.

Table 5.15.4: Scour in test T11 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS24 (Start of LA)	0.03
2	Between CS24 & CS23	-1.47
3	CS23	-2.28
4	CS22	-2.37
5	CS21	-4.02
6	CS20	-5.97
7	CS19	-7.32
8	CS18	-7.74
9	CS17	-6.75
10	CS16	-6.84
11	CS15	-6.00
12	CS14	-5.64
13	CS13	-5.13
14	Between CS13 & CS12	1.53
15	CS12 (End of LA)	0.06

From the above table, it can be seen that the maximum scour 7.74 m at CS18 along the end of the launching apron.

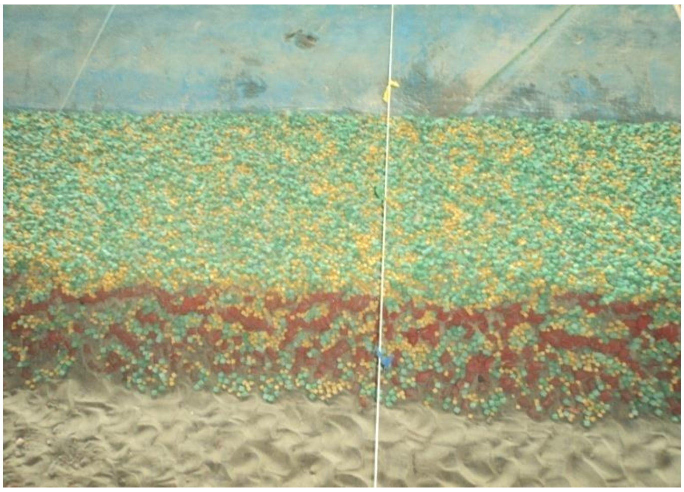

Figure 5.15.4: Launching pattern after test run (T11)

5.15.1 Findings

Along the end of the launching apron, scour occurred as the main channel is subjected to oblique flow. Maximum velocity along the end of launching apron is found around 2.74 m/s (CS16/CS20). Maximum scour along the end of launching apron is found around 7.74 m (CS18).

Due to the combination of straight and oblique flow, launching of composite apron (geo-bags + CC blocks) occurs nicely and covers the maximum sloping portion. Developed slope due to launching of composite apron is found better. The combined launching apron provides better performance than when using only geo-bags or only CC blocks as launching materials. Mass failure is found relatively lower than geo-bags.

5.16 Test T12

This test is same as test T11 but in this case, the inflow at the main channel is closed and the oblique channel is fed with total discharge (2025 m^3/s). The whole discharge from the oblique channel is passing through the main channel. The launching materials and their distribution are same as suggested by BWDB. The average velocity & scour depths were measured and flow field was recorded in this test. The performance of composite apron (CC blocks at top layer + geo-bags at bottom layer) was tested here.

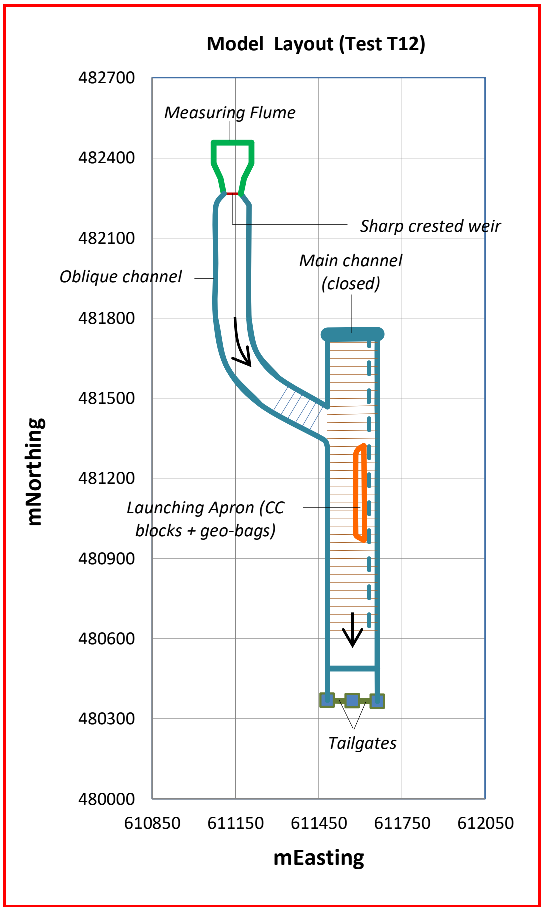

Figure 5.16.1: Layout of the model for test T12

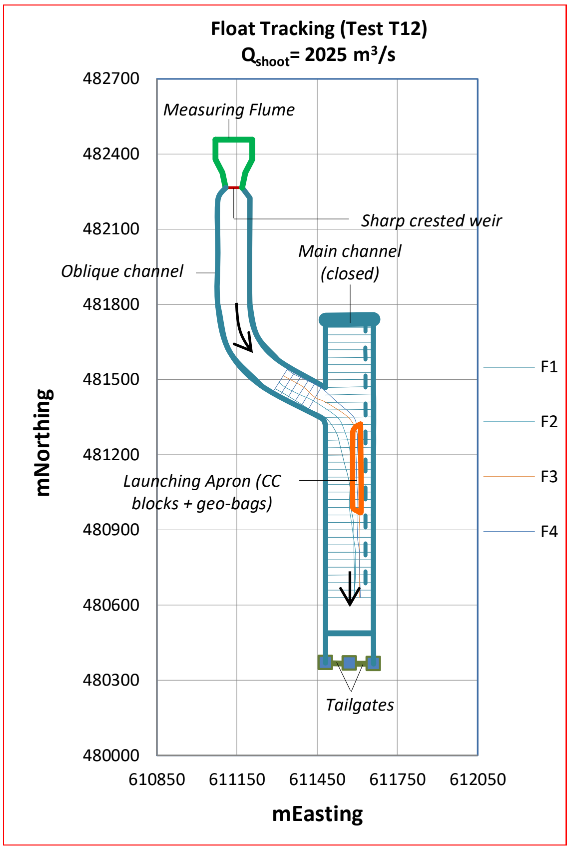

Figure 5.16.2: Flow field recorded by tracking floats from u/s to d/s in test T12

Table 5.16.1: Flow velocity in test T12 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.57	3.01	2.74	2.85	2.41	2.36	2.19	1.86	1.42	1.10
2	CS24	-	1.10	2.57	2.52	2.46	2.08	2.08	1.81	1.37	1.26
3	CS23	-	-	1.20	2.63	2.08	2.03	1.97	2.08	1.64	1.64
4	CS22	-	-	1.92	2.68	2.68	2.52	2.63	1.97	1.92	2.19
5	CS21	-	-	1.70	2.14	2.25	2.57	2.57	1.92	1.75	2.08
6	CS20	0.66	0.55	1.86	2.74	2.63	2.68	3.01	2.63	2.36	2.46
7	CS19	0.16	0.99	1.92	2.74	2.90	2.74	2.96	2.52	2.14	2.08
8	CS18	0.66	0.00	1.59	2.19	2.46	2.68	2.57	2.30	2.08	2.25
9	CS17	1.10	0.88	1.48	1.97	2.19	2.74	3.07	2.57	2.36	2.36
10	CS16	0.77	1.37	1.97	2.74	2.57	2.85	3.01	2.46	2.30	2.46
11	CS15	0.77	0.93	1.20	2.14	2.36	2.63	2.74	2.36	2.19	2.08
12	CS14	1.53	1.75	2.14	2.25	2.41	2.68	2.90	2.46	2.08	2.30
13	CS13	1.31	1.26	2.30	2.63	2.36	2.85	3.18	2.79	2.36	2.41
14	CS12	1.53	1.97	2.46	2.63	2.41	3.01	3.29	2.41	1.75	2.19
15	CS11	1.53	1.97	2.30	2.46	2.19	2.96	2.74	2.46	1.26	1.64
16	CS10	1.64	2.03	2.30	2.36	1.81	2.52	2.85	2.52	1.37	1.75
17	C9	1.75	1.97	2.41	2.41	2.19	2.30	2.96	3.01	2.08	1.92
18	CS8	1.75	1.75	1.70	1.64	1.64	1.75	2.30	2.63	1.92	1.75
19	CS7	1.97	2.25	2.41	2.46	1.70	2.41	2.74	2.63	2.41	1.86
20	CS6	1.75	1.42	1.75	1.75	1.42	1.53	2.19	2.41	2.25	1.97

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
21	CS5	1.86	2.08	2.14	2.03	1.97	2.19	2.52	2.30	2.19	1.75
22	CS4	1.53	1.59	1.42	1.10	1.10	1.64	3.01	3.01	2.85	1.10
23	CS3	1.92	1.97	1.86	1.75	1.75	2.08	2.63	2.85	2.63	2.08
24	CS2	1.31	1.48	1.53	2.14	1.75	1.92	2.30	2.63	2.30	2.19
25	CS1	1.31	1.75	1.92	1.97	2.03	2.57	2.57	2.85	2.74	2.14

Table 5.16.2: Flow velocity in test T12 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	1.93	2.16	2.18	2.11	2.00	2.29	2.11	2.19	2.16
2	CS3	1.97	1.90	1.97	1.84	1.90	1.97	1.92	1.75	1.97
3	CS1	1.84	1.85	1.90	1.90	1.93	1.92	1.97	1.90	1.91

Table 5.16.3: Flow velocity in test T12 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	1.48
2	Between CS24 & CS23	1.97
3	CS23	2.08
4	CS22	2.14
5	CS21	2.08
6	CS20	2.57
7	CS19	2.30
8	CS18	2.63
9	CS17	2.25
10	CS16	2.74
11	CS15	2.19
12	CS14	3.18
13	CS13	2.57
14	Between CS13 & CS12	1.97
15	CS12 (End of LA)	2.25

From the above table, it can be seen that the maximum velocity 3.18 m/s at CS14 along the end of the launching apron.

Table 5.16.4: Scour in test T12 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS24 (Start of LA)	0.00
2	Between CS24 & CS23	-1.29
3	CS23	-6.00
4	CS22	-10.44
5	CS21	-11.52
6	CS20	-11.79
7	CS19	-11.82
8	CS18	-11.28

Sl. No.	CS No.	Scour along the end of launching apron (m)
9	CS17	-7.74
10	CS16	-7.68
11	CS15	-8.22
12	CS14	-7.83
13	CS13	-6.39
14	Between CS13 & CS12	-2.70
15	CS12 (End of LA)	-0.24

From the above table, it can be seen that the maximum scour 11.82 m at CS19 along the end of the launching apron.

Figure 5.16.3: Launching pattern after test run (T12)

5.16.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 3.18 m/s (CS14). Maximum scour along the end of launching apron is found around 11.82 m (CS19).

Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron and covers the maximum slope portion. The combined launching apron (CC blocks + geo-bags) provides better performance than when using only geo-bags as launching materials. Due to the combination of straight and oblique flow, launching of composite apron (geo-bags + CC blocks) provides better performance. Aerial coverage of the slope by the composite materials is found good. Launching slope is found better than when providing only geo-bags. Mass failure is relatively lower than geo-bags.

5.17 Test T13

This test is same as test T12 but in this case, the length of the launching apron is 25 m instead of 30 m. Therefore, the thickness of launching apron is 2.4 m keeping the total volume of launching material same (60 m^3/m). The thickness of CC block & geo-bag is 1.2 m individually. The average velocity along the cross-sections & scour depths were measured and flow field was recorded in this test. The performance of composite apron (CC blocks + geo-bags) of reduced length was tested here.

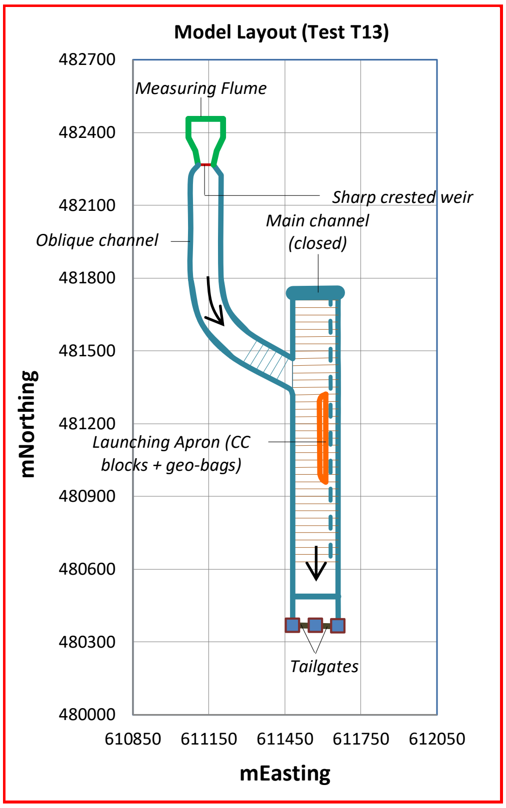

Figure 5.17.1: Layout of the model for test T13

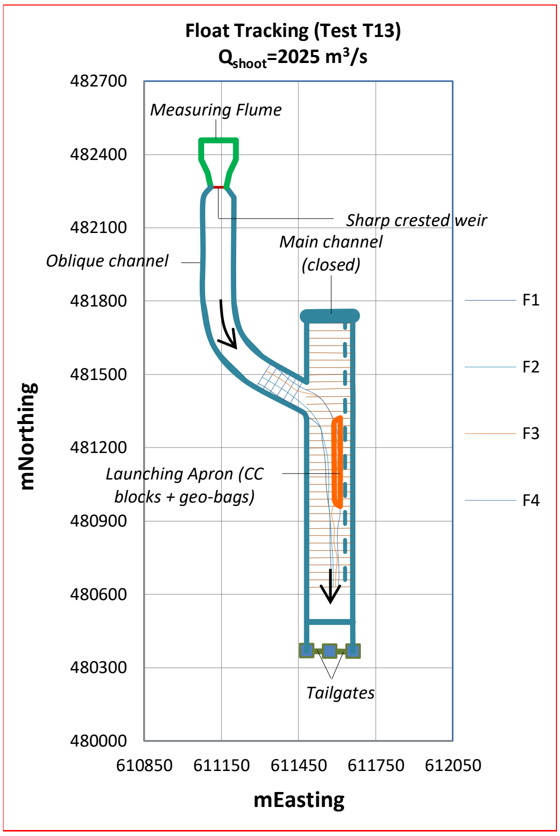

Figure 5.17.2: Flow field recorded by tracking floats from u/s to d/s in test T13

Table 5.17.1: Flow velocity in test T13 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.30	1.86	1.70	2.08	2.14	1.92	1.97	1.42	1.04	0.33
2	CS24	-0.22	0.49	1.59	1.81	1.70	1.64	1.70	1.75	1.48	1.31
3	CS23	-0.22	0.16	0.82	1.70	1.53	1.75	1.81	1.75	1.86	1.53
4	CS22	0.55	0.49	0.88	1.97	2.63	2.90	2.68	2.30	1.97	1.70
5	CS21	0.00	0.00	0.71	1.10	1.97	3.23	2.52	2.25	1.37	1.70
6	CS20	0.00	0.00	1.10	2.03	2.46	2.85	2.90	2.57	2.19	2.14
7	CS19	0.66	0.82	1.64	1.31	2.52	2.96	2.68	2.52	1.53	1.48
8	CS18	0.77	0.93	1.70	2.30	2.57	2.74	3.01	2.57	1.97	2.25
9	CS17	0.82	0.99	1.75	2.30	1.86	2.57	3.18	2.63	2.30	2.90
10	CS16	0.88	1.75	2.25	2.74	3.01	3.01	3.01	2.74	2.19	2.30
11	CS15	1.20	1.53	2.36	2.85	3.01	3.07	3.07	3.01	2.25	2.19
12	CS14	1.10	1.86	2.52	2.90	2.41	2.96	3.07	2.68	2.08	2.30
13	CS13	1.20	1.86	1.86	1.97	1.53	3.07	3.07	2.41	1.86	2.41
14	CS12	1.42	1.75	2.57	2.74	2.57	3.07	3.07	3.01	1.75	1.75
15	CS11	1.31	1.75	2.41	2.63	2.63	2.85	3.07	3.07	1.53	1.64
16	CS10	1.20	1.31	1.86	2.30	2.30	3.07	3.07	2.85	1.37	1.20
17	C9	1.31	1.48	1.59	1.75	1.75	2.41	2.46	3.07	1.86	1.42
18	CS8	1.64	1.70	2.14	2.19	2.30	2.46	3.07	3.07	2.30	1.86
19	CS7	1.59	1.48	1.86	1.75	1.86	2.30	2.52	2.96	2.41	1.81
20	CS6	1.86	2.03	2.41	2.03	1.75	2.41	2.41	2.52	2.41	2.03

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
21	CS5	1.42	1.75	1.86	1.92	1.86	2.19	2.46	2.46	2.30	1.86
22	CS4	1.86	2.19	1.97	2.41	2.41	2.96	2.96	3.07	2.96	2.41
23	CS3	2.14	2.30	2.30	2.08	1.97	2.41	3.07	3.07	2.30	2.08
24	CS2	2.14	2.36	2.19	2.03	2.30	2.74	3.07	2.74	3.07	1.64
25	CS1	2.30	2.57	2.63	2.52	2.14	2.68	3.07	3.07	2.85	2.63

Table 5.17.2: Flow velocity in test T13 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS6	2.15	2.18	2.16	2.26	1.72	2.35	2.23	2.13	2.29
2	CS4	2.01	2.07	2.10	2.14	2.50	2.42	2.30	1.92	2.25
3	CS2	2.08	1.74	1.86	1.90	1.92	2.63	1.75	1.76	1.81

Table 5.17.3: Flow velocity in test T13 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	1.37
2	Between CS24 & CS23	1.81
3	CS23	2.25
4	CS22	2.52
5	CS21	3.12
6	CS20	2.90
7	CS19	3.29
8	CS18	2.85
9	CS17	3.72
10	CS16	2.90
11	CS15	3.12
12	CS14	3.29
13	CS13	3.72
14	Between CS13 & CS12	3.01
15	CS12 (End of LA)	2.63

From the above table, it can be seen that the maximum velocity 3.72m/s at CS17 along the end of the launching apron.

Table 5.17.4: Scour in test T13 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS24 (Start of LA)	-0.09
2	Between CS24 & CS23	-1.65
3	CS23	-8.34
4	CS22	-7.86
5	CS21	-7.17
6	CS20	-7.89
7	CS19	-9.00
8	CS18	-8.43

Sl. No.	CS No.	Scour along the end of launching apron (m)
9	CS17	-8.04
10	CS16	-7.95
11	CS15	-8.04
12	CS14	-7.65
13	CS13	-6.90
14	Between CS13 & CS12	-0.18
15	CS12 (End of LA)	0.00

From the above table, it can be seen that the maximum scour 9.0 m at CS19 along the end of the launching apron.

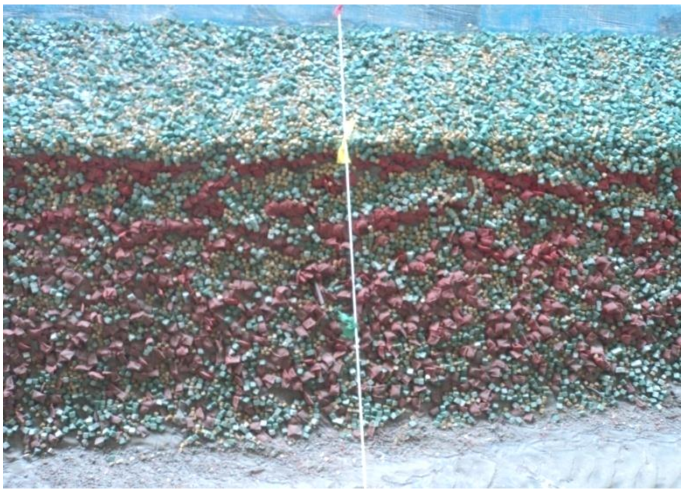

Figure 5.17.3: Launching pattern after test run (T13)

5.17.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 3.72m/s (CS17). Maximum scour along the end of launching apron is found around 9.0 m (CS19).

Due to oblique flow, launching of CC blocks + geo-bags occurs and covers the maximum slope portion but mass failure of geo-bag is more than test T12. The combined apron (CC blocks + geo-bags) provides no better performance than when its apron length is 30 m.

5.18 Test T14

This test is same as test T13 but in this case, the length of the launching apron is 35 m instead of 25m (Test T13). Therefore, the thickness of launching apron is 1.71 m keeping the total volume of launching material same (60 m^3/m). The thickness of CC block & geo-bag is 0.855m individually. The depth averaged velocity & scour depths were measured along cross-sections and flow field was recorded in this test. The performance of CC blocks + geo-bags was tested here

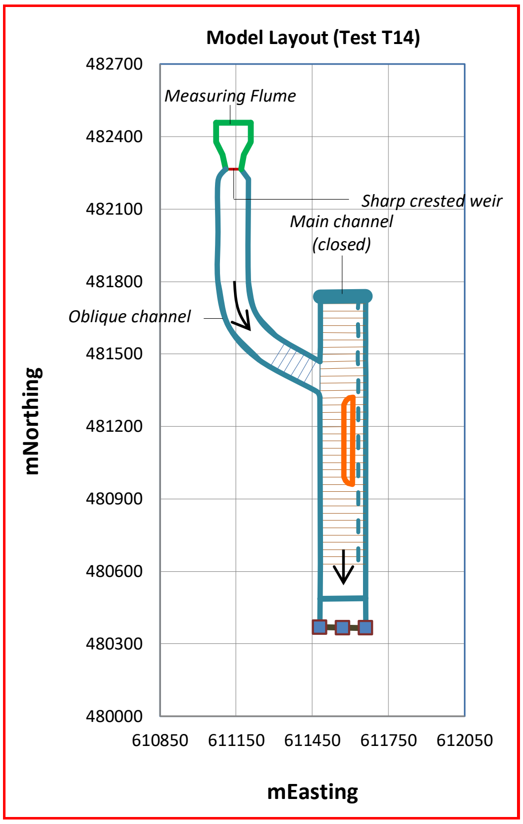

Figure 5.18.1: Layout of the model for test T14

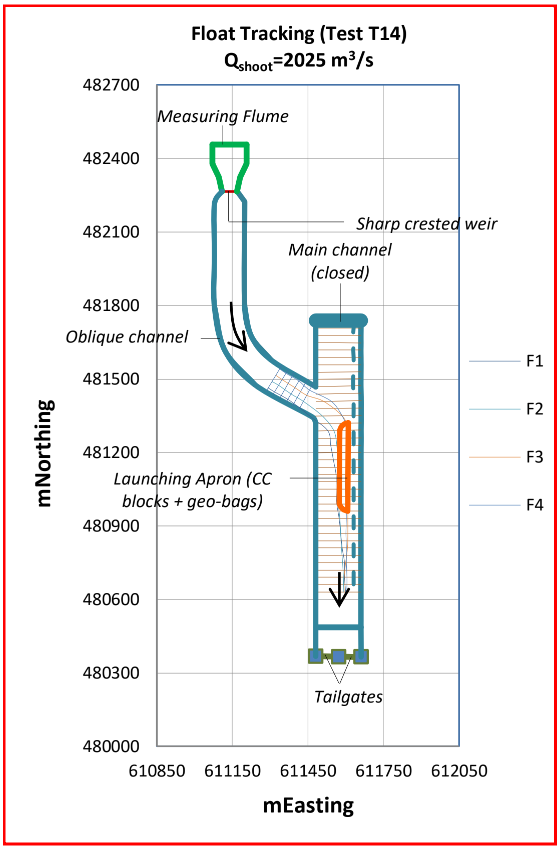

Figure 5.18.2: Flow field recorded by tracking floats from u/s to d/s in test T14

Table 5.18.1: Flow velocity in test T14 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.19	2.30	2.03	2.08	2.19	1.86	1.92	1.37	0.66	0.60
2	CS24	-	0.11	1.92	2.08	2.03	1.92	1.86	1.42	1.20	0.99
3	CS23	0.16	-	0.88	2.30	2.30	2.08	2.52	2.19	2.19	2.25
4	CS22	0.49	0.60	1.48	2.57	2.41	2.57	2.68	2.36	2.19	2.46
5	CS21	0.60	0.77	1.86	2.30	2.52	2.74	2.96	2.63	2.36	2.30
6	CS20	1.15	1.37	2.19	2.52	2.63	3.01	3.29	2.52	2.41	2.46
7	CS19	1.10	1.48	2.30	3.01	2.96	3.56	3.45	2.90	2.63	2.41
8	CS18	1.20	1.81	2.41	2.90	2.74	2.90	3.07	2.85	2.57	2.74
9	CS17	1.48	1.97	2.68	2.85	2.68	3.01	3.18	2.74	2.46	2.74
10	CS16	1.59	1.86	2.52	2.85	2.63	2.90	3.01	2.57	2.36	2.68
11	CS15	1.53	1.97	2.68	3.01	2.96	3.07	2.63	2.41	2.30	2.68
12	CS14	1.48	1.75	2.52	2.52	2.41	2.63	2.63	2.19	2.46	2.74
13	CS13	1.86	2.19	2.85	2.85	2.96	3.29	3.18	2.41	2.41	2.74
14	CS12	1.97	2.08	2.68	2.79	2.74	2.96	3.29	1.70	1.75	2.19
15	CS11	1.92	2.41	2.96	2.74	2.68	3.07	3.29	2.08	1.64	1.86
16	CS10	2.08	2.14	2.63	2.74	2.14	3.01	3.07	1.97	1.53	1.75
17	C9	1.86	2.52	2.74	2.68	2.46	3.01	3.29	2.63	1.92	1.70
18	CS8	2.08	2.41	2.63	2.74	2.63	2.52	3.01	3.01	2.14	1.97
19	CS7	1.86	2.46	2.74	2.74	2.19	2.52	3.01	3.01	2.30	2.19
20	CS6	2.08	2.19	2.46	2.74	2.30	2.52	2.85	3.01	2.57	2.19
21	CS5	2.08	2.46	2.74	2.96	2.52	2.74	3.07	3.07	2.46	2.25
22	CS4	2.30	2.52	2.52	2.68	2.25	2.36	2.30	2.41	2.03	2.08
23	CS3	2.19	2.63	2.96	2.74	2.30	2.90	3.01	3.07	2.74	2.30
24	CS2	1.97	2.08	2.36	2.25	2.08	1.64	1.86	2.08	1.70	1.59
25	CS1	2.25	2.25	2.30	2.25	2.19	2.63	2.85	2.74	2.36	2.08

Table 5.18.2: Flow velocity in test T14 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	2.15	2.16	2.11	2.36	2.11	2.11	2.22	2.36	2.01
2	CS4	1.64	1.97	1.73	1.97	1.87	1.87	1.74	1.90	1.87
3	CS1	1.90	1.95	1.94	1.90	1.92	1.73	1.84	1.90	1.82

Table 5.18.3: Flow velocity in test T14 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	0.99
2	Between CS24 & CS23	1.97
3	CS23	2.41
4	CS22	2.85
5	CS21	3.29
6	CS20	3.01
7	CS19	3.18

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
8	CS18	3.29
9	CS17	3.18
10	CS16	3.34
11	CS15	3.18
12	CS14	3.07
13	CS13	3.18
14	Between CS13 & CS12	1.97
15	CS12 (End of LA)	2.19

From the above table, it can be seen that the maximum velocity 3.34 m/s at CS16 along the end of the launching apron.

Table 5.18.4: Scour in test T14 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS24 (Start of LA)	-0.21
2	Between CS24 & CS23	-0.60
3	CS23	-4.80
4	CS22	-10.32
5	CS21	-10.11
6	CS20	-9.72
7	CS19	-9.90
8	CS18	-8.88
9	CS17	-8.10
10	CS16	-7.32
11	CS15	-6.00
12	CS14	-4.98
13	CS13	-3.60
14	Between CS13 & CS12	-0.33
15	CS12 (End of LA)	0.15

From the above table, it can be seen that the maximum scour 10.32 m at CS22 along the end of the launching apron.

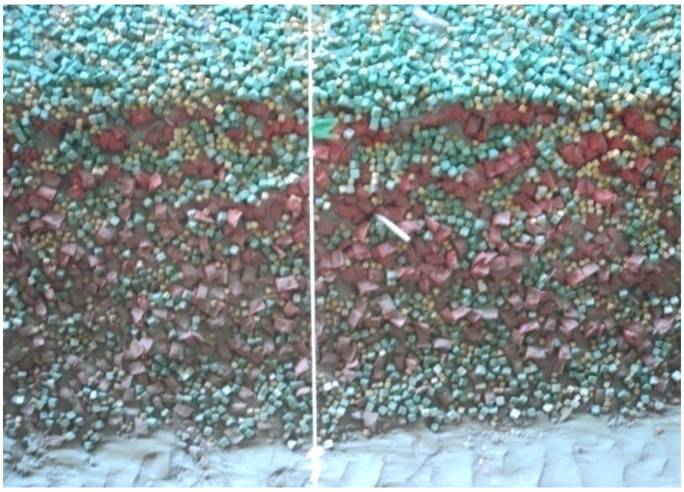

Figure 5.18.3: Launching pattern after test run (T14)

5.18.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 3.34 m/s (CS16). Maximum scour along the end of launching apron is found around 10.32 m (CS22).

Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron and it provides better performance than when the combined length of apron is 25 m. Mass failure of geo-bag is relatively less than that of test T13. Percentage of bare space is less than that of test T13.

5.19 Test T15

This test is same as test T14 but here the proportion of CC block & geo-bag is kept 40% & 60% in the launching apron. Total thickness of launching apron is 1.71 m keeping the total volume of launching material same (60 m^3/m). The thickness of CC block & geo-bag is 0.69 m & 1.02 m respectively. The depth averaged velocity & scour depths were measured and flow field was recorded in this test. The performance of CC blocks + geo-bags was tested here.

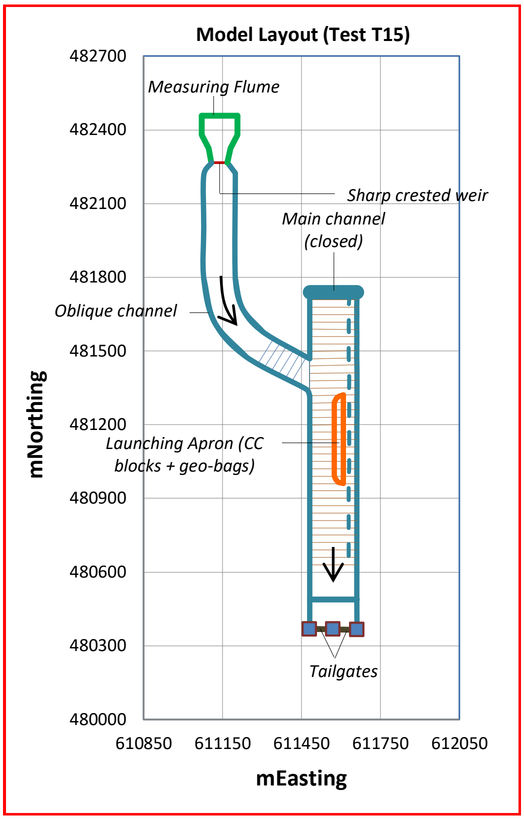

Figure 5.19.1: Layout of the model for test T15

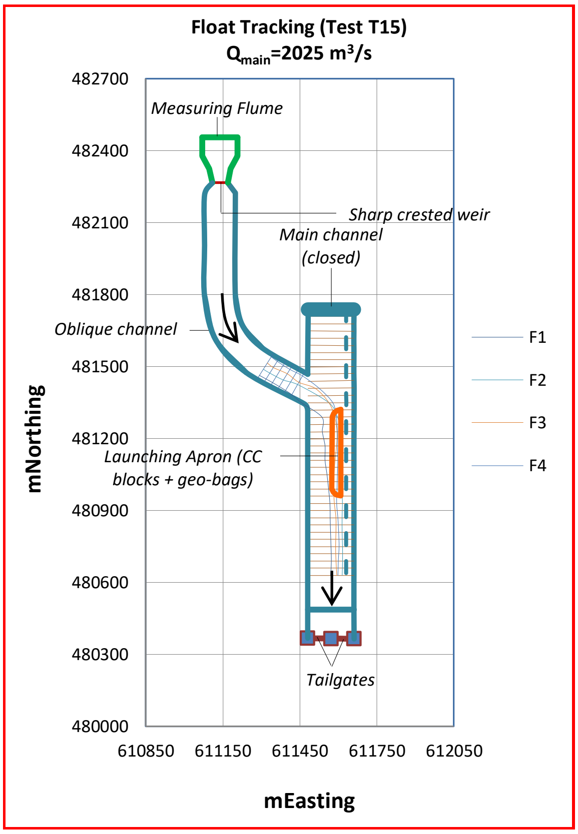

Figure 5.19.2: Flow field recorded by tracking floats from u/s to d/s in test T15

Table 5.19.1: Flow velocity in test T15 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	1.86	2.14	2.36	1.86	1.97	1.97	1.86	1.64	1.53	1.48
2	CS24	0.33	0.44	0.88	0.82	0.82	0.49	0.93	0.88	0.66	0.77
3	CS23	0.33	1.42	2.30	2.19	2.30	2.08	2.08	1.75	1.81	0.00
4	CS22	-	-	1.20	1.48	1.37	1.15	1.26	1.20	0.99	0.99
5	CS21	-	-	0.99	1.92	2.19	2.36	2.41	2.08	1.81	1.75
6	CS20	-	1.10	1.64	1.97	2.36	2.46	2.41	2.14	1.92	2.03
7	CS19	0.88	1.15	1.75	2.36	2.36	2.46	2.57	1.97	1.86	1.86
8	CS18	0.99	1.04	1.86	2.41	2.52	2.63	2.46	1.53	1.53	1.59
9	CS17	0.82	1.37	1.86	2.19	2.14	2.57	2.85	2.14	1.92	2.30
10	CS16	1.10	1.75	2.52	2.85	2.68	2.68	2.79	2.25	1.75	2.25
11	CS15	1.20	1.31	1.42	1.75	2.25	2.36	2.30	1.75	1.75	1.92
12	CS14	1.31	1.48	2.25	2.25	2.63	2.57	2.46	1.70	1.75	2.08
13	CS13	1.53	1.86	1.15	0.99	2.63	2.79	2.79	2.14	1.64	2.14
14	CS12	1.20	1.59	2.08	1.86	1.86	2.41	1.97	1.26	1.04	1.26
15	CS11	1.04	1.70	1.86	1.92	2.30	2.14	2.85	1.75	1.37	1.37
16	CS10	1.70	1.92	2.36	2.14	1.92	2.19	2.41	1.64	1.04	1.10
17	C9	1.92	1.97	2.14	2.30	2.08	2.19	2.79	2.63	1.53	1.53
18	CS8	2.19	2.41	2.41	2.41	2.36	2.52	3.01	2.68	1.75	1.70
19	CS7	1.64	1.75	1.75	1.86	2.25	2.19	2.68	2.68	1.92	1.70
20	CS6	2.14	1.86	1.86	1.92	1.86	1.86	2.41	2.30	1.86	1.75
21	CS5	1.81	2.08	2.08	2.08	1.92	2.08	2.46	2.41	1.97	1.75
22	CS4	2.08	1.86	1.81	1.81	1.75	1.86	2.25	2.36	2.08	1.70
23	CS3	1.75	1.86	1.86	1.86	1.75	1.92	2.36	2.68	2.30	2.08
24	CS2	2.03	1.86	1.86	1.81	1.81	1.75	2.14	1.86	2.08	1.86
25	CS1	1.97	2.14	2.08	2.08	1.97	2.03	1.86	2.52	1.97	2.03

Table 5.19.2: Flow velocity in test T15 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	2.40	2.01	2.00	2.31	2.42	2.11	1.94	2.11	1.72
2	CS3	2.08	1.92	2.34	1.75	1.75	1.81	1.92	1.70	1.70
3	CS1	2.15	2.26	2.04	2.26	2.10	1.93	1.88	1.96	1.89

Table 5.19.3: Flow velocity in test T15 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS24 (Start of LA)	0.99
2	Between CS24 & CS23	1.15
3	CS23	2.19
4	CS22	1.15
5	CS21	2.08
6	CS20	2.68
7	CS19	2.63
8	CS18	2.85

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
9	CS17	2.96
10	CS16	3.01
11	CS15	2.52
12	CS14	3.18
13	CS13	2.90
14	Between CS13 & CS12	1.20
15	CS12 (End of LA)	0.82

From the above table, it can be seen that the maximum velocity 3.18 m/s at CS14 along the end of the launching apron.

Table 5.19.4: Scour in test T15 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS24 (Start of LA)	0.18
2	Between CS24 & CS23	-1.08
3	CS23	-10.92
4	CS22	-11.97
5	CS21	-11.79
6	CS20	-12.18
7	CS19	-11.85
8	CS18	-10.74
9	CS17	-9.42
10	**CS16**	-11.31
11	CS15	-8.22
12	CS14	-7.44
13	CS13	-5.88
14	Between CS13 & CS12	-3.96
15	CS12 (End of LA)	-0.18

From the above table, it can be seen that the maximum scour 12.18 m at CS20 along the end of the launching apron.

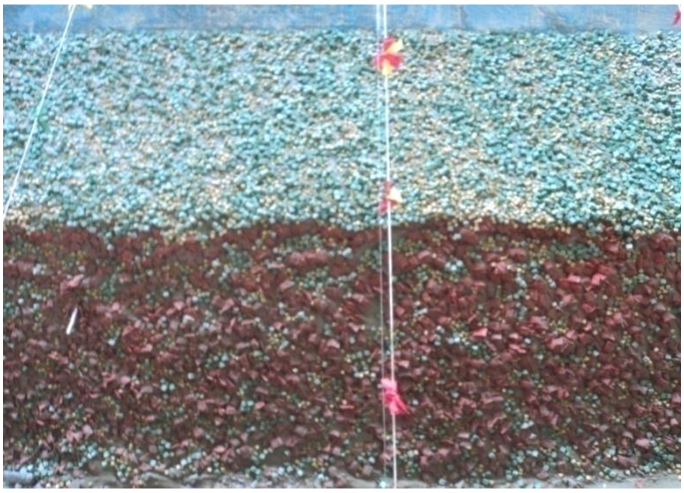

Figure 5.19.3: Launching pattern after test run (T15)

5.19.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 3.18 m/s (CS14). Maximum scour along the end of launching apron is found around 12.18 m (CS20).

Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron. The combined launching apron (CC blocks 40% + geo-bags 60%) provides poor performance relative to test T14 (CC blocks 50% + geo-bags 50%). Mass failure of geo-bag is more than that of test T14. Percentage of bare space is also more than test T14.

5.20 Test T16

This test is same as test T14 but here the launching apron is shifted 60 m upstream at CS26 instead of CS24. The launching apron consists of CC block 50% and geo-bag 50%. Total thickness of launching apron is 1.71 m. The thickness of CC block & geo-bag is 0.855 m individually. The depth averaged velocity & scour depths were measured and flow field was recorded in this test. The performance of CC blocks + geo-bags was tested here.

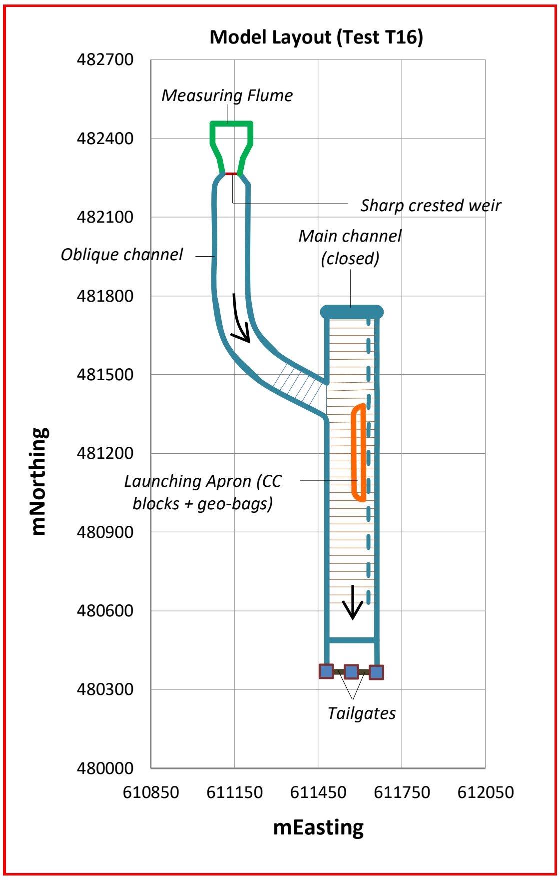

Figure 5.20.1: Layout of the model for test T16

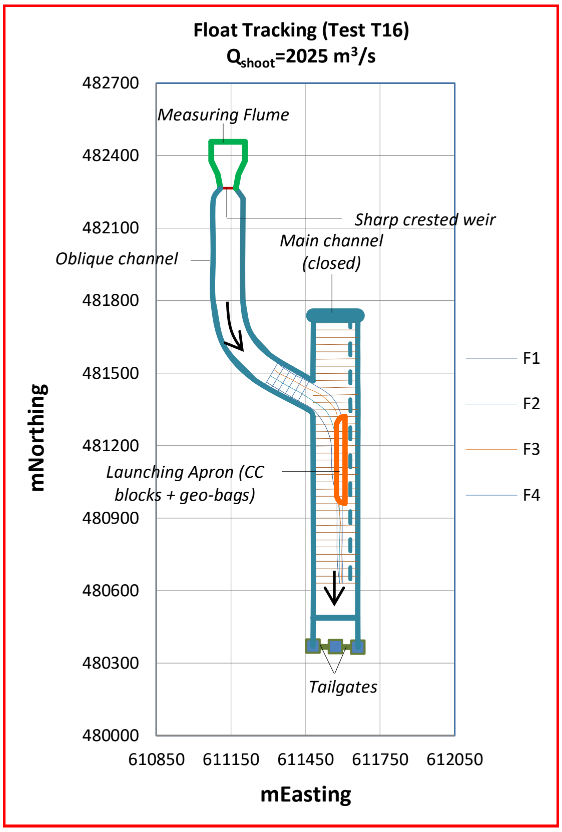

Figure 5.20.2: Flow field recorded by tracking floats from u/s to d/s in test T16

Table 5.20.1: Flow velocity in test T16 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.14	2.25	2.41	2.08	1.97	1.75	1.59	1.48	1.20	0.99
2	CS24	-	0.22	0.77	0.93	1.31	0.99	1.53	1.48	1.37	1.37
3	CS23	-	-	2.08	2.46	2.52	2.52	2.19	2.14	1.86	1.86
4	CS22	-	-	1.04	0.88	0.11	-0.44	0.05	2.25	1.81	1.75
5	CS21	-	-	1.59	2.41	2.41	2.68	2.03	2.19	1.86	2.03
6	CS20	-	-	2.08	2.41	1.70	1.53	2.79	2.52	2.46	2.52
7	CS19	-	-	2.08	2.57	2.63	2.74	2.57	2.52	2.52	2.68
8	CS18	0.33	1.31	2.36	2.79	2.68	2.85	3.01	2.46	2.41	2.63
9	CS17	0.66	1.53	1.53	2.68	2.57	2.74	3.18	2.19	2.19	2.52
10	CS16	0.93	1.64	2.46	2.14	1.53	1.37	2.96	2.52	2.41	2.41
11	CS15	1.37	1.64	2.19	2.74	2.46	2.74	3.29	2.19	2.19	2.08
12	CS14	1.10	1.64	2.19	2.03	2.14	2.36	2.68	1.64	1.37	2.03
13	CS13	1.10	1.10	1.64	1.64	1.97	2.46	2.74	2.19	1.59	1.97
14	CS12	1.42	1.64	2.19	2.19	2.14	2.08	2.19	2.74	1.70	1.64
15	CS11	1.10	1.70	2.19	2.08	2.19	2.19	2.36	2.68	1.64	1.75
16	CS10	1.48	1.64	1.70	1.97	1.42	1.97	2.19	2.68	2.19	1.70
17	C9	1.64	2.19	2.19	1.86	1.97	2.19	2.68	2.90	2.30	2.08
18	CS8	1.64	1.75	1.97	1.75	1.70	1.10	2.19	2.14	2.14	2.03
19	CS7	2.25	2.36	2.52	2.46	2.14	2.74	2.96	2.74	2.19	2.30
20	CS6	1.92	2.03	2.08	2.30	1.92	2.08	2.85	3.01	2.74	1.97

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
21	CS5	2.41	2.57	2.46	2.41	2.30	2.63	3.01	3.07	2.63	2.41
22	CS4	1.75	1.97	1.75	1.75	1.20	0.88	1.97	2.30	2.30	1.64
23	CS3	2.41	2.46	2.52	2.19	1.97	2.74	3.07	3.01	2.96	2.52
24	CS2	2.52	2.57	2.52	2.19	2.41	1.97	2.30	3.29	3.01	2.46
25	CS1	2.19	2.46	2.14	2.08	2.19	2.63	2.74	3.01	2.19	2.46

Table 5.20.2: Flow velocity in test T16 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	2.07	2.10	2.17	2.15	2.34	2.36	2.14	2.29	2.19
2	CS3	2.31	1.66	1.88	1.77	2.20	2.31	2.53	1.91	1.85
3	CS1	1.94	1.73	1.76	1.95	1.90	1.91	1.64	1.82	1.91

Table 5.20.3: Flow velocity in test T16 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.16
2	Between CS26 & CS25	0.55
3	CS25	1.53
4	CS24	2.03
5	CS23	2.25
6	CS22	2.41
7	CS21	2.63
8	CS20	2.63
9	CS19	2.57
10	CS18	2.68
11	CS17	2.68
12	CS16	3.18
13	CS15	3.29
14	Between CS15 & CS14	1.10
15	CS14 (End of LA)	1.92

From the above table, it can be seen that the maximum velocity 3.29 m/s at CS15 along the end of the launching apron.

Table 5.20.4: Scour in test T16 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS26 (Start of LA)	0.00
2	Between CS26 & CS25	0.48
3	CS25	-0.72
4	CS24	-8.37
5	CS23	-11.31
6	CS22	-12.48
7	CS21	-12.45
8	CS20	-12.75

Sl. No.	CS No.	Scour along the end of launching apron (m)
9	CS19	-12.09
10	CS18	-10.68
11	CS17	-9.09
12	CS16	-8.40
13	CS15	-7.50
14	Between CS15 & CS14	-6.96
15	CS14 (End of LA)	-0.18

From the above table, it can be seen that the maximum scour 12.75 m at CS20 along the end of the launching apron.

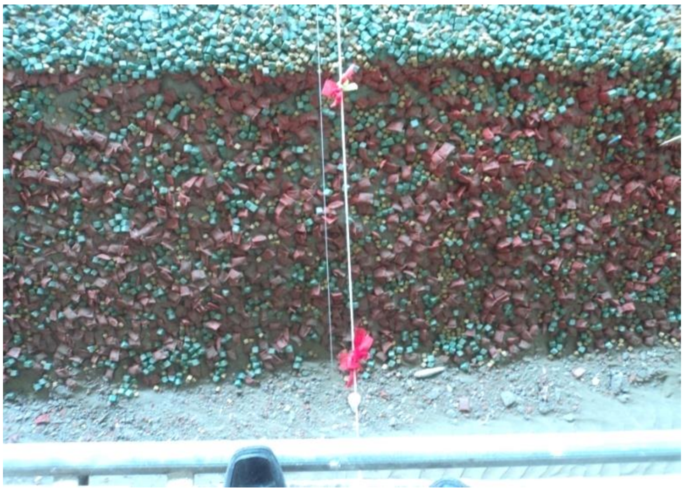

Figure 5.20.3: Launching pattern after test run (T16)

5.20.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 3.29 m/s (CS15). Maximum scour along the end of launching apron is found around 12.75 m (CS20).

Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron. The combined launching apron (CC blocks 50% + geo-bags 50%) provides better performance relative to test T15 (CC blocks 40% + geo-bags 60%) because of lower mass failure of geo-bag is observed along the slope. Bare space is relatively lower than that of single composition of geo-bag.

5.21 Test T17

This test is same as test T12 but here the launching apron is shifted 60 m upstream at CS26 instead of CS24 and the CC blocks portion of launching apron consists of 45 cm cube- 50% (instead of 60% as in the suggested design by BWDB) and 35 cm cube- 50% (instead of 40% as in the suggested design by BWDB). The proportion of geo-bags (250 kg bag 50% and 175 kg bag 50%) is kept same as in the suggested design. Total thickness of launching apron is 2.0 m (1 m thick CC blocks and 1 m thick geo-bags). The depth averaged velocity & scour depths were measured and flow field was recorded in this test. The performance of CC blocks + geo-bags was tested here.

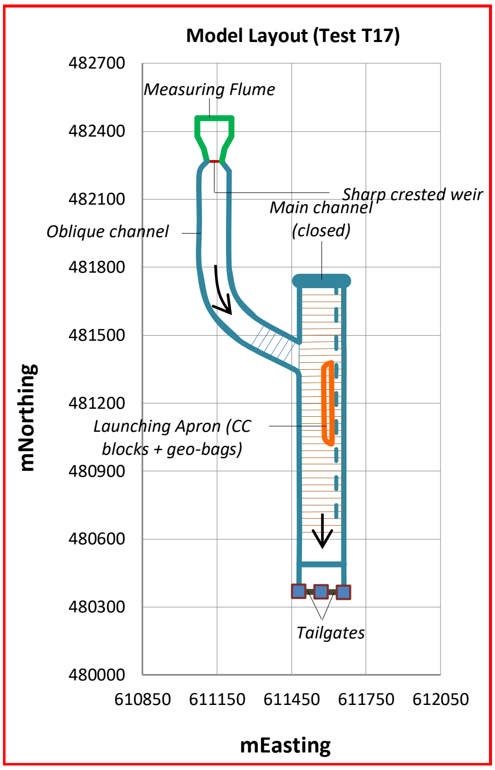

Figure 5.21.1: Layout of the model for test T17

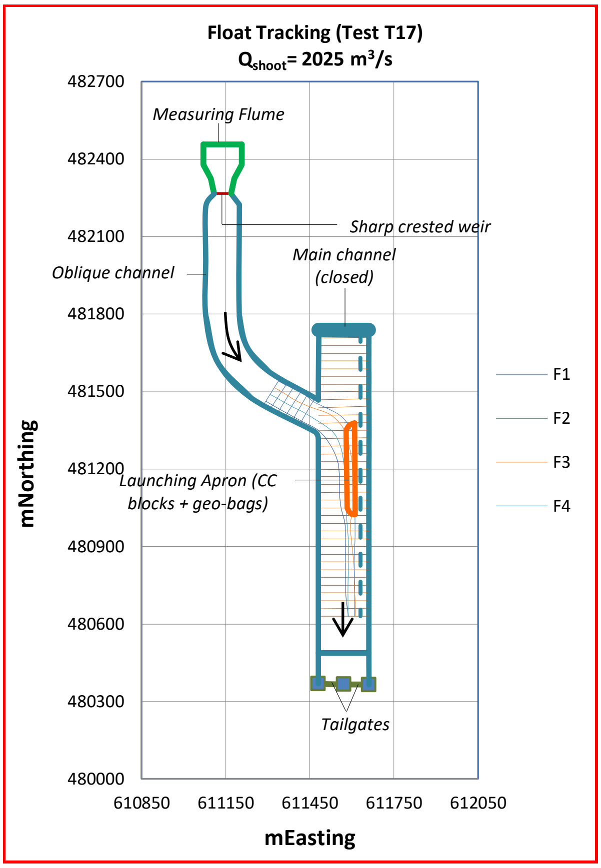

Figure 5.21.2: Flow field recorded by tracking floats from u/s to d/s in test T17

Table 5.21.1: Flow velocity in test T17 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.41	2.57	2.36	2.30	2.03	1.75	1.53	1.53	1.26	1.04
2	CS24	-	2.74	2.46	2.25	2.25	2.14	1.75	1.26	0.71	0.60
3	CS23	-	-	1.10	2.25	2.63	2.36	2.08	1.75	1.53	1.48
4	CS22	-	-	1.15	2.25	2.68	2.74	2.68	2.30	1.92	1.75
5	CS21	-	-	1.53	1.92	1.86	2.25	2.14	2.08	1.92	1.86
6	CS20	-	-	1.64	2.41	3.01	2.74	2.74	2.19	1.92	1.75
7	CS19	-	-	1.26	1.97	2.41	2.52	2.57	2.25	2.08	2.36
8	CS18	0.11	0.33	0.99	1.75	2.03	2.30	2.63	2.19	2.14	2.19
9	CS17	0.44	0.77	1.64	2.08	2.46	2.68	2.90	2.30	2.03	2.19
10	CS16	0.33	0.99	1.86	2.63	2.90	2.85	3.34	2.63	2.19	2.30
11	CS15	0.71	1.37	1.97	2.36	2.52	2.74	3.01	2.52	1.92	2.19
12	CS14	0.99	1.15	1.48	2.19	1.92	2.41	3.12	2.36	1.81	2.25
13	CS13	1.31	1.42	1.64	2.08	2.30	2.36	2.57	2.30	1.92	1.81
14	CS12	1.42	1.53	1.75	1.97	2.25	2.30	2.90	3.07	2.46	2.03
15	CS11	1.53	1.75	1.86	2.03	2.19	2.41	2.63	2.85	2.57	2.08
16	CS10	1.75	2.14	2.36	2.41	2.46	2.85	3.01	3.29	2.68	2.57
17	C9	1.86	2.03	1.97	1.97	2.08	2.30	2.57	2.74	2.52	2.19
18	CS8	2.19	2.25	2.14	2.03	1.97	2.03	2.08	2.52	2.03	1.92
19	CS7	1.97	1.92	2.03	2.19	2.46	2.74	2.85	2.63	2.52	2.41

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
20	CS6	1.86	1.81	1.92	1.81	1.75	2.19	2.41	2.46	2.52	2.30
21	CS5	2.03	1.97	1.81	1.92	1.97	2.41	2.68	2.57	2.63	2.46
22	CS4	1.75	1.86	2.03	1.86	1.92	2.08	2.52	2.63	2.57	2.41
23	CS3	1.97	2.19	2.30	2.08	2.30	2.63	2.74	2.85	2.74	2.63
24	CS2	1.92	1.81	1.86	1.75	1.92	2.57	2.85	3.01	3.18	2.74
25	CS1	2.08	2.25	2.19	1.97	1.86	2.46	2.52	2.63	2.57	2.46

Table 5.21.2: Flow velocity in test T17 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	2.18	2.07	2.40	2.34	2.29	2.53	2.56	2.52	2.40
2	CS3	1.93	1.99	1.92	1.86	1.90	1.90	2.31	1.77	1.49
3	CS1	2.13	2.56	2.36	1.95	1.93	1.93	1.91	1.90	1.90

Table 5.21.3: Flow velocity in test T17 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.49
2	Between CS26 & CS25	0.88
3	CS25	1.64
4	CS24	0.99
5	CS23	2.25
6	CS22	2.46
7	CS21	2.74
8	CS20	2.46
9	CS19	2.63
10	CS18	2.74
11	CS17	2.74
12	CS16	2.63
13	CS15	2.85
14	Between CS15 & CS14	2.19
15	CS14 (End of LA)	2.08

From the above table, it can be seen that the maximum velocity 2.85 m/s at CS15 along the end of the launching apron.

Table 5.21.4: Scour in test T17 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS26 (Start of LA)	0.15
2	Between CS26 & CS25	0.66
3	CS25	-1.32
4	CS24	-7.35
5	CS23	-10.23
6	CS22	-11.46
7	CS21	-12.81

Sl. No.	CS No.	Scour along the end of launching apron (m)
8	CS20	-12.42
9	CS19	-12.36
10	CS18	-11.52
11	CS17	-9.99
12	CS16	-9.78
13	CS15	-8.13
14	Between CS15 & CS14	-6.78
15	CS14 (End of LA)	-0.06

From the above table, it can be seen that the maximum scour 12.81 m at CS21 along the end of the launching apron.

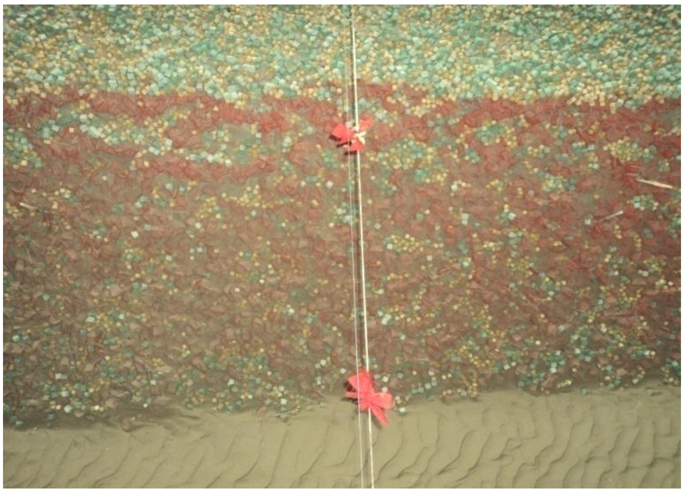

Figure 5.21.3: Launching pattern after test run (T17)

5.21.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 2.85m/s (CS15). Maximum scour along the end of launching apron is found around 12.81 m (CS21).

Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron. The combined launching apron (CC blocks 1 m thick: 45 cm cube 50% & 35 cm cube 50% + geo-bags 1 m thick: 250 kg bag 50% & 175 kg bag 50%) provides better performance relative to test T12 (CC blocks 1 m thick- 45 cm cube 60% & 35 cm cube 40% + geo-bags 1 m thick- 250 kg bag 50% and 175 kg bag 50%) because of bare space is relatively lower than test T16. Smooth channel is formed along the LA.

5.22 Test T18

This test is same as test T17 but here the CC blocks portion of launching apron consists of 45 cm cube 40% (instead of 50% in test T17) and 35 cm cube 60% (instead of 50% in test T17). The proportion of geo-bags (250 kg bag 50% and 175 kg bag 50%) is same as in the proposed design. Total thickness of launching apron is 2m (1m thick CC blocks and 1m thick geo-bags). The depth averaged velocity & scour depths were measured and flow field was recorded in this test. The performance of CC blocks +geo-bags was tested here.

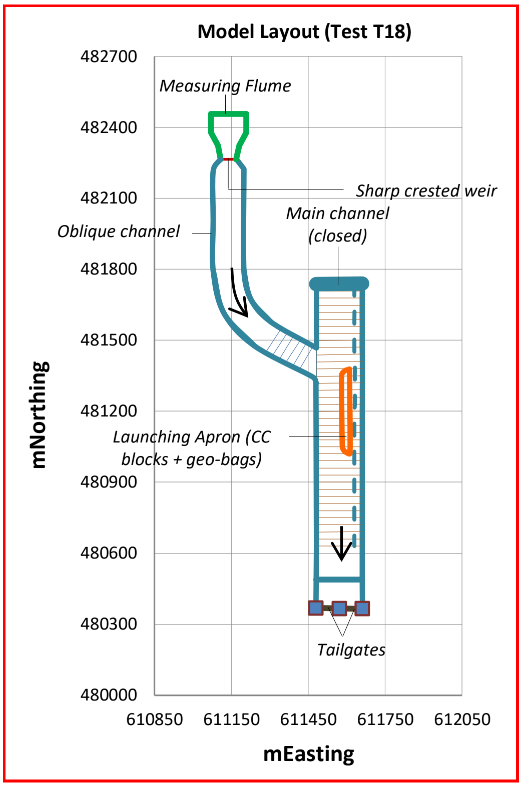

Figure 5.22.1: Layout of the model for test T18

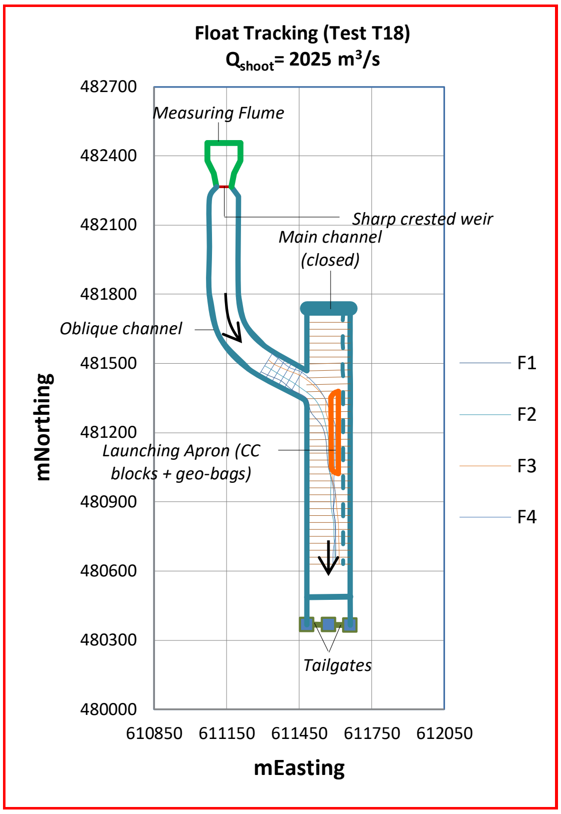

Figure 5.22.2: Flow field recorded by tracking floats from u/s to d/s in test T18

Table 5.22.1: Flow velocity in test T18 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS25	2.30	2.63	2.30	2.19	1.75	1.10	1.64	1.42	1.26	1.53
2	CS24	-	1.31	2.68	2.63	2.46	2.41	1.75	1.53	1.42	1.64
3	CS23	-	-	0.88	2.08	2.14	2.19	1.86	1.86	1.64	1.75
4	CS22	-	-	1.20	1.75	1.86	1.70	1.86	1.75	1.42	1.59
5	CS21	-	1.20	1.31	1.75	1.92	1.97	2.03	1.92	1.86	1.86
6	CS20	0.33	0.55	1.42	1.64	2.08	1.75	2.19	1.75	1.59	2.08
7	CS19	-	0.77	1.42	1.86	2.08	2.08	2.30	2.19	2.08	2.19
8	CS18	0.77	0.88	1.10	1.75	2.08	1.86	2.19	1.97	1.97	2.08
9	CS17	0.88	0.71	1.53	2.19	2.41	2.63	2.41	2.14	1.97	2.30
10	CS16	0.55	0.66	1.15	1.53	1.86	2.19	2.85	2.14	1.75	1.64
11	CS15	0.88	0.99	1.31	1.75	2.36	2.19	2.63	1.86	1.10	2.19
12	CS14	0.77	0.99	1.42	1.59	1.31	1.53	3.01	1.10	1.10	1.75
13	CS13	0.93	1.31	1.59	1.64	1.97	2.30	2.41	2.46	1.64	1.59
14	CS12	0.82	0.99	0.99	0.99	1.31	1.20	1.59	1.37	0.99	1.10
15	CS11	1.10	1.42	1.64	1.64	1.86	1.97	2.41	2.57	1.64	1.59
16	CS10	0.88	1.20	1.59	1.64	1.59	1.37	2.08	2.41	1.86	1.64
17	C9	1.42	1.75	1.86	1.75	1.75	1.86	2.30	2.52	2.14	1.97
18	CS8	1.53	1.42	1.48	1.20	1.20	1.10	1.10	1.31	1.20	0.99
19	CS7	1.86	1.75	1.86	1.64	1.70	2.03	2.25	2.30	2.19	1.92
20	CS6	1.59	1.97	1.86	1.86	1.86	2.08	2.41	3.01	2.68	2.03

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
21	CS5	1.86	1.81	1.97	1.86	1.86	2.25	2.46	2.52	2.41	2.19
22	CS4	1.64	1.53	1.75	1.75	1.81	1.64	1.59	1.81	2.08	2.14
23	CS3	1.92	2.19	2.36	2.19	2.03	2.30	2.63	2.68	2.46	2.30
24	CS2	1.75	1.81	2.25	2.14	2.08	2.41	2.74	3.01	2.74	2.36
25	CS1	2.19	2.36	2.30	2.25	2.14	2.52	2.68	2.74	2.63	2.46

Table 5.22.2: Flow velocity in test T18 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	**CS**5	2.10	2.35	2.10	2.01	2.20	2.36	2.24	2.45	2.43
2	**CS**3	2.53	1.90	1.90	1.90	1.94	1.66	1.99	1.86	1.91
3	**CS** 1	1.90	1.88	1.99	1.71	1.66	1.66	1.66	1.77	1.99

Table 5.22.3: Flow velocity in test T18 along the end of launching apron

Sl. No.	CS No.	Flow velocity along the end of launching apron (m/s)
1	CS26 (Start of LA)	0.99
2	Between CS26 & CS25	1.10
3	CS25	1.31
4	CS24	1.64
5	CS23	1.75
6	CS22	2.08
7	CS21	1.92
8	CS20	1.86
9	CS19	2.19
10	CS18	2.30
11	CS17	2.46
12	CS16	2.19
13	CS15	2.30
14	Between CS15 & CS14	2.19
15	CS14 (End of LA)	2.25

From the above table, it can be seen that the maximum velocity 2.46 m/s at CS17 along the end of the launching apron.

Table 5.22.4: Scour in test T18 along the end of launching apron

Sl. No.	CS No.	Scour along the end of launching apron (m)
1	CS26 (Start of LA)	0.21
2	Between CS26 & CS25	0.75
3	CS25	-1.53
4	CS24	-5.79
5	CS23	-9.24
6	CS22	-10.83
7	CS21	-11.67
8	CS20	-12.09
9	CS19	-11.43

Sl. No.	CS No.	Scour along the end of launching apron (m)
10	CS18	-10.86
11	CS17	-10.08
12	CS16	-9.51
13	CS15	-7.71
14	Between CS15 & CS14	-6.03
15	CS14 (End of LA)	-0.09

From the above table, it can be seen that the maximum scour 12.09 m at CS20 along the end of the launching apron.

Figure 5.22.3: Launching pattern after test run (T18)

5.22.1 Findings

Along the end of the launching apron, scour occurred as the oblique channel is fed with total discharge (2025 m^3/s). Maximum velocity along the end of launching apron is found around 2.46 m/s (CS17). Maximum scour along the end of launching apron is found around 12.09 m (CS20). Due to oblique flow, launching of CC blocks + geo-bags occurs along the end of the launching apron. The combined launching apron (CC blocks 1 m thick: 45 cm cube 40% & 35 cm cube 60% + geo-bags 1 m thick: 250 kg bag 50% & 175 kg bag 50%) provides best performance relative to test T17 (CC blocks 1 m thick: 45 cm cube 50% & 35 cm cube 50% + geo-bags 1 m thick: 250 kg bag 50% &175 kg bag 50%) because of bare space is relatively lower than test T17. Developed channel around the launching apron is well shaped. The numbers of CC blocks rolled in the developed channel are less. More numbers of CC blocks are retained on the developed slope. Test T18 is the recommended test among all tests in case of revetment.

5.23 Test T19

Test T19 is conducted with 2 spurs (S1 & S2). Each shank length is 30m and launching apron (LA) length is 30 m. The LA of spur S1 has two layers and each layer is 1 m thick. Top layer of LA of spur S1 consists of 45 cm cube 40% & 35 cm 60% and bottom layer of LA consists of 250 kg geo-bag 50% & 150 kg geo-bag 50% (same material composition as in test T18). The launching apron of spur S2 is 2 m thick and LA consists of 125 kg geo-bag. Both the shank & slope of spurs S1 & S2 are fixed by cement plastering. Spurs S1 (u/s) & S2 (d/s) are placed at CS20 & CS13 respectively. And distance between them is 210 m. The discharge 2025 m^3/s is distributed in such a way that the discharge ratio of shoot channel to main channel is 0.80. The discharge through the main and shoot channel is 1125

m^3/s and 900 m^3/s respectively. The depth averaged velocity & scour depths were measured flow field was recorded in this test. Here maximum scour around spurs S1 & S2 was determined. Also the performance of LA around spurs S1 & S2 was tested here.

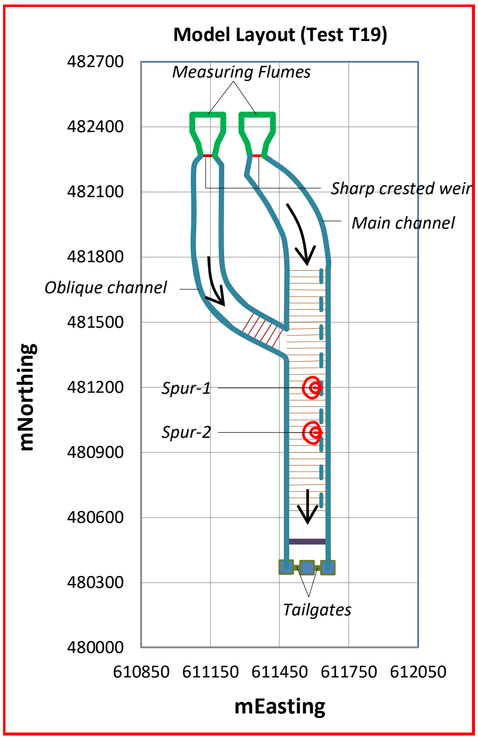

Figure 5.23.1: Layout of the model for test T19

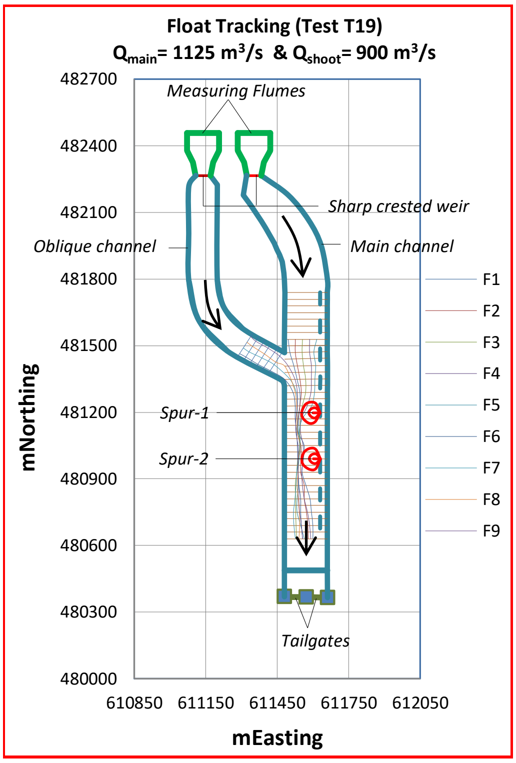

Figure 5.23.2: Flow field recorded by tracking floats from u/s to d/s in test T19

Table 5.23.1: Flow velocity in test T19 (main channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS32	1.37	1.26	1.42	1.59	1.64	1.48	1.53	1.64	1.31	1.20
2	CS31	1.31	1.48	1.53	1.75	1.75	1.64	1.64	1.81	1.59	1.53
3	CS30	1.53	1.37	1.48	1.64	1.81	1.92	2.19	2.36	2.19	2.14
4	CS29	1.15	1.37	1.26	1.48	1.37	1.48	1.75	1.81	1.92	1.81
5	CS28	1.37	1.64	1.70	1.59	1.64	1.53	1.48	1.53	1.81	1.75
6	CS27	1.42	1.81	1.97	1.75	1.75	1.70	1.92	1.81	1.92	1.70
7	CS26	1.92	2.08	2.19	2.14	1.53	1.48	1.53	1.86	1.59	1.64
8	CS25	2.46	2.30	2.14	1.97	1.64	1.31	1.20	1.59	1.75	1.64
9	CS24	0.11	2.57	2.30	1.97	1.75	1.53	1.42	1.48	1.48	1.75
10	CS23	0.88	0.55	2.30	2.14	1.97	1.53	1.10	1.20	1.42	1.59
11	CS22	0.88	1.31	1.26	2.30	1.97	1.86	1.64	1.26	1.48	0.99
12	CS21	1.64	1.59	1.53	1.97	1.64	1.31	0.99	0.82	0.55	0.22
13	CS20	1.42	1.64	2.08	2.19	2.25	2.74	2.85	2.57	-	-
14	CS19	1.53	1.53	1.75	2.08	1.86	0.66	0.05	-0.11	-0.33	-0.22
15	CS18	1.15	1.15	1.75	1.92	2.14	0.44	-0.22	-0.60	-0.22	-0.44
16	CS17	1.42	1.53	1.75	1.75	2.30	1.20	0.66	0.05	0.00	-0.33
17	CS16	1.59	1.59	1.53	1.75	1.97	1.31	0.88	0.66	0.44	0.00
18	CS15	2.08	1.92	2.03	2.30	2.52	1.97	1.31	1.04	0.88	0.49
19	CS14	2.03	2.08	2.36	1.92	2.14	1.42	1.53	1.20	0.82	0.60
20	CS13	1.97	1.97	2.03	2.41	2.36	2.08	1.86	1.97	-	-
21	CS12	1.64	2.19	2.41	2.30	2.63	2.14	2.41	0.44	0.00	0.16
22	CS11	2.14	2.19	2.52	2.52	2.52	1.37	0.66	0.33	0.00	0.00
23	CS10	2.14	2.63	3.56	3.56	3.01	1.97	1.31	1.20	0.66	0.44
24	CS9	2.08	2.03	3.67	2.30	2.08	1.86	1.75	1.31	0.88	0.99
25	CS8	2.41	2.63	2.68	2.52	2.36	2.30	2.14	1.53	0.99	0.88
26	CS7	2.03	2.74	2.68	2.41	2.52	2.41	2.46	2.03	1.37	1.10
27	CS6	2.36	2.41	2.63	2.46	2.63	2.85	2.63	2.08	1.59	1.20
28	CS5	1.86	2.63	2.30	2.57	3.29	3.29	2.63	2.52	2.19	1.64
29	CS4	2.74	2.85	2.79	2.74	3.01	2.90	2.41	2.19	1.75	1.42
30	CS3	2.57	2.68	2.74	2.79	2.85	2.57	2.46	2.08	1.86	1.31
31	CS2	2.41	2.63	2.41	2.74	2.68	2.46	2.36	2.36	1.81	1.48
32	CS1	2.46	2.85	2.57	2.63	2.74	2.63	2.52	2.46	2.08	1.70

Table 5.23.2: Flow velocity in test T19 (shoot channel)

Sl. No.	CS No.	Velocity (m/s) Distance from right boundary (m)							
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	1.86	1.64	1.75	1.84	1.94	1.70	1.92	1.64	1.93
2	CS3	1.90	1.91	1.97	1.99	1.53	1.92	1.73	1.59	1.75
3	CS 1	1.87	1.96	1.81	1.77	1.92	1.94	1.99	1.86	1.92

Table 5.23.3: Flow velocity at different points around the launching apron (LA) of spurs from u/s LA end to d/s LA end in test T19

Sl. No.	Flow velocity around the spurs (m/s)	
	S1	S2
1	0.93	0.44
2	2.19	0.66
3	2.30	1.31
4	2.52	1.75
5	2.52	2.41
6	2.74	2.90
7	3.01	3.01
8	2.36	2.63
9	0.99	2.36
10	0.00	2.30
11	0.00	1.53

From the above table, the maximum velocity is found as 3.01 m/s around the LA of spurs S1 & S2 each.

Table 5.23.4: Scour at different points around the launching apron of spurs from u/s end to d/s end in test T19

Sl. No.	Scour around the spurs (m/s)	
	S1	S2
1	0.03	0.48
2	0.09	1.83
3	-1.11	2.34
4	-3.66	-2.31
5	-6.15	-7.59
6	-9.03	-7.68
7	-10.44	-7.83
8	-10.71	-7.44
9	-12.48	-6.96
10	-4.56	0.42
11	1.50	0.60

From the above table, it can be seen that the maximum scour around the LA of spurs S1 & S2 is 12.48 & 7.83 m. The maximum scour is found as 15.95 m which is d/s of LA of spur S1.

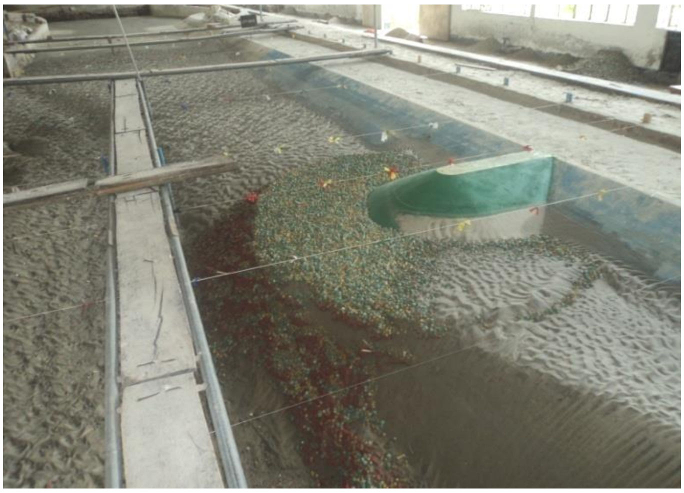

Figure 5.23.3: Launching pattern around spur S1 after test run (T19)

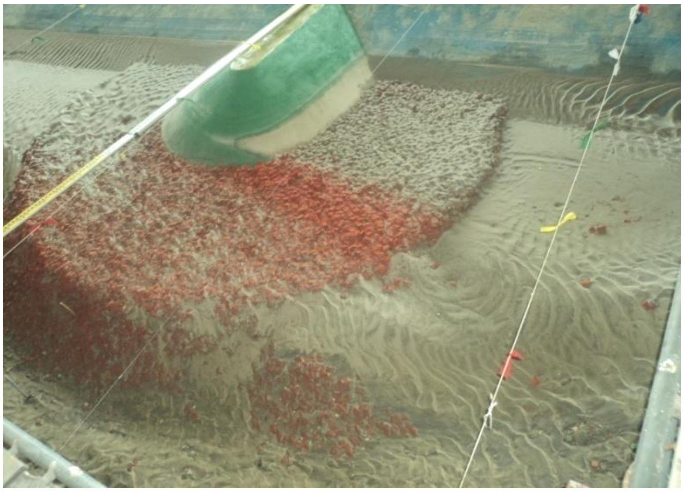

Figure 5.23.4: Launching pattern around spur S2 after test run (T19)

5.23.1 Findings

In this test, scour is occurred around the spurs due to the combined flow (main flow is subjected to oblique flow). Maximum scour is found as 12.48 m & 7.83 m in the vicinity of LA of spurs S1 & S2 respectively. Maximum velocity is found as 3.01 m/s in the vicinity of the LA of spurs S1 & S2 each. Maximum scour is found as 15.95 m which is d/s of LA of spur S1.

Launching pattern of combined material (CC block + geo-bag) is better than providing only geo-bag because of less bare space on the launching slope. There is a massive scour hole d/s of spur which does not allow launching material to retain on the developed slope. From the d/s part of LA of spur S1 (start from spur axis), more CC blocks & geo-bags were displaced towards d/s. Bare space is more. Mass failure of geo-bag is observed.

5.24 Test T20

Test T20 is same as test T19 but the d/s part of LA of spurs S1 & S2 (start from spur axis) consists of stone-chips only at the top & bottom layer. The of u/s part of LA of spurs S1 & S2 (from shank axis) is same as test T19. The depth averaged velocity & scour depths were measured and flow field was recorded in this test. Here maximum scour around the spurs S1 & S2 was determined. Also the performance of LA around spurs S1 & S2 was tested here.

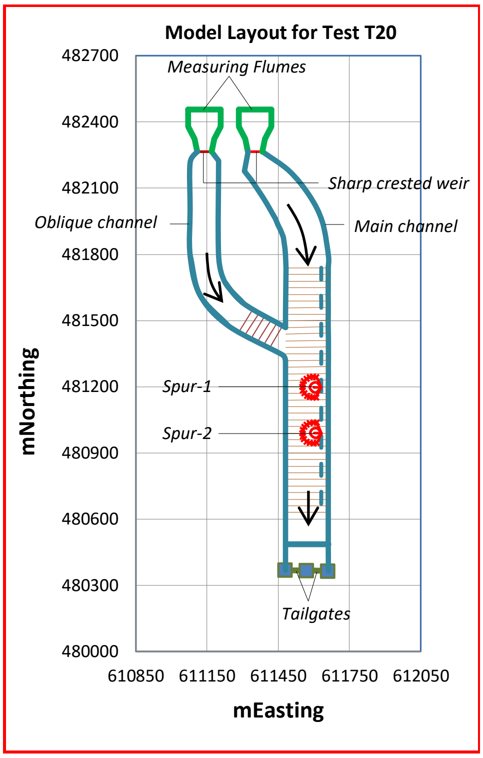

Figure 5.24.1: Layout of the model for test T20

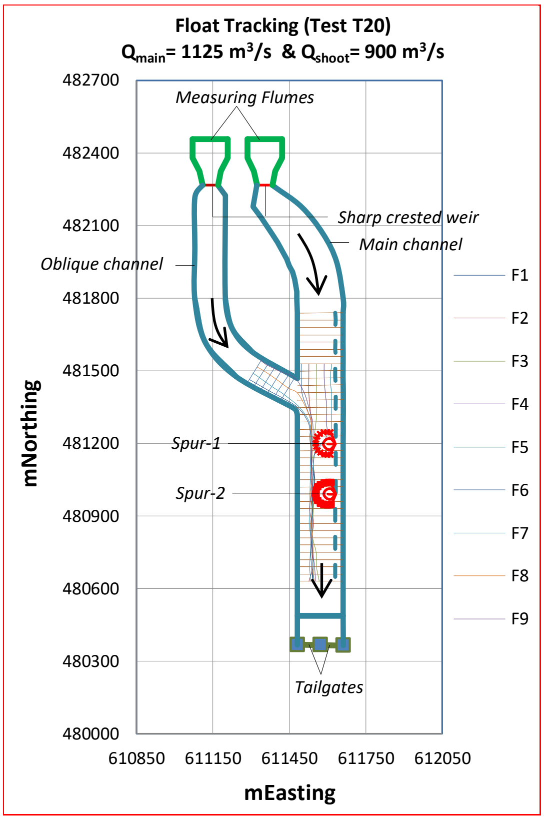

Figure 5.24.2: Flow field recorded by tracking floats from u/s to d/s in test T20

Table 5.24.1: Flow velocity in test T20 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS32	1.37	1.64	1.64	1.53	1.42	1.37	1.37	1.53	1.53	1.31
2	CS31	1.20	1.04	1.26	1.48	1.37	1.31	1.53	1.75	1.70	1.42
3	CS30	0.77	1.75	1.86	1.81	1.70	1.86	1.81	2.08	1.92	1.81
4	CS29	0.44	1.20	1.81	1.64	0.99	1.20	1.37	1.64	1.42	1.31
5	CS28	0.82	1.20	1.42	1.42	1.42	1.42	1.64	1.53	1.64	1.64
6	CS27	1.59	1.86	1.97	1.86	1.75	1.75	1.86	1.92	1.86	1.64
7	CS26	0.66	0.66	0.33	0.16	0.22	0.44	0.55	1.42	0.93	0.82
8	CS25	2.63	2.68	2.63	2.30	2.36	2.08	1.42	1.59	1.86	1.75
9	CS24	-0.44	-0.11	0.22	0.55	0.77	1.04	1.20	1.31	1.31	1.31
10	CS23	-	0.44	0.77	1.10	1.26	1.20	1.37	1.26	1.10	1.10
11	CS22	0.44	0.66	0.55	0.49	1.04	1.20	1.42	1.53	1.48	0.33
12	CS21	0.77	1.04	0.99	1.10	1.20	1.86	1.97	1.64	1.31	0.66
13	CS20	0.77	1.42	1.31	1.31	1.20	1.97	2.30	1.31	-	-
14	CS19	1.20	1.53	1.59	1.31	1.86	1.75	1.42	0.88	0.44	0.44
15	CS18	1.81	1.64	2.03	2.08	1.75	0.22	0.00	0.00	0.00	0.00
16	CS17	2.19	2.19	2.08	1.75	1.75	0.33	0.00	0.00	0.00	0.00
17	CS16	2.19	2.30	2.57	2.19	2.25	1.64	0.93	0.00	0.00	0.00
18	CS15	1.97	2.03	1.92	2.46	2.41	2.19	1.64	1.37	0.66	0.22
19	CS14	1.92	1.86	1.97	2.14	2.08	1.59	1.53	1.15	0.55	0.27
20	CS13	2.14	2.36	2.25	2.68	2.36	2.08	1.86	2.08	-	-
21	CS12	1.86	1.64	1.75	2.30	2.63	1.42	1.26	0.22	0.00	0.00
22	CS11	1.97	2.14	2.41	2.52	2.63	1.15	1.10	0.82	0.38	0.44
23	CS10	1.97	2.36	2.57	2.46	2.14	1.20	1.04	0.93	0.66	0.55
24	CS9	2.46	2.74	2.57	2.36	2.14	1.92	1.97	1.48	1.10	0.60
25	CS8	2.03	2.36	2.52	2.30	2.46	2.36	2.46	2.30	1.48	1.10
26	CS7	2.19	2.57	2.41	2.36	2.46	2.14	2.30	2.36	1.64	1.48
27	CS6	2.14	2.46	2.74	2.85	2.63	2.74	2.68	2.52	2.19	1.64
28	CS5	2.36	2.30	1.97	2.36	2.52	2.36	2.25	1.92	1.64	1.53
29	CS4	2.30	2.41	2.74	2.68	2.74	2.57	2.52	2.36	2.03	1.81
30	CS3	2.36	2.57	2.41	2.52	2.63	2.46	2.30	2.19	1.92	2.19
31	CS2	1.92	2.85	2.74	2.79	2.90	2.96	2.90	2.36	2.03	2.14
32	CS1	2.19	2.74	2.63	2.46	2.52	2.68	2.30	2.08	1.81	2.03

Table 5.24.2: Flow velocity in test T20 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	1.91	1.92	1.64	1.94	1.59	1.93	1.90	1.98	1.91
2	CS3	1.99	1.82	1.64	1.75	1.75	1.64	1.75	1.83	1.91
3	CS1	1.97	1.96	1.91	1.97	1.92	1.84	1.89	1.86	1.82

Table 5.24.3: Flow velocity at different points around the launching apron (LA) of spurs from u/s LA end to d/s LA end in test T20

Sl. No.	Flow velocity around the spurs (m/s)	
	S1	S2
1	0.05	0.22
2	0.44	0.44
3	1.31	0.66
4	1.26	1.75
5	1.97	1.48
6	1.75	1.53
7	1.59	1.10
8	1.10	2.08
9	1.10	1.75
10	1.86	1.10
11	0.66	0.77
12	0.38	0.22
13	0.33	0.11

From the above table, it can be seen that the maximum velocity around the LA of spurs S1 & S2 is 1.97 & 2.08 m/s respectively.

Table 5.24.4: Scour at different points around the launching apron of spurs from u/s end to d/s end in test T20

Sl. No.	Scour around the spurs (m/s)	
	S1	S2
1	-0.90	-0.12
2	0.12	2.01
3	-1.68	1.62
4	-4.08	-3.51
5	-8.28	-6.99
6	-11.04	-6.84
7	-10.80	-6.54
8	-9.99	-5.85
9	-11.94	-4.92
10	-10.83	-2.40
11	-2.19	0.84
12	1.89	1.29
13	0.12	0.12

From the above table, it can be seen that the maximum scour around the LA of spurs S1 & S2 is 11.94 & 6.99 m. The maximum scour is found as 17.36 m which is d/s of LA of spur S1.

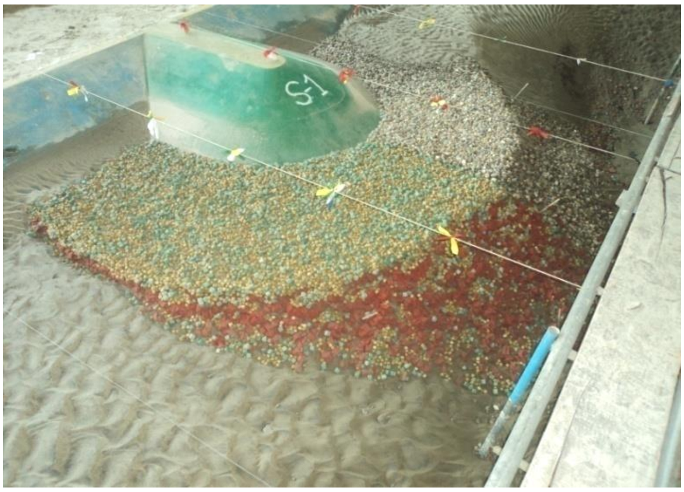

Figure 5.24.3: Launching pattern after test run (T20)

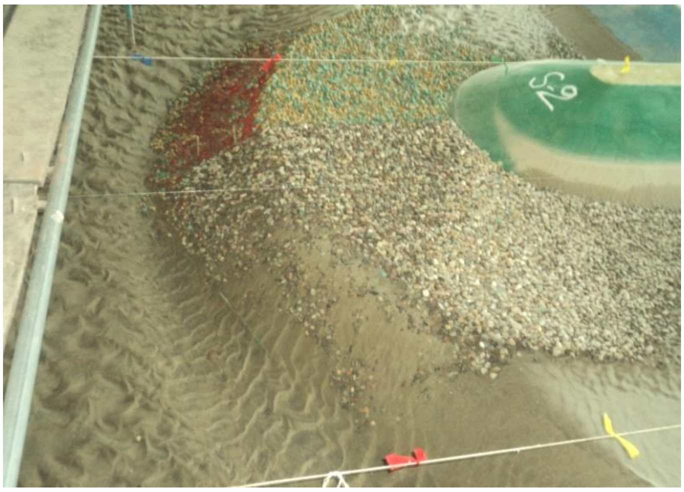

Figure 5.24.4: Launching pattern after test run (T20)

5.24.1 Findings

In this test, scour is occurred around the spurs due to the combined flow (main flow is subjected to oblique flow). Maximum scour around the curved LA is found 11.94 m & 6.99 m in the vicinity of spurs S1 & S2 respectively. Maximum velocity around the curved LA is found 1.97 m/s & 2.08 m/s in the vicinity of spurs S1 & S2 spurs respectively. Maximum scour is found as 17.36 m which is d/s of LA of spur S1.

The launching characteristics of stones are much better than other materials. Because the scour developed at the toe of the LA of stones is less than that of other materials. Stones are capable to resist scour development but other materials have no such ability. From the d/s part of LA of spur S1, few stone-chips were displaced towards d/s. Bare space is much less than test T19.

5.25 Test T21

Test T21 is same as test T20 but here d/s part of LA of spurs S1 & S2 (start from shank axis) consists of 60 cm cube 60% & 45 cm cube 40%. The u/s part (start from shank axis) of LA of spurs S1 & S2 is same as test T20. The depth averaged velocity & scour depths were measured and flow field was recorded in this test. Here, maximum scour depth in the vicinity of spurs S1 & S2 was determined. Also the performance of LA around spurs S1 & S2 was tested here.

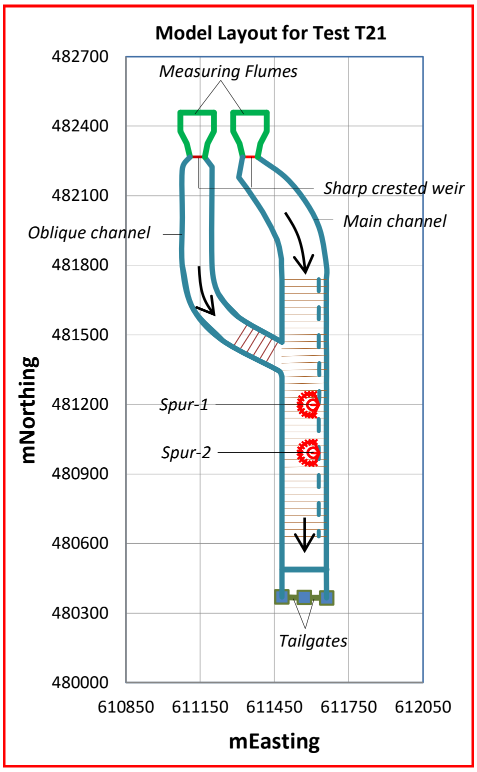

Figure 5.25.1: Layout of the model for test T21

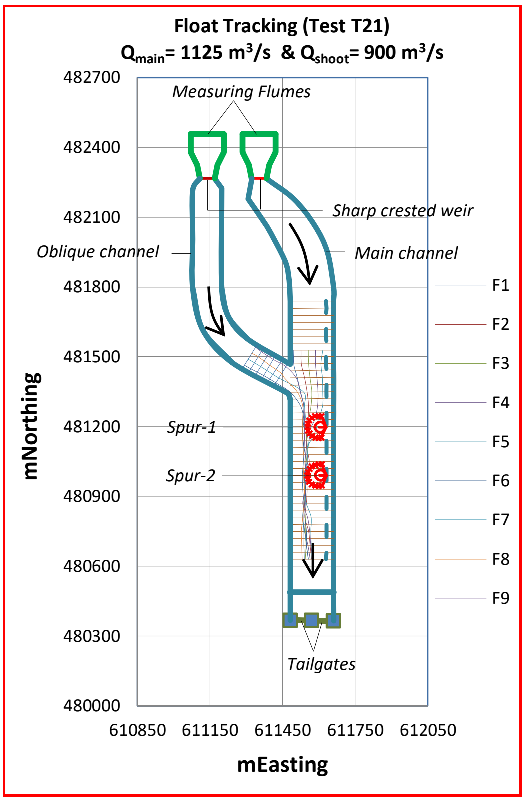

Figure 5.25.2: Flow field recorded by tracking floats from u/s to d/s in test T21

Table 5.25.1: Flow velocity in test T21 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS31	1.48	1.75	1.59	1.70	1.75	1.75	1.86	1.86	1.97	1.70
2	CS30	1.59	1.75	1.86	1.70	1.70	1.75	1.86	1.86	2.08	1.75
3	CS29	1.20	1.48	1.75	1.53	1.70	1.86	1.86	1.75	1.53	1.86
4	CS28	1.70	1.86	1.75	1.81	1.75	1.81	1.92	1.97	1.81	1.75
5	CS27	1.92	1.97	2.14	1.75	1.59	1.42	1.53	1.64	1.53	1.48
6	CS26	2.52	2.30	2.14	2.19	1.86	1.70	1.92	1.86	1.70	1.97
7	CS25	2.30	2.68	2.63	2.63	2.19	2.19	2.19	2.03	1.81	1.92
8	CS24	0.33	2.85	2.90	2.19	1.81	1.59	1.59	1.64	1.59	1.64
9	CS23	0.11	0.77	2.08	2.52	1.92	1.75	1.31	1.20	1.53	1.48
10	CS22	0.71	0.88	1.37	1.97	1.86	1.10	0.77	0.71	0.77	0.82
11	CS21	0.88	1.48	1.92	2.14	2.14	1.92	1.53	1.31	1.04	0.44
12	CS20	0.93	0.99	1.31	1.42	1.75	1.37	0.44	1.20	-	-
13	CS19	1.10	1.86	2.03	2.19	2.36	0.55	0.22	-	-	-
14	CS18	1.53	2.19	2.36	2.57	2.74	1.15	0.33	-0.44	-	-
15	CS17	1.81	2.30	2.14	1.86	2.08	0.99	1.04	0.44	0.33	0.11
16	CS16	2.30	1.86	2.08	2.19	2.08	1.81	0.99	1.20	0.99	0.55
17	CS15	2.08	1.97	2.52	2.30	2.36	2.08	1.48	1.04	0.77	0.49
18	CS14	1.92	1.86	2.03	1.53	2.14	1.75	1.42	1.10	0.66	0.33
19	CS13	2.30	2.74	2.63	2.90	2.63	2.14	1.97	2.03	-	-
20	CS12	2.57	2.74	2.52	2.46	1.75	2.08	2.30	0.55	0.33	0.00
21	CS11	2.74	2.63	2.57	3.12	2.74	1.10	0.88	0.44	0.22	0.00
22	CS10	3.01	3.29	3.56	3.45	2.46	1.37	0.99	0.33	0.27	0.33
23	CS9	2.63	3.01	2.85	3.12	3.01	2.36	2.08	1.64	0.88	0.77
24	CS8	2.41	2.85	2.85	3.01	2.79	1.53	1.20	0.71	0.77	0.88
25	CS7	2.79	3.12	3.01	2.90	2.74	2.63	1.75	1.10	1.64	1.37
26	CS6	2.36	2.68	2.57	2.30	1.59	1.42	1.42	0.77	0.71	0.82
27	CS5	2.90	3.12	2.68	2.74	2.52	2.08	1.92	1.31	1.37	1.31
28	CS4	2.74	3.01	2.79	2.63	2.74	2.46	1.92	1.53	1.64	1.70
29	CS3	2.63	2.57	2.90	2.68	2.14	2.14	1.81	1.64	1.70	1.53
30	CS2	2.46	2.63	2.79	2.46	2.19	2.30	1.64	1.81	1.42	1.31
31	CS1	2.36	2.90	3.01	2.74	1.92	2.03	1.70	1.97	1.59	1.59

Table 5.25.2: Flow velocity in test T21 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	1.94	1.98	1.91	1.93	1.97	1.90	1.90	1.99	1.93
2	CS3	1.94	1.94	1.75	1.90	1.94	1.98	1.93	1.79	1.89
3	CS1	1.97	2.19	2.46	2.08	2.03	2.08	1.81	1.64	1.93

Table 5.25.3: Flow velocity at different points around the launching apron (LA) of spurs from u/s LA end to d/s LA end in test T21

Sl. No.	Flow velocity around the spurs (m/s)	
	S1	S2
1	1.10	0.77
2	1.75	1.20
3	1.92	1.64
4	1.70	1.97
5	1.81	1.75
6	2.85	1.92
7	2.85	2.36
8	2.85	1.42
9	0.88	1.31
10	0.11	1.31
11	0.22	0.49
12	0.00	0.44
13	0.00	0.00

From the above table, it can be seen that the maximum velocity around the LA of spurs S1 & S2 is 2.85 & 2.36 m/s respectively.

Table 5.25.4: Scour at different points around the launching apron of spurs from u/s end to d/s end in test T21

Sl. No.	Scour around the spurs (m/s)	
	S1	S2
1	-0.06	-0.60
2	-0.18	1.59
3	-0.84	1.89
4	-2.64	-0.45
5	-5.61	-5.22
6	-11.31	-6.66
7	-11.04	-6.21
8	-7.77	-6.06
9	-11.70	-5.52
10	-11.82	1.38
11	1.59	0.24
12	1.41	0.60
13	0.00	0.09

From the above table, it can be seen that the maximum scour around the LA of spurs S1 & S2 is 11.82 & 6.66 m. The maximum scour is found as 12.71 m which is d/s of LA of spur S1.

Figure 5.25.3: Launching pattern after test run (T21)

Figure 5.25.4: Launching pattern after test run (T21)

5.25.1 Findings

In this test, scour occurred around the spurs due to the combined flow (main flow is subjected to oblique flow). Maximum scour around the curved LA is found 11.82 m & 6.66 m in the vicinity of spurs S1 & S2 respectively. Maximum velocity around the curved LA is found 2.85 m/s & 2.36 m/s in the vicinity of spurs S1 & S2 spurs respectively. Maximum scour is found as 12.71 m which is d/s of LA of spur S1.

From the d/s part of LA of spur S1, some CC blocks of 45 cm & 60 cm sizes were displaced towards d/s. Bare space is more than test T20.

5.26 Test T22

Test T22 is same as test T21 but here d/s part of LA of spurs S1 & S2 (start from shank axis) consists of 60 cm cube 60% & 45 cm cube 40% at the top layer and 500 kg geo-bag at the bottom layer. The u/s part (start from shank axis) of launching apron of spurs S1 & S2 is same as test T21. The depth averaged velocity & scour depths were measured and flow field was recorded in this test. Here, maximum scour depth in the vicinity of spurs S1 & S2 was determined. Also the performance of LA around spurs S1 & S2 was tested here.

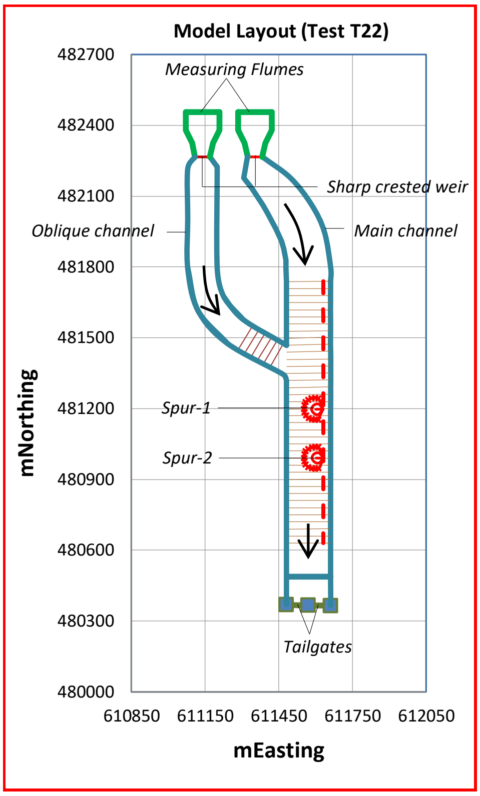

Figure 5.26.1: Layout of the model for test T22

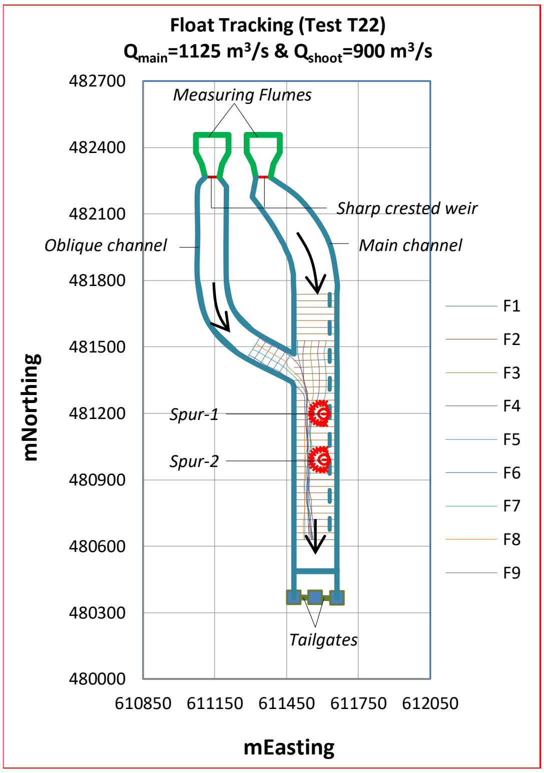

Figure 5.26.2: Flow field recorded by tracking floats from u/s to d/s in test T22

Table 5.26.1: Flow velocity in test T22 (main channel)

Sl. No.	CS No.	Velocity (m/s)									
		Distance from right boundary (m)									
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	130.5
1	CS31	1.53	1.97	1.97	2.08	1.81	1.86	2.08	2.03	2.03	1.31
2	CS30	1.42	1.75	1.86	2.03	1.97	2.03	2.14	1.75	1.75	2.08
3	CS29	1.26	1.64	1.75	1.86	1.75	2.08	2.08	2.19	2.08	2.14
4	CS28	2.03	1.97	2.14	1.97	1.97	2.41	2.30	2.19	2.19	2.14
5	CS27	2.19	2.08	2.41	2.19	2.08	2.46	2.19	2.14	2.08	1.86
6	CS26	2.19	2.19	2.08	2.03	1.92	1.92	2.08	2.14	2.19	1.92
7	CS25	2.30	2.68	2.46	2.46	2.19	2.19	1.92	1.64	1.70	1.64
8	CS24	0.55	2.74	2.74	2.30	2.19	2.08	1.75	1.92	1.64	1.92
9	CS23	0.16	0.66	2.30	2.74	2.30	2.08	1.97	1.75	1.64	1.64
10	CS22	0.82	1.10	1.53	2.19	2.19	2.14	1.64	1.37	1.64	1.20
11	CS21	1.37	1.37	1.64	2.19	2.63	2.19	1.92	1.64	1.53	1.10
12	CS20	1.10	1.37	1.53	1.64	2.63	2.19	1.64	1.37	-	-
13	CS19	1.64	1.92	1.64	2.46	2.63	1.64	0.66	0.27	0.00	0.00
14	CS18	1.64	2.30	3.01	3.07	2.74	1.37	0.82	0.27	0.00	0.00
15	CS17	1.92	2.30	2.19	2.30	2.25	1.64	0.82	0.82	0.27	0.00
16	CS16	2.46	3.01	2.74	2.68	2.85	2.19	1.20	0.82	0.55	0.16
17	CS15	2.74	2.63	2.68	3.01	2.85	2.74	2.30	1.92	1.37	0.82
18	CS14	2.19	2.63	2.74	2.19	2.30	2.19	1.92	1.64	0.82	0.66
19	CS13	3.29	3.29	3.01	2.74	3.40	3.01	2.46	2.19	-	-
20	CS12	2.46	3.01	2.74	3.29	3.40	1.64	0.44	0.16	0.00	0.00
21	CS11	3.29	3.56	3.83	3.83	3.94	1.86	1.20	0.77	0.22	0.00
22	CS10	3.56	3.83	3.56	3.29	2.19	1.75	1.48	1.10	0.77	0.66
23	CS9	2.08	2.63	2.90	1.53	1.70	1.53	2.03	1.97	1.42	1.15
24	CS8	3.56	3.56	3.40	3.40	3.40	3.29	2.74	2.36	1.70	1.53
25	CS7	2.41	3.56	3.29	3.29	3.40	3.29	3.01	2.08	2.08	1.26
26	CS6	3.83	3.83	3.83	3.83	3.29	2.74	2.25	2.19	1.81	1.75
27	CS5	3.07	3.40	3.29	3.18	3.83	3.29	3.01	2.57	1.81	1.75
28	CS4	3.01	3.29	3.29	3.56	3.72	3.29	2.85	2.36	2.08	2.08
29	CS3	2.41	3.01	3.01	2.74	2.57	2.68	2.41	1.53	1.37	1.10
30	CS2	3.40	4.11	3.56	3.56	3.72	3.29	2.63	2.30	2.08	2.03
31	CS1	2.19	4.66	4.38	3.56	3.56	3.56	3.29	2.46	1.75	1.86

Table 5.26.2: Flow velocity in test T22 (shoot channel)

Sl. No.	CS No.	Velocity (m/s)								
		Distance from right boundary (m)								
		0.0	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0
1	CS5	1.75	1.92	1.81	1.81	1.81	1.94	1.70	1.98	1.91
2	CS3	1.81	1.81	1.97	2.03	1.86	1.99	1.75	1.64	1.99
3	CS1	1.94	1.90	1.94	1.82	1.66	1.49	1.66	1.60	1.44

Table 5.26.3: Flow velocity at different points around the launching apron (LA) of spurs from u/s LA end to d/s LA end in test T22

Sl. No.	Flow velocity around the spurs (m/s)	
	S1	S2
1	1.48	0.49
2	1.48	0.99
3	1.59	1.59
l4	0.88	2.36
5	1.26	0.82
6	1.70	0.82
7	1.92	1.20
8	1.97	1.10
9	1.97	2.52
10	1.04	2.25
11	0.11	0.66
12	0.00	0.33
13	0.00	0.00

From the above table, it can be seen that the maximum velocity around spurs S1 & S2 is 1.97 & 2.52 m/s respectively.

Table 5.26.4: Scour at different points around the launching apron (LA) of spurs from u/s end to d/s end in test T22

Sl. No.	Scour around the spurs (m/s)	
	S1	S2
1	0.12	0.03
2	-0.09	2.13
3	-0.90	2.61
4	-3.42	-0.03
5	-5.55	-4.83
6	-10.86	**-5.52**
7	-11.13	-5.22
8	-9.87	-4.68
9	-10.65	-1.59
10	-13.56	0.03
11	1.08	0.30
12	1.05	0.66
13	-1.05	0.09

From the above table, it can be seen that the maximum scour around spurs S1 & S2 is 13.56 & 5.52 m. The maximum scour is found as 16.13 m which is d/s of LA of spur S1.

Figure 5.26.3: Launching pattern after test run (T22)

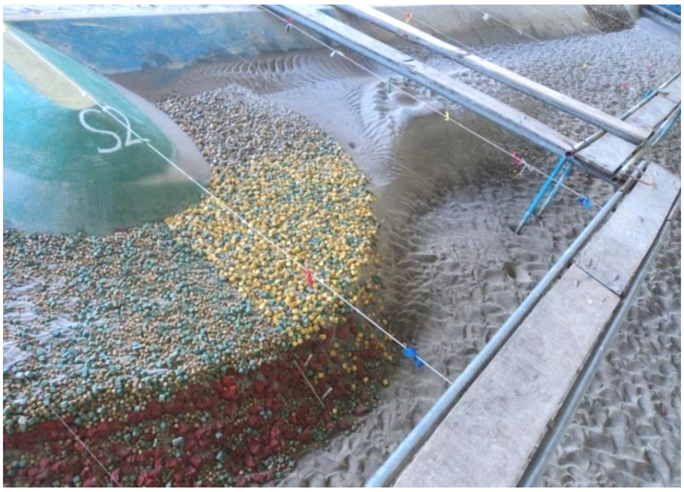

Figure 5.26.4: Launching pattern after test run (T22)

5.26.1 Findings

In this test, scour was occurred around the spurs due to the combined flow (main flow is subjected to oblique flow). Maximum scour around the LA is found 13.56 m & 5.52 m in the vicinity of spurs S1 & S2 respectively. Maximum velocity around the LA is found 1.97 m/s & 2.52 m/s in the vicinity of spurs S1 & S2 respectively. Maximum scour is found as 16.13 m which is d/s of LA of spur S1.

From the d/s part of spur S1, nos. of CC blocks/geo-bags displaced towards d/s are less than test T21. Bare space is less than test T21. Mass failure of geo-bag is relatively less.

Figure 5.26.5: A Seminar on "Investigation on launching characteristics of different material to find out the cost-effective and sustainable solution for river bank protection" held at RRI on 20th June 2016.

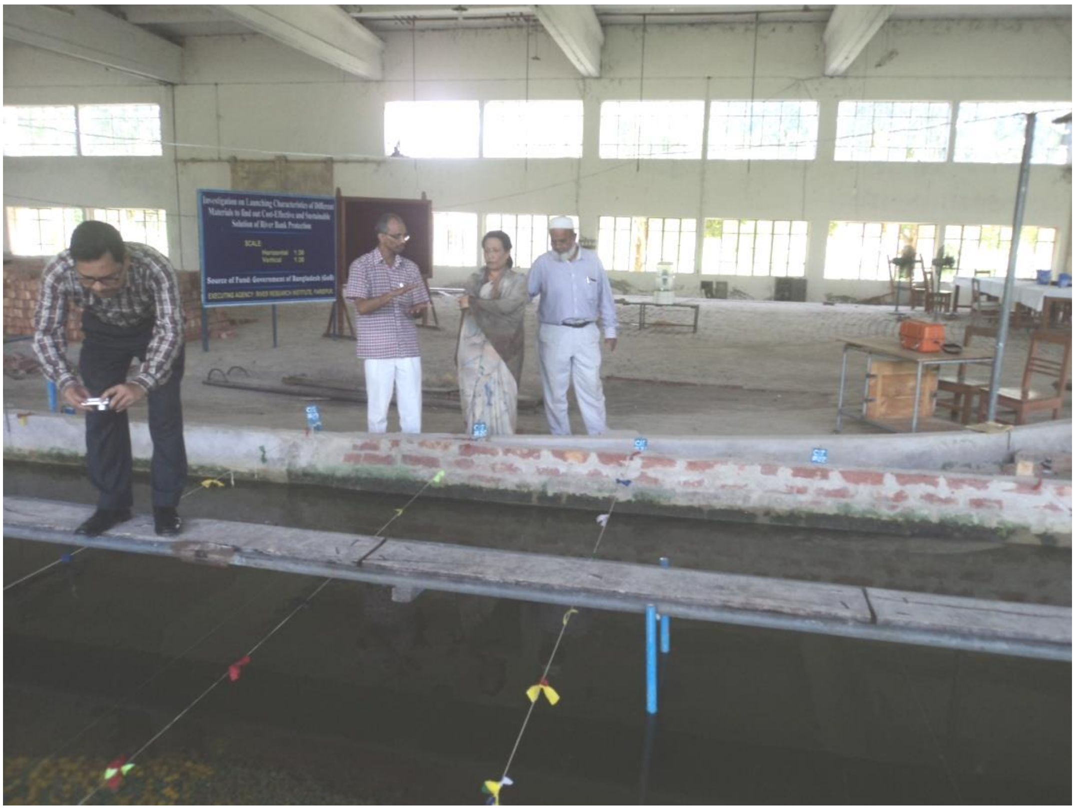

Figure 5.26.6: Mrs. Sadia Naznin, Chief Engineer (Design), BWDB and Md. Motaher Hossain, Additional Chief Engineer, BWDB observing the research model at RRI on 20th June 2016.

6 Results and Discussion

6.1 Interpretation of Test Results

In test T0 (calibration test), scour occurred near the left bank along the main channel. The maximum value of scour is 11.7m and the maximum velocity measured as 2.5 m/s.

Test T1, T2 & T3 are conducted with geo-bags, CC blocks & stone chips respectively. Here no significant scour or launching occurred as the flow is parallel to the bankline.

Test T4.1 & 4.2 are carried out with stone chips with discharge ratios (shoot to main channel) 0.8 & 1.0 respectively. Scour and launching occurred as the main channel is subjected to oblique flow. Here stone chips cover the developed slope completely and there are no bare spaces.

Test T5.1 & 5.2 are carried out with geo-bags with discharge ratios 0.8 & 1.0 respectively. Scour and launching occurred as the main channel is subjected to oblique flow. Here there are some bare spaces on the launching slope and mass failure of geo-bags occurs.

Test T6.1 & 6.2 are carried out with CC blocks with discharge ratios 0.8 & 1.0 respectively. Scour and launching occurred as the main channel is subjected to oblique flow. Here CC blocks cannot cover the launching slope completely and there are bare spaces on the developed slope

Test T7, T8 & T9 are conducted with CC blocks, stone chips & geo-bags respectively. The main channel is closed & shoot channel feeds the total discharge (2025 m^3/s) to the main channel. Scour and launching occurred as the launching apron is subjected to fully oblique flow. In test T7, CC blocks cannot cover the launching slope completely and at some places there are some bare spaces on the launching slope. Stone chips cover the launching slope completely and there is no bare space on the launching slope in test T8. In test T9, mass failure of geo-bags occurred and there are some bare spaces on the launching slope.

Test T10 is conducted with 3 spurs (S1, S2 & S3) and these are subjected to oblique flow. Maximum scour around the spurs is measured as 19.62, 12.72 & 8.13 m respectively.

Test T11 & T12 are conducted with composite launching apron as per design suggested by Design Circle-VI of BWDB under oblique flow (discharge ratio 0.8) & fully oblique flow (inflow at the main channel is closed and the oblique channel is fed with total discharge, 2025m^3/s) respectively. Here the composite launching apron consists of CC blocks (top layer) & geo-bags (bottom layer). In these tests, launching occurs nicely and covers the maximum launching portion. Developed slope is found better. The combined apron provides better performance than when using only geo-bags or only CC blocks as launching materials. Mass failure is found relatively lower than geo-bags.

Test T13 is carried out with composite LA having length 25 m under fully oblique flow condition. Here mass failure of geo-bag is more than test T12 (L=30 m) due to increased thickness of LA and provides no better performance than when its apron length is 30 m.

Test T14 is carried out with composite LA having length 35 m under fully oblique flow condition. Mass failure of geo-bag is relatively less than that of test T13 due to decreased thickness of LA.

Test T15 is carried out with composite LA having length 35m under fully oblique flow condition but here the proportion of CC block & geo-bag is kept 40% & 60% in the launching apron. Mass failure of geo-bag and percentage of bare space is more than test T14 due to increased proportion of geo-bags.

Test T16 is same as test T14 but here composite LA is shifted u/s by 60m to produce more severe condition. Here Lower mass failure of geo-bag is observed along the slope. Bare space is relatively lower than single composition of geo-bag.

Test T17 is same as test T12 but here the composite LA is shifted u/s by 60 m and CC blocks portion consists of 45 cm cube 50% and 35 cm cube 50%. Here bare space is relatively lower than test T16. Smooth channel is formed along the LA.

Test 18 is same as test T17 but here CC blocks portion consists of 45 cm cube 40% and 35 cm cube 60%. Bare space is relatively lower and developed channel is well shaped. CC blocks rolled in the developed channel are less. More CC blocks are retained on the developed slope. Test T18 provides better result in case of revetment.

Low cost material composition for revetment: LA consists of 45 cm cube 40% & 35 cm cube 60% at the top layer and 250 kg geo-bag 50% & 175 kg geo-bag 50% at the bottom layer.

Test T19 is conducted with 2 spurs (S1 & S2). Here Launching pattern of combined material is better than when providing only geo-bag because of less bare space on the developed slope. Scour hole d/s of spur does not allow launching material to hold on the developed slope. From d/s part of LA of spur S1, more CC blocks & geo-bags were displaced towards d/s. Bare space is more and mass failure of geo-bag is observed.

Test T20 is same as test T19 but the d/s part of LA of spurs S1 & S2 consists of stone-chips only at the top & bottom layer. Due to better launching characteristics, stones are capable to resist scour development. From the d/s part of LA of spur S1, few stone-chips were displaced towards d/s. Bare space is much less than test T19.

Test T21 is same as test T20 but here d/s part of LA of spurs S1 & S2 consists of 60 cm cube 60% & 45 cm cube 40%. From the d/s part of LA of spur S1, some CC blocks were displaced towards d/s. Bare space is more than test T20.

Test T22 is same as test T21 but here d/s part of LA of spurs S1 & S2 consists of 60 cm cube 60% & 45 cm cube 40% at the top layer and 500kg geo-bag at the bottom layer. From the d/s part of spur S1, CC blocks/geo-bags displaced towards d/s are less than test T21. Bare space is less than test T21. Mass failure of geo-bag is also relatively less. Test T22 provides better result in case of spur.

Low cost material composition for u/s part of LA of spur: LA consists of 45 cm cube 40% & 35 cm cube 60% at top layer and 250 kg geo-bag 50% & 175 kg geo-bag 50% at bottom layer.

Low cost material composition for d/s part of LA of spur: LA consists of 60 cm cube 60% & 45 cm cube 40% at top layer and 500 kg geo-bag at bottom layer.

6.2 Comparison of launching pattern for different launching materials

A comparison is made among tests T7, T8, T9 & T18 showing the launching behavior of CC blocks, stone-chips, geo-bags and composite materials (CC blocks + geo-bags) for revetment under oblique flow condition (60-degree) for discharge 2025m^3/s as shown below. From the figures it is evident that stone chips has best launching pattern as there is no bare space on the launching slope. The composite materials, CC blocks and geo-bags stand 2nd, 3rd and 4th position with respect to launching pattern respectively.

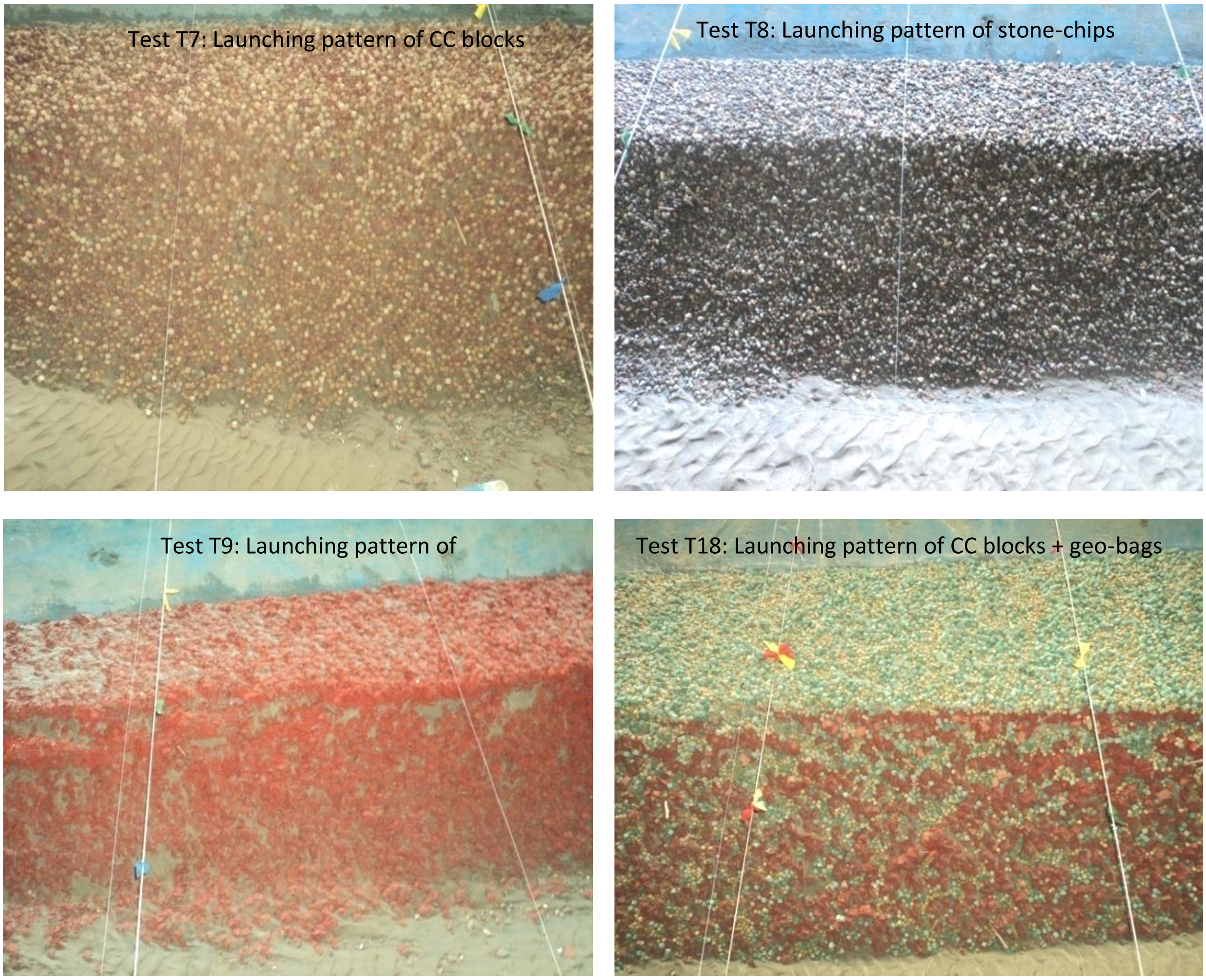

Figure 6.2.1: Launching pattern of different launching materials.

6.3 Comparison of launching behavior for composite materials having different apron length and thickness when launching apron consists of 50% CC blocks (top) + 50% geo-bags (bottom) in case of revetment

The following figure shows the launching behavior of composite materials (CC blocks + geo-bags) with the variation of apron length of revetment for tests T12, T13 & T14 (discharge 2025m^3/s) under fully oblique flow condition (60-degree). It is evident from these figures that test T12 provides better launching pattern in comparison to tests T13 & T14.

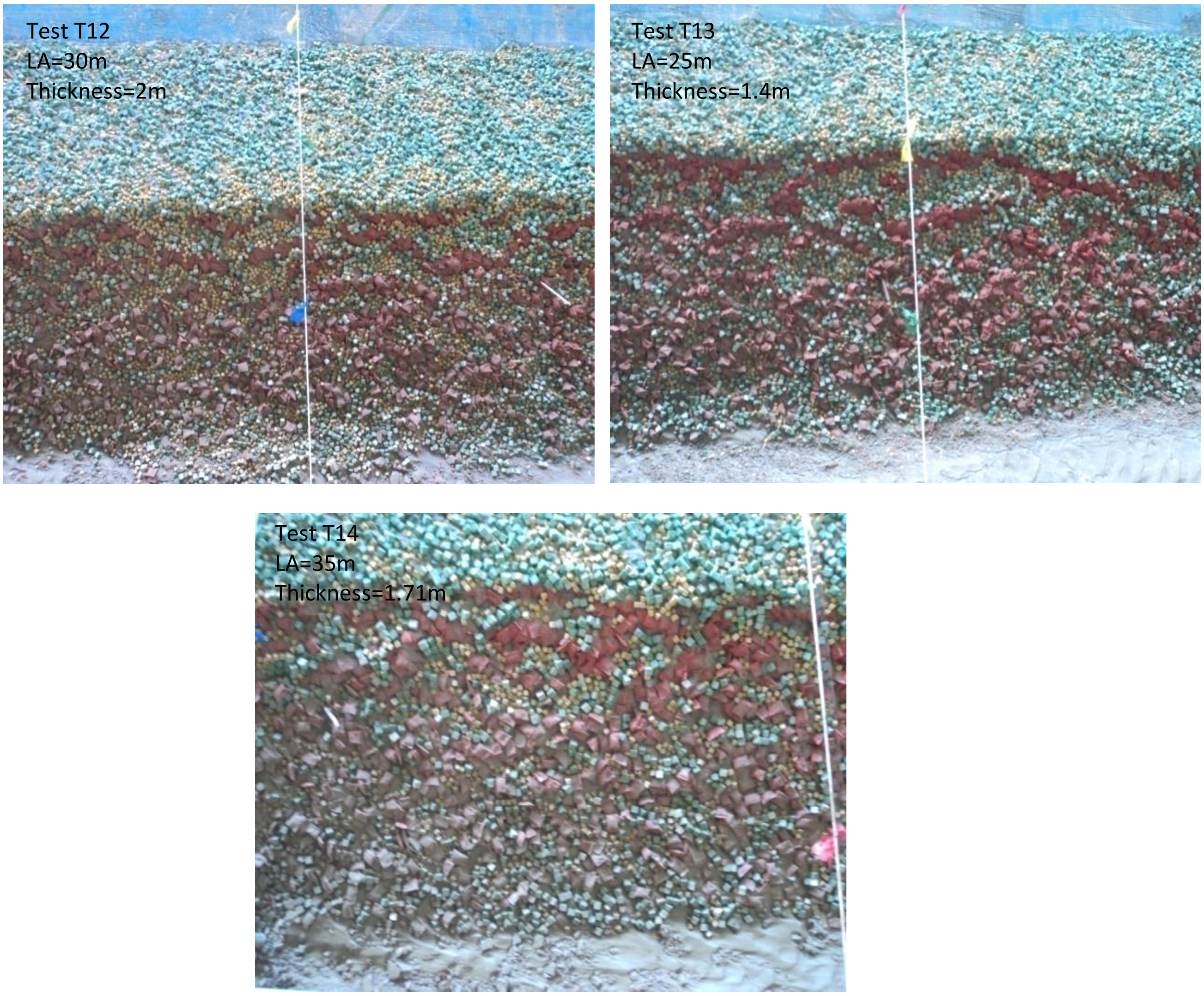

Figure 6.3.1: Launching behavior of composite materials for different apron length.

6.4 Comparison of launching behavior for composite materials with different proportion of CC blocks in the LA in case of revetment

A comparison is made among tests T7, T8, T9 & T18 showing the launching behavior of CC blocks, stone-chips, geo-bags and composite materials (CC blocks + geo-bags) for revetment under oblique flow condition (60-degree) for discharge 2025m^3/s as shown below. It is evident from the figures that test T18 provides best result as bare space is relatively lower. Developed channel around the LA is well shaped. The numbers of CC blocks rolled in the developed channel are less. More numbers of CC blocks are retained on the developed slope.

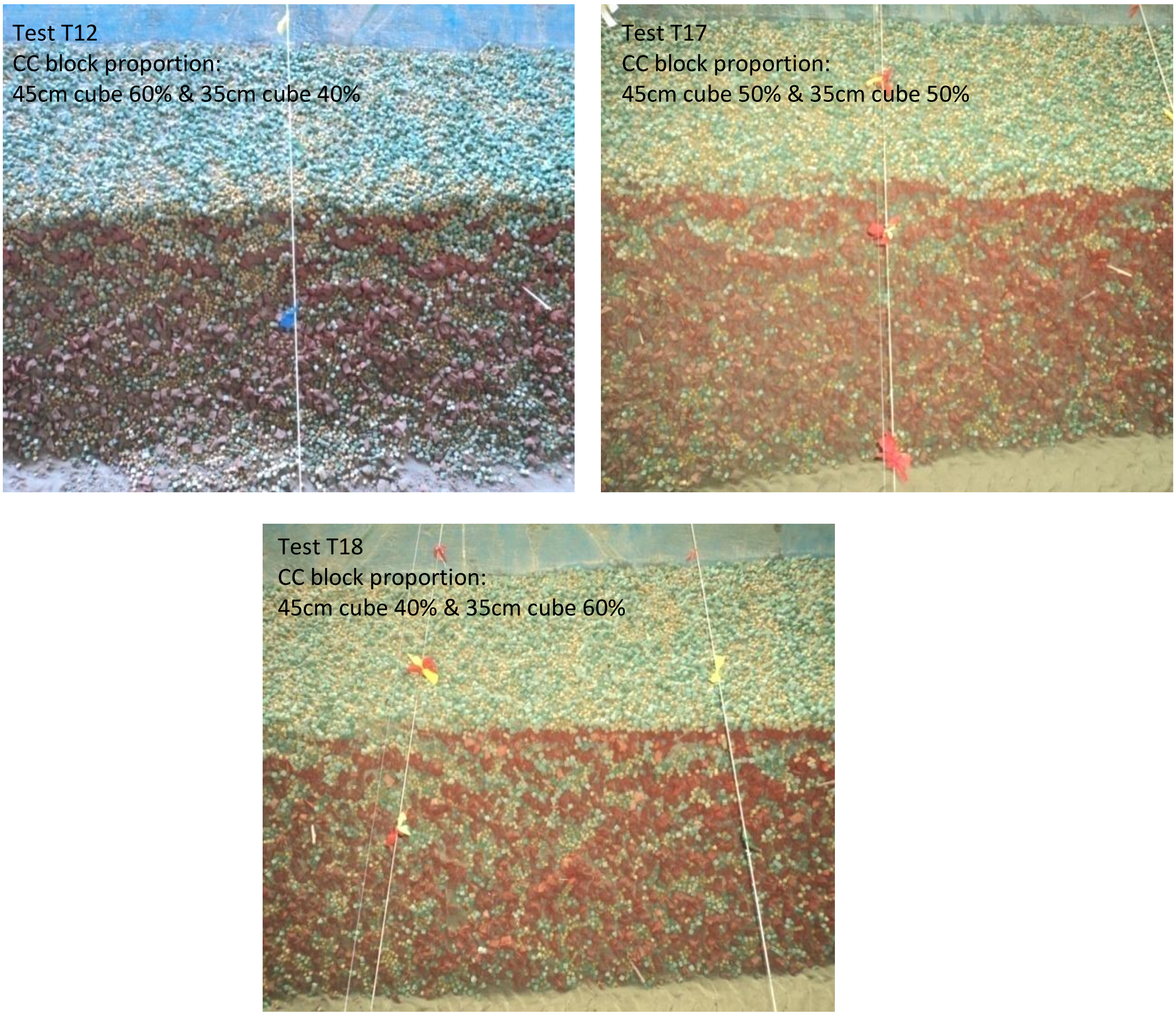

Figure 6.4.1: Launching behavior of composite materials for different CC block proportion.

6.5 Comparison of launching pattern with the variation of material composition of launching apron in the d/s part of spur S1

The figure shows the launching pattern with the variation of material composition for d/s part of launching apron of spur S1 (start from spur axis) when the material composition in the u/s part remains same for tests T19, T20, T21 & T22 under fully oblique flow condition (60-degree) in case of spur. Test T20 provides best results as the launching characteristics of stones are much better than other materials. Because the scour developed at the toe of the LA of stones is less than that of other materials. Stones are capable to resist scour development but other materials have no such ability. From the d/s part of LA of spur S1, few stone-chips have been displaced towards d/s. Bare space is much less than test T19.

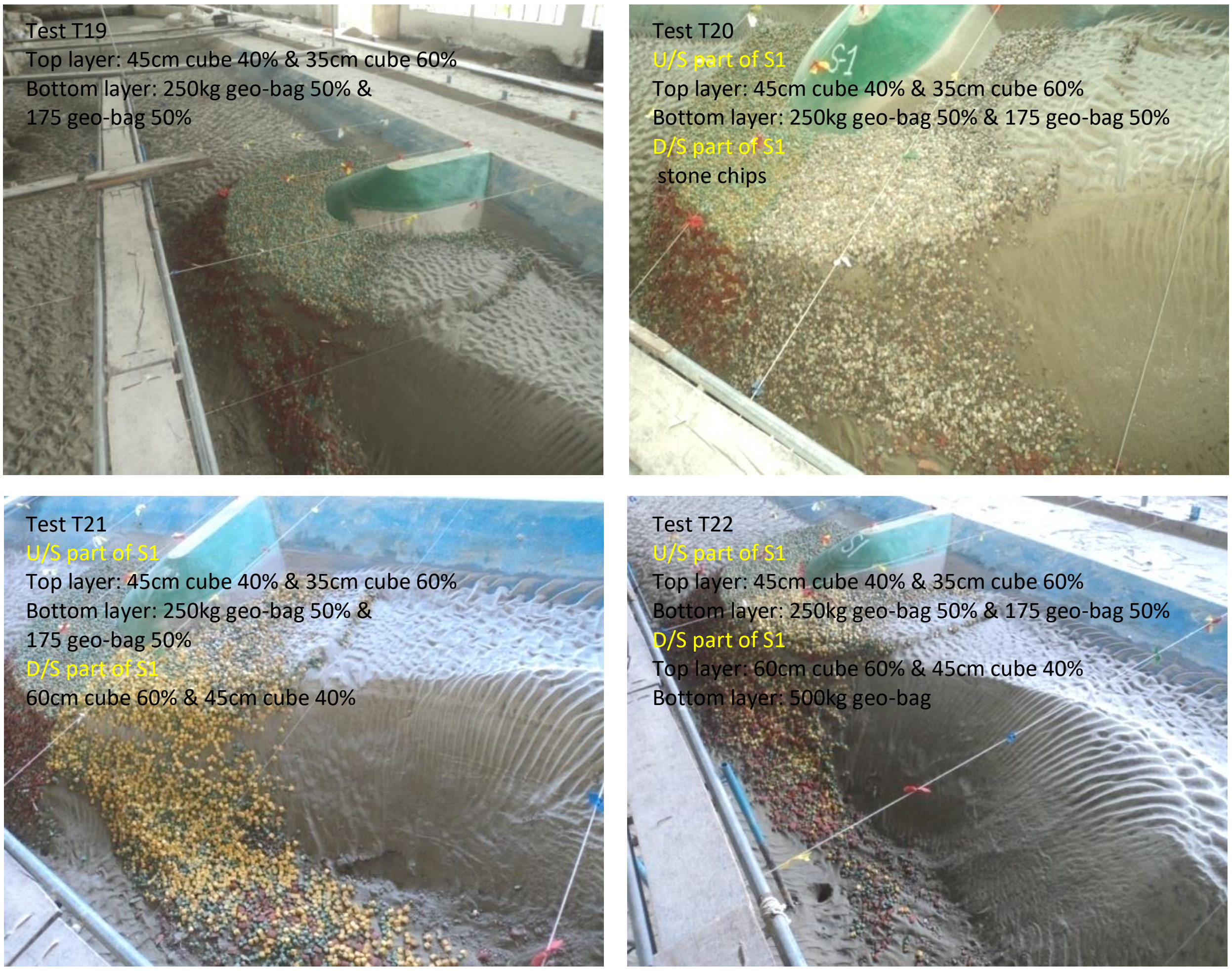

Figure 6.5.1: Launching behavior of composite materials for different material compositions in the d/s part of spur S1.

6.6 Maximum scour against different launching materials under fully oblique flow (60^0) in case of revetment [T7, T8 & T9]

The figure below shows that scour depth is minimum for geo-bags (T9) and close to stone chips (T8).

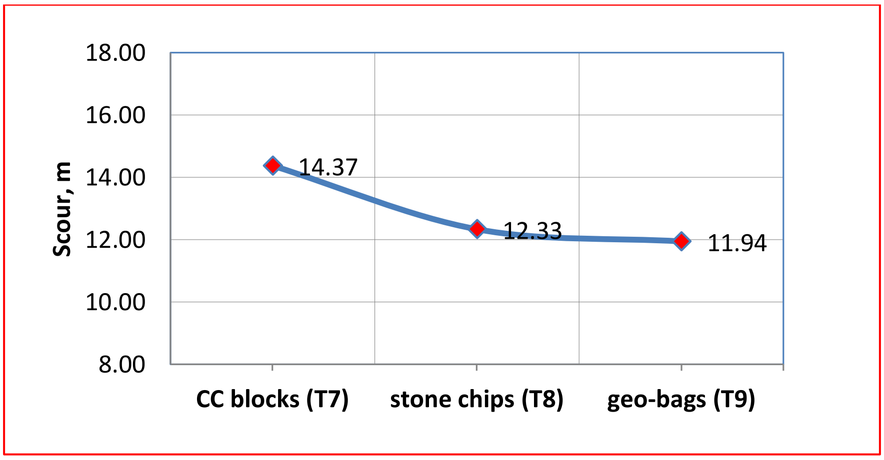

Figure 6.6.1: Maximum scour against tests T7, T8 & T9 under fully oblique flow (60-degree)

6.7 Maximum scour against different length of LA of CC blocks + geo-bags under fully oblique flow (60 degree) in case of revetment [T12, T13 & T14]

The figure below shows that scour depth is minimum when the apron length of composite material is 25m.

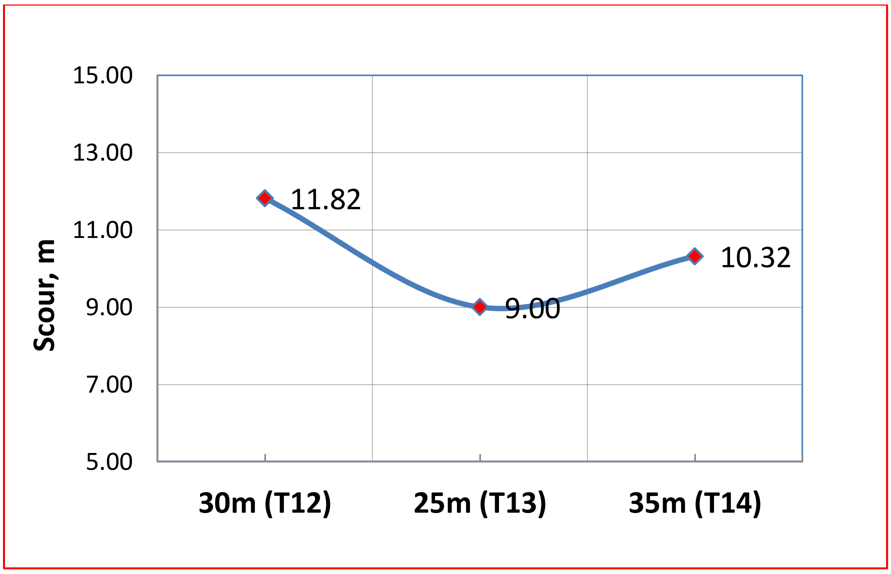

Figure 6.7.1: Maximum scour against tests T12, T13 & T14 under fully oblique flow (60-degree)

6.8 Variation of scour depth around LA for spur S1 under different combination of launching materials in case of spur (T19, T20, T21 & T22)

The figure below shows that scour depth is minimum for test T21 and close to test T20.

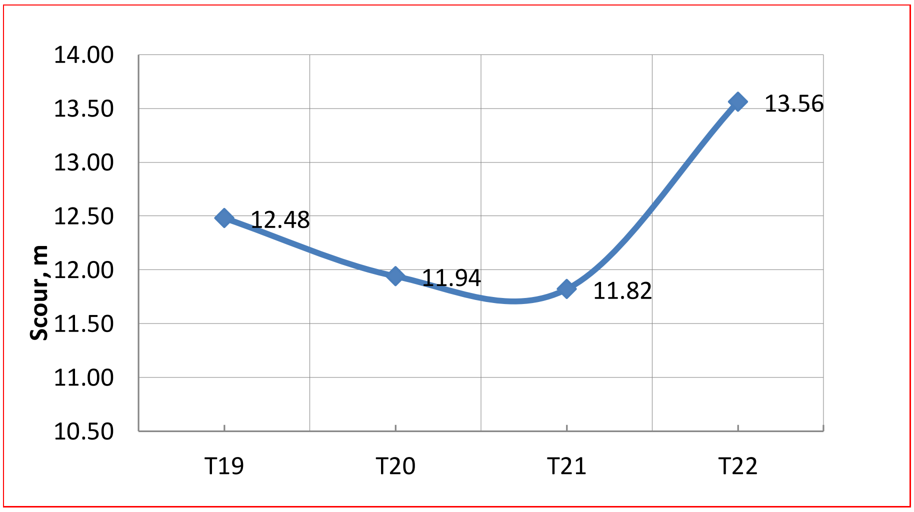

Figure 6.8.1: Variation of scour depth around LA for spur S1 under different combination of launching materials

6.9 Section across the revetment after test run along CS20 (T18)

The figure shows that for the low cost material composition (T18) for LA of revetment, the launching slope is 28.15 degree (1:1.87) and 27% launched out of 30m.

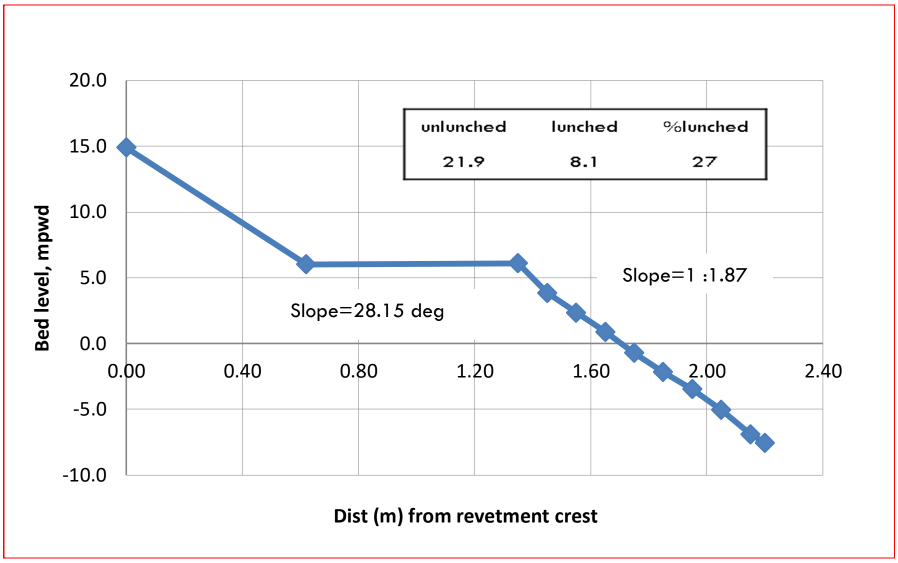

Figure 6.9.1: Section perpendicular to the revetment after test run

6.10 Section across the revetment after test run along spur S1 axis (CS20) [T22]

The figure shows that for the low cost material composition (T18) for LA of spur S1, the launching slope is 32.14 degree (1:1.59) and 40% launched out of 30m.

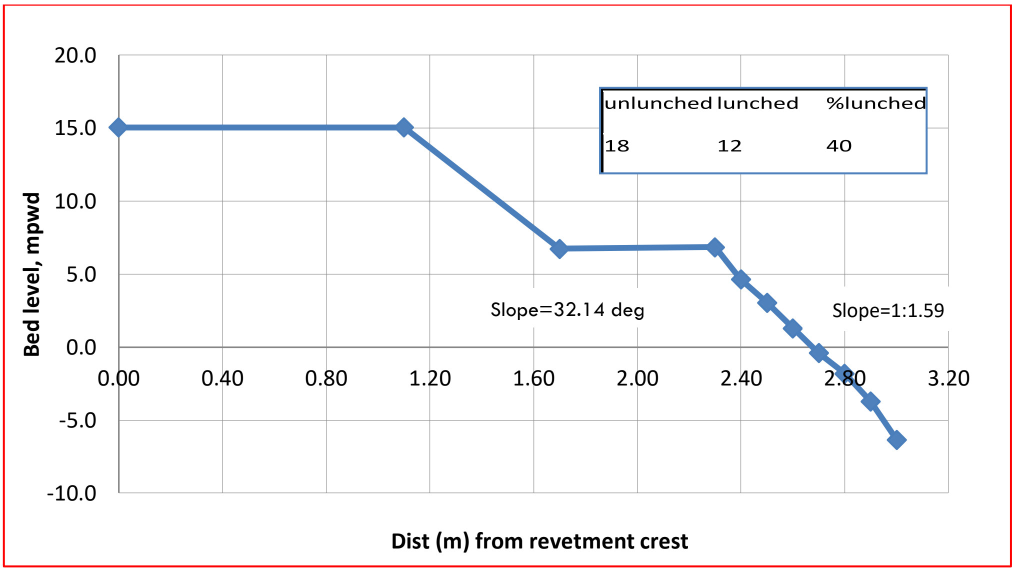

Figure 6.10.1: Section perpendicular to the revetment after test run along spur S1 axis

6.11 Development of scour with time for T18: (CS20, 75m from RB)

The following figure shows the scour developed with time for test T18 in case of revetment.

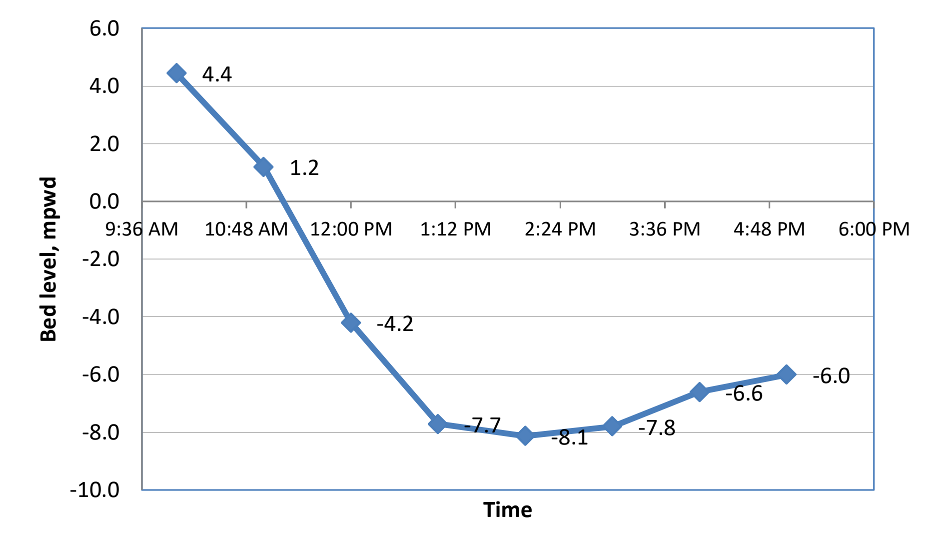

Figure 6.11.1: Development of scour with time for T18 (CS20, 75m from RB)

The figure below shows the scour developed with time for test T22 in case of spur.

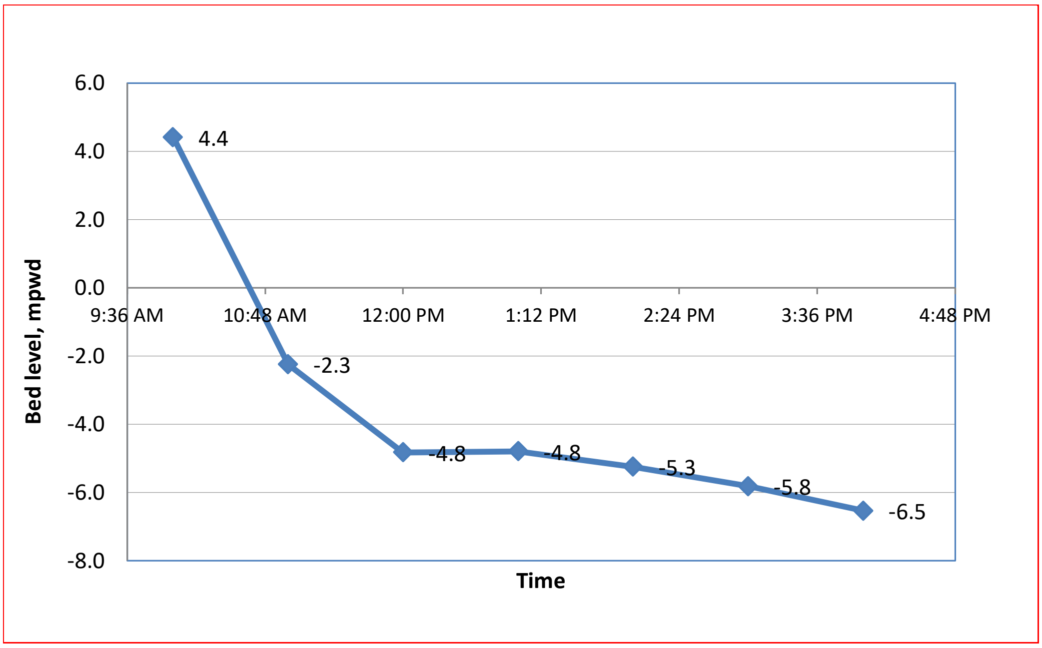

Figure 6.11.2: Development of scour with time for T22 (CS20, 60m from RB)

6.12 Comparison of test results in terms of velocity and scour depths

The following table shows the design parameters (velocity & scour) for different launching materials under different test conditions.

Table 6.12.1: Comparison of design parameters among different tests

Test No.	Test	channel-condition	Discharge-condition	Discharge-ratio	Launching materials/spur	Max velocity	Max scour
1	T0	main channel	Q_{main}= 2025 m^3/s (q=450 m^2/s)	-	-	2.5 m/s at CS23	11.7m at CS26
2	T1	main channel	Q_{main}= 2025 m^3/s (q=450 m^2/s)	-	Geo-bags	Max velocity 2.41m/s at CS18 around LA	Max scour 1.44m at CS14 around LA
3	T2	main channel	Q_{main}= 2025 m^3/s (q=450 m^2/s)	-	CC blocks	Max velocity 2.32m/s at CS23 around LA	Max scour 1.95m at CS16 around LA
4	T3	(main channel)	Q_{main}= 2025 m^3/s (q=450 m^2/s)	-	Stone chips	Max velocity 2.58 m/s at CS22 around LA	Max scour 1.65m at CS20 around LA
5	T4.1	(main + shoot channel)	Q_{main}= 1125 m^3/s (q=250 m^2/s) Q_{shoot}= 900 m^3/s (q=225 m^2/s)	Qr= Q_{shoot}/Q_{main}= 0.8	Stone chips	Max velocity 2.8m/s at CS15 around LA	Max scour 7.71m at CS 22 around LA
6	T4.2 Ext 26-12	(main + shoot channel)	Q_{main}= 1012.5 m^3/s (q=225 m^2/s) Q_{shoot}= 1012.5 m^3/s (q=253 m^2/s)	Qr=1.0	Stone chips	Max velocity 3.07m/s at CS14 around LA	Max scour 6.3m at CS18 around LA
7	T5.1	(main + shoot channel)	Q_{main}= 1125 m^3/s Q_{shoot}= 900 m^3/s	Qr=0.8	Geo-bags	Max velocity 3.14m/s at CS18 around LA	Max scour 8.91m at CS21 around LA
8	T5.2	(main + shoot channel)	Q_{main}= 1012.5 m^3/s Q_{shoot}= 1012.5 m^3/s	Qr=1.0	Geo-bags	Max velocity 3.24m/s at CS14 around LA	Max scour 7.02m at CS19 around LA
9	T6.1	(main + shoot channel)	Q_{main}= 1125 m^3/s Q_{shoot}= 900 m^3/s	Qr=0.8	CC blocks	Max velocity 2.67 m/s at CS14 around LA	Max scour 8.7m at CS21 around LA
10	T6.2 Ext 26-12	(main + shoot channel)	Q_{main}= 1012.5 m^3/s Q_{shoot}= 1012.5 m^3/s	Qr=1.0	CC blocks	Max velocity 3.01m/s at CS14 around LA	Max scour 6.1m at CS18 around LA
11	T7 Ext 26-12	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	CC blocks	Max velocity 3.29m/s at CS14 around LA	Max scour 14.37m at CS21 around LA
12	T8 Ext 26-12	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	Stone chips	Max velocity 3.56m/s at CS13 around LA	Max scour 12.33 m at CS20 around LA
13	T9 Ext 26-12	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	Geo-bags	Max velocity 3.18m/s at CS15 around LA	Max scour 11.94 m at CS20 around LA
14	T10	(main + shoot channel)	Q_{main}= 1125 m^3/s Q_{shoot}= 900 m^3/s	Qr=0.8	S1 (solid), S2 (CC blocks) & S3 (geo-bags)	Max velocity 2.19m/s (S1), 2.96m/s(S2) & 3.09m/s(S3) around LA	Max scour 19.62m (S1), 12.72m(S2) & 8.13m(S3) around LA

Test No.	Test	channel-condition	Discharge-condition	Discharge-ratio	Launching materials/spur	Max velocity	Max scour
15	T11	(main + shoot channel)	Q_{main}= 1125 m^3/s Q_{shoot}= 900 m3/s	Qr=0.8	50%geo-bags (bottom)+50%CC blocks (top) as launching materials	Max velocity 2.74m/s at CS20 around LA=30r	Max scour 7.74m at CS18around LA
16	T12	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials	Max velocity 3.18m/s at CS14 around LA=30r	Max scour 11.82m at CS19 around LA
17	T13	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials	Max velocity 3.72m/s at CS17 around LA=25r	Max scour 9.00m at CS19 around LA
18	T14	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials	Max velocity 3.34m/s at CS16 around LA=35r	Max scour10.32m at CS22 around LA
19	T15	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	60%geo-bags (bottom)+40%CC blocks (top) as launching materials	Max velocity 3.18m/s at CS14 around LA=35r	Max scour 12.18m at CS20 around LA
20	T16 Ext 26-14	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials	Max velocity 3.29m/s at CS15 around LA=35r	Max scour 12.75m at CS20 around LA
21	T17 Ext 26-14	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials. CC blocks portion of LA consists of 45cm cube 50% and 35cm cube 50%.	Max velocity 2.85 m/s at CS15 around LA=30r	Max scour 12.81m at CS21 around LA
22	T18 Ext 26-14	shoot to main channel	Q_{shoot}= 2025 m^3/s (q=506 m^2/s)	-	50%geo-bags (bottom)+50%CC blocks (top) as launching materials. CC blocks portion of LA consists of 45cm cube 40% and 35cm cube 60%.	Max velocity 2.46 m/s at CS17 around LA=30r	Max scour 12.09m at CS20 around LA
23	T19	(main + shoot channel)	Q_{main}= 1125 m^3/s (q=250 m^2/s) Q_{shoot}= 900 m^3/s (q=225 m^2/s)	Qr=0.8	S1 (CC block + geo-bags) & S2 (geo-bags)	Max velocity 3.01m/s (S1) & 3.01m/s (S2) around LA	Max scour 12.48m (S1) & 7.83m(S2) around LA
24	T20	(main + shoot channel)	Q_{main}= 1125 m^3/s (q=250 m^2/s) Q_{shoot}= 900 m^3/s (q=225 m^2/s)	Qr=0.8	S1 & S2: u/s of LA (CC block + geo-bags) & d/s of LA (only stone-chips)	Max velocity 1.97m/s (S1) & 2.08m/s (S2) around LA	Max scour 11.94m (S1) & 6.99m(S2) around LA
25	T21	(main + shoot channel)	Q_{main}= 1125 m^3/s (q=250 m^2/s) Q_{shoot}= 900 m^3/s (q=225 m^2/s	Qr=0.8	S1 & S2: u/s of LA (CC block + geo-bags) & d/s of LA (CC blocks: 60cm 60% & 45cm 40%)	Max velocity 2.85m/s (S1) & 2.36m/s (S2) around LA	Max scour 11.82m (S1) & 6.66m(S2) around LA
26	T22	(main + shoot channel)	Q_{main}= 1125 m^3/s (q=250 m^2/s) Q_{shoot}= 900 m^3/s (q=225 m^2/s	Qr=0.8	S1 & S2: u/s of LA (CC block + geo-bags) & d/s of LA [CC blocks: 60cm 60%& 45cm 40%+500kg geo-bags]	Max velocity 1.97m/s (S1) & 2.52m/s (S2) around LA	Max scour 13.56m (S1) & 5.52m(S2) around LA

6.13 Cost Analysis

Cost analysis is made based on Standard Schedule of Rates Manual, 2012-13, O&M Circle, BWDB, Faridpur for different material composition (tests T12, T17, T18 & T22) in case of revetment and spur. The cost is around 34-35% is less for LA of composite materials than providing single composition of CC blocks in case of revetment and spur.

Table 6.13.1: Cost analysis for revetment and spur

Test No.	LA for Revetment	Costing (Tk.)/m	If only CC blocks used	% Savings
T12	Top: 45 cm cube 60%+35 cm cube 40%+bottom:250 kg geo-bag 50%+175 kg geo-bag 50%	378495	573365	33.99%
T17	Top: 45 cm cube 50%+35 cm cube 50%+bottom:250 kg geo-bag 50%+175 kg geo-bag 50%	375756	567887	33.83%
T18	Top: 45 cm cube 40%+35 cm cube 60%+bottom:250 kg geo-bag 50%+175 kg geo-bag 50%	373017	562409	33.68%
T22	LA (u/s part) for Spur			
	Top: 45 cm cube 40%+35 cm cube 60%+bottom:250 kg geo-bag 50%+175 kg geo-bag 50%	373017	562409	33.68%
	LA (d/s part) for Spur			
	Top: 60 cm cube 60%+45 cm cube 40%+bottom:500 kg geo-bag 100%	360376	558099	35.43%

7 Conclusion and Recommendation

7.1 Conclusions

On the basis of model results, the following recommendations have been made:

1) When there is parallel flow *i.e.* no oblique flow, insignificant scour or launching around the launching apron of different materials occurs.

2) It is seen from the test results that scour decreases when the discharge ratio of shoot to main channel changes from 0.8 to 1.0.

3) Scour is more under fully oblique flow condition than that of under oblique flow condition at discharge ratio either 0.8 or 1.0.

4) The best composition of materials for revetment: LA consists of 45 cm cube 40% & 35 cm cube 60% at the top layer and 250 kg geo-bag 50% & 175 kg geo-bag 50% at the bottom layer. In this case, maximum scour & velocity is found around 12.09 m & 2.46 m/s respectively under fully oblique flow (60^0). [T18]

5) Maximum absolute (without LA) scour is found 19.62 m around spur (shank length=30 m) under oblique flow condition. [T10]

6) The best composition of materials for u/s part of LA of spur: LA consists of 45 cm cube 40% & 35 cm cube 60% at top layer and 250 kg geo-bag 50% & 175 kg geo-bag 50% at bottom layer.

7) The best composition of materials for d/s part of LA of spur: LA consists of 60 cm cube 60% & 45 cm cube 40% at top layer and 500 kg geo-bag at bottom layer. In this case, maximum scour & velocity is found around 13.56 m & 2.52 m/s respectively under oblique flow condition (60^0). [T22]

8) It is seen from the test results that the combined apron (geo-bags + CC blocks) works better than when using only geo-bags (as per Standard Schedule of Rates Manual, 2012-13, O&M Circle, BWDB, Faridpur) or even only CC blocks as launching materials.

9) Among the 3-LA materials, stone chips are the best as it provides nice launching pattern. But it is too much expensive and not available in our country.

10) CC blocks have better launching capability but it is expensive relative to geo-bags.

11) Geo-bags can be made easily, available and less costly. But it (made as per design manual of BWDB) has relatively poor launching compared to CC blocks or composite material (geo-bag + CC bags).

12) The cost is around 34-35% is less for LA of composite materials than providing single composition of CC blocks in case of revetment and spur.

13) In this research work, plain bathymetry was used. The performance of composite material (of geo-bag & CC blocks) as launching materials can be verified in future using real bathymetry.

7.2 Recommendations

On the basis of model results, the following recommendations have been made:

1) Performance of composite launching material (geo-bag + CC block) in straight revetment construction in terms of attained areal coverage, developed slope and scour depth is found to be good under generalized bathymetry. Before implementation of the composite launching material, the result may be verified using real bathymetry.

2) At the d/s part of the spur, the launching material (geo-bag + CC block) used in this study needs more test to get optimum results considering variation of the size of geo-bag and CC block. In this study only one size geo-bag & CC block have been tested.

3) The composite launching material may be tested at u/s termination of the revetment by simulating the flow condition like u/s of Sirajganj Hard Point.

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