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Hydraulic capacity of culverts under sediment transport - Multibarrel Setup

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MASTEROPPGAVE

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Title: **Hydraulic capacity of culverts under sediment transport -
Multibarrel setup**

1 BACKGROUND

Culverts are important hydraulic control structures that allow water to flow under a road, railroad, trail, or similar obstruction. The proper understanding of flow and sediment transport through culverts is therefore necessary to evaluate and improve their performance in flood situations in order to guarantee safe roads and further infrastructure installations.

The hydraulic performance of culverts is presently investigated in a scale model study carried out in the NTNU hydraulic laboratory (Vassdragslaboratoriet). The project is embedded in the research project *Naturfare-infrastruktur, flom og skred* (NIFS) which is carried out jointly by Norges vassdrags- og energidirektorat (NVE), Jernbaneverket and Statens vegvesen. The objective of the culvert scale model study is to contribute to the development of new design guidelines for culverts taking into account the effect of debris and sediments. For this purpose, experiments are carried out in the NTNU hydraulic laboratory to investigate the effect of different boundary conditions on the discharge capacity. In detail, the experiments are carried out using different inlet geometries, varying sizes of the sedimentation basin, and coarse sediment as bed load. The measurements are used to establish discharge curves for the different culvert designs with and without effect from accumulated sediments and debris.

2 TASKS

The recent work carried out in the existing model focused on the establishment of discharge curves under clear water and sediment transport conditions for different inlet geometries and varying lengths and widths of the sedimentation basin. The present thesis will extend the data set by focusing on the improvement of the hydraulic and sediment transport capacity by using a multi-barrel setup. Therefore, the thesis should cover the following issues:

1. Literature review of culvert hydraulics and sedimentation transport through culverts with particular focus on culverts in steep streams and multi-barrel setups
2. Development of a test program for culvert-sedimentation experiments with particular focus on the effect of the multi-barrel setup on hydraulics and sediment transport
3. Carrying out experiments to investigate issues related to culvert-sedimentation and hydraulic capacity
4. Data analyses and discussion of results
5. Preparation of a report

Discussions with the supervisor will be used to refine details of the experimental setup and the experimental procedure.

3 SUPERVISION AND DATA

Professor Jochen Aberle from NTNU will be main-supervisor of the thesis. Discussions and input from colleagues and other researchers at NTNU, Statens Vegvesen, SINTEF etc. is recommended. Significant inputs from others shall, however, be referenced in an adequate manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context.

Other contact persons available: Geir Tesaker, NTNU; Harald Norem, Statens Vegvesen; Joakim Sellevold, Statens Vegvesen

4 REPORT FORMAT AND REFERENCE STATEMENT

The MSc-thesis shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary of not more than 450 words that is suitable for electronic reporting, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified and referred. The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) as the main target group. The thesis should be submitted in pdf-form in DAIM and in the form of three hardcopies that should be sent to the supervisor/department via the printing shop. The thesis should not be delivered later than Monday, June 30, 2014.

Trondheim, 16. januar 2014

Jochen Aberle
Professor

Abstract

As a part of the research program *Natural hazards – Infrastructure for floods and Landslides* (NIFS), the hydraulic performance of the culverts are presently investigated in a scale model study carried out in the NTNU hydraulic laboratory. The background for this model study is the nonexistence of the culvert design guidelines with the sediment effect, and insufficient knowledge on culvert design in steep streams under consideration of sediment transport. The model consists of a collecting reservoir, an approach channel, an expansion section and a culvert system installed in a 45° embankment. The approach channel with a slope of 1:9 presents a steep stream in which the flow is always supercritical. The purpose of the model is to test the effect of different parameters on the culvert capacity under sediment transport conditions. The test parameters include length and width of the expansion section, inlet geometry, slope of the stream, size and amount of sediments, and the different ways by which sediments approach the culvert (i.e. continuous sediment transport and landslide transport in the stream) and number of the culvert barrels.

Recent studies on the model investigated the effect of the length, the width of the expansion section and the slope of the approach channel. The present study focuses on the use of multibarrel culvert system. In each experiment, headwater was measured for different discharge increments, and the results were used to make performance curves or headwater-discharge curves for each parameter.

Results showed that the inlet geometry is the most influential parameter on the culvert hydraulic and capacity, and the sediment transport. Both wingwalls inlet and cut inlet gave similar capacity results, but wingwalls inlet presented a more stable flow condition in the expansion section. The ability of these two inlet types to transport sediment was very poor. On the other hand projecting inlet gave a lower capacity but it was able to transport more sediments than the other two inlet types. However, by comparing the results with previous study, it was determined that the increased water level and a flow with reduced energy in the expansion section caused by the energy dissipater blocks was the actual reason for the low sediment transport by wingwalls and cut inlet. Both continuous sediment and landslide transport showed some elevation in headwater results but it was not significant enough to change the capacity of the culvert. However, increased amount and size of the sediment did not give any further significant elevation in the headwater.

The main function of the reserve culvert in this multibarrel system was found to be the reduction of the headwater, as it did not have any effect on the pattern of sediment deposition. Sediments were deposited mostly on the centre line. However, in comparison with single barrel system it gave a flow with higher velocity towards the main culvert for the same headwater.

The results of this study did not give a complete solution for culvert in steep rivers, but these results can be more helpful in combination with the other studies.

Samandrag

Som ein del av forskingsprogrammet *Naturfare-infrastruktur, flom og skred (NIFS)*, er dei hydrauliske forholda i kulvertar undersøkt nærare ved bruk av skalerte modellar. Teststudiane er gjennomført i NTNU sitt Vassdrags-og havnelaboratorie. Bakgrunnen for denne studien er manglande rettningslinjer for utforming av dagens kulvertar med sediment effekt, og lite kunnskap knytta til utforming av kulvertar i bratte elvar samt sedimenttransport. Modellen består av eit oppsamlingsreservoar, ein tilløpskanal, ein ekspansjonskanal og eit kulvertsystem installert i ein 45° fylling. Tilløpskanalen har ei helling på 1:9 og skal representere ei bratt elv der strøyminga alltid er overkritisk. Målet med modellen er å dokumentere hvilke effektar ulike parametrar har på kapasiteten til kulverten, med spesiell fokus på forhold med ulik sedimenttransport. Testparametrane for modellen er lengde og breidde på ekspansjonskanal, innløpsgeometri til kulvert, helling på kanal, størrelse og mengde sediment, måten sediment nærmar seg kulverten (f.eks. kontinuerleg sedimenttransport og intens transport ved landskred) og antall kulvertløp.

Tidlegare studier på modellen har undersøkt effekten av lengde og breidde parameterar på ekspansjonskanalen samt ulike hellingar på tilløpskanalen. Denne studien, derimot, fokuserar på bruken av fleire kulvertløp. I kvart eksperiment vart vasstanden oppstraums kulverten målt for ulike inkrement av vassføringa. Resultatet av desse vasstandmålingane vart nytta til å plote prestasjonskurver, eller meir korrekt, vasstand-vassføringskurver for kvart parameter.

Resultatet av eksperimentera viste at innløpsgeometrien er den parameteren som i størst grad påverkar dei hydrauliske forholda, kulvertkapasiteten og sedimenttransporten. Både vingemurinnløp og kutta innløp ga liknande resultat, men vingemurinnløp resulterte i meir stabile strøymingsforhold i ekspansjonskanalen. Evna til å transportere sediment var låge for både vingemurinnløp og kutta innløp. Utstikkande innløp, derimot, skulle vise seg å handtere sediment mykje bedre enn vingemurinnløp og kutta innløp. Dessverre viste det seg også at det utstikkande innløpet har lågare kapasitet enn både vingemurinnløp og kutta innløp. Men, ved å studere resultat frå tidlegare studier vart det avslørt at dei låge resultat for sedimenttransport for både vingemurinnløp og kutta innløp skuldast energidissipatorane i ekspansjonskanalen. Energidissipatorane auka vasstanden oppstraums og reduserte vassenergien i ekspansjonskanalen. Både kontinuerleg sedimenttransport og landskredtransport viste høgare vasstand oppstraums innløpet, men dette var ikkje signifikant nok til å endre kapasiteten til kulverten. Ein auke av sedimentstørrelse gjorde ikkje utslag på vasstanden oppstraums innløpet.

Hovudfunksjonen til det ekstra kulvertløpet i multikulvertløpsystemet skulle vise seg å vere redusert vasstand oppstraums innløpet. Multikulvertsystemet hadde ingen effekt på sedimenttransportmønsteret og mesteparten av sediment vart avsett rundt senterlinja. Samanlikna med enkeltkulvertsystemet ga multikulvertsystemet høgare vasshastigheit mot hovudkulverten ved same vasstand oppstraums innløpet.

Resultata frå denne studien gir ikkje ei fullstendig løysing på kulvertproblema i bratte elvar, men resultatata kan med fordel nyttast saman med tidlegare studier for å nærme seg ein endeleg konklusjon på temaet.

Preface

This Master Thesis, *Hydraulic capacity of culverts under sediment transport- Multibarrel setup* is performed under the Department of Hydraulic and Environment Engineering at the Norwegian University of Science and Technology.

The Thesis is a physical model study of culverts in Hydraulic Laboratory of NTNU. All the experimental work for this study is performed by me, *Khoshal Faqiri*. However, this work would have not been possible without the academic support of my supervisor *Jochen Aberle*. Therefore, I use this opportunity to thank him for all his support, which was of great importance throughout this master thesis.

I would also like to present my thanks to *Geir Tesaker* for his technical support in the laboratory, *Harald Norem* and *Joakim Sellevold* from NRPA for their informative meetings, and *Masdiwati Minati Putri* my fellow student for providing me with some important knowledge from her part of experiments on the same model.

Khoshal Faqiri

Trondheim 30. June 2014

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1 Introduction

Culverts are important hydraulic control structures that convey surface water across a road, railroad, trail or other types of embankments. The flow capacity of culverts depends not only on the hydraulic conditions of the flow but also on the amount of sediments and debris carried by the stream. Most especially during the flood events, increased sediment deposition in front of the culvert inlets can reduce the capacity of the culverts or completely block them. Therefore, to insure safe roads and further infrastructure installations a proper understanding of not only flow but also sediment transport through the culvert is necessary to evaluate and improve their performance in flood situations. Unfortunately, the existing guidelines for culvert design are derived only under clear water conditions without considering sediment transport issues and its influence on the capacity of the culvert.

Due to insufficient knowledge on culvert design in steep mountainous areas under consideration of sediment transport, the Norwegian Public Roads Administration (NPRA), the Norwegian National Rail Administration (NNRA), and the Norwegian Water Resources and Energy Directorate (NVE) initiated a research project together with the Norwegian University of Science and Technology within the research programme Natural hazards – Infrastructure for floods and Landslides (NIFS). As a part of this programme, the hydraulic performance of culverts is presently investigated in a scale model study carried out in the NTNU hydraulic laboratory. The culvert scale model replicates a culvert in a steep stream and its objective is to contribute to the development of new design guidelines for culverts taking into account the effect of debris and sediments in steep streams. The model is used to carry out experiments to determine the effect of different parameters on the discharge capacity of the culverts under inlet control flow conditions. The different parameters that will be tested during the experiments are inlet geometry, length and width of the expansion section, flow regime in the expansion section, slope of the stream, size and amount of sediments, the different ways by which sediments approach the culvert, and the number of the culvert barrels. Headwater measurements from each experiment are used to obtain performance curves for different culvert design with and without effect of the sediments.

Recent studies carried on the model focussed on how the length (Gotvassli, 2013) and width (Putri, 2014) of the expansion section, affect the capacity of the culvert under sediment transport conditions. However, this thesis will focus on the use of a multibarrel culvert system. Results of the experiments will be used to determine how the capacity of multibarrel culvert system is affected by the sediment transport and on the other hand, how an extra barrel effect the sediment transport through the main barrel.

2 Culverts

Culverts are constructed from a variety of materials and are available in many different shapes and configurations (Schall et al., 2012). The selection of materials for a culvert depends upon structural strength, hydraulic roughness durability and constructability. Concrete, corrugated metal and plastic are the most common materials used for culvert construction. Cross-sectional shapes of the culverts can be circular, rectangular, elliptical, and pipe-arch. The most common used configurations include projecting culvert barrels, cast in place headwalls and wingwalls, precast end sections, culvert ends mitred to conform the slope to the fill slope, single- multi box culverts, and bottomless culverts. The selection of a proper culvert type depends upon many different factors such as roadway profiles, channel characteristics, flood damage evaluations, constructions and maintenance costs, and estimates of service life (Schall et al., 2012).

Multibarrel Culverts

Multibarrel culverts may be required due to the site conditions, stream characteristics or economic considerations (Schall et al., 2012). Often roadway profiles with low fills, wide shallow channel that do not allow high headwaters, require multiple barrels. Multibarrel culverts typically require a smaller upstream driving head, relative to a larger single barrel culvert, which is particularly beneficial when dealing with a shallow road prism (Haderlie and Tulis, 2008). In streams with sediment transport, one of the barrels are installed at the flow line of the stream and the others at the higher elevations. This will help the flow and the sediment to follow the lower barrel. Sediment and debris accumulation in the other barrels will be minimized since the barrels will only be operating in the higher than normal flows (Schall et al., 2012). An illustration of multibarrel system is shown in figure 2.1.

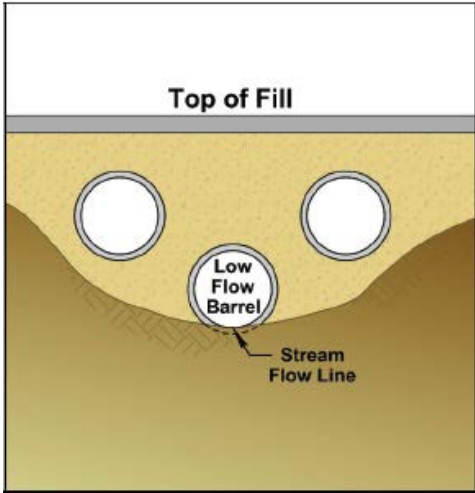


Figure 2.1 Multibarrel culvert system (Schall et al., 2012)

2.1 Hydraulics of Culvert

Over the time, different types of hydraulic flow conditions can occur in any given culvert barrel. Both pressure flow and free surface flow can occur in the culvert barrel. The types of flow in a culvert barrel depends upon the hydraulic conditions upstream and downstream of the culvert barrel characteristics and inlet geometry (Schall et al., 2012).

2.1.1 Head and Tailwater

Energy is required to force the flow through a culvert. The energy takes the form of an increased water surface elevation on the upstream side of the culvert. The depth of the upstream water surface measured from the invert at the culvert entrance is called headwater, HW. The depth of the headwater is an important factor in designing a culvert under inlet control conditions. The design headwater should not exceed the allowable headwater, which is the maximum possible headwater from the upstream side of the culvert. Allowable headwater is often defined by the regulatory constraints (Schall et al., 2012).

The hydraulic resistance or other obstruction in the downstream channel can cause the water surface to increase. The depth of the water surface downstream measured from the outlet invert is called tailwater, TW. Tailwater is an important factor in determining the performance of a culvert under the outlet conditions (Schall et al., 2012). Head and tailwater are illustrated in figure 2.2(b).

2.1.2 Flow Conditions

Two types of flow, pressure flow and free surface flow can appear in a culvert. This section describes both types.

Pressure flow

Pressure flow is a hydraulic condition in which the culvert flows full. This type of flow is usually caused by backpressure of a high downstream water surface elevation. A high headwater can also cause a pressure flow. The factors that affects the hydraulic capacity of the culvert under pressure flow are upstream and downstream conditions, as well as hydraulic characteristics of the culvert (Schall et al., 2012).

Free Surface Flow

A free surface flow is a type of flow in which the water surface is exposed to atmospheric pressure. This type of flow is also called open channel flow (Crowe et al., 2010). In culverts, free surface flow occurs when the culvert is flowing partly full. Depending on the magnitude of the dimensionless number (Fr) called Froude number, free surface flow can further be categorized as subcritical, critical or supercritical. Froude number is given by equation 2.1.

$$Fr = \frac{V}{\sqrt{gy}} \quad (2.1)$$

In equation 2.1, V is the average velocity of the flow in the culvert, g is the acceleration due to the gravity, and y is the representative depth of flow in the channel. For circular cross sections, the representative depth is defined by the equivalent depth, which is equal to the square root of one-half of the cross-sectional flow area, $(A/2)^{0.5}$. If F_r is larger than unity, the flow is supercritical and is characterized as rapid. If F_r smaller than the unity the flow is subcritical and is characterized as tranquil. When F_r is equal to the unity, the flow is defined as critical (Schall et al., 2012). The three categories of free surface flow can be illustrated by flow conditions over a small dam in figure 2.2(a). On the upstream of the dam crest where the water is deep and velocity is low, the flow is subcritical. Subcritical flow can be affected by downstream disturbance or restrictions. For example, the water level upstream will rise if an obstruction is placed on the dam crest. On the downstream of the dam crest, the depth is shallow and the velocity is high, representing supercritical flow. Flow characteristics in supercritical flow are not affected by downstream disturbance. For example, the water level upstream will not rise, if an obstruction is placed at the toe of the dam. Critical flow, which is the dividing point between subcritical and supercritical flow, occurs at the dam crest. The section where critical flow occurs is called control section, and the depth of water at this section is called critical depth. Identification of control section and critical depth is necessary for the analyses of free surface flow conditions (Schall et al., 2012).

In situation of a free surface flow in culverts, the critical depth and control section occurs at culvert inlet, subcritical flow exists in the upstream channel and supercritical in the culvert barrel. Figure 2.2(b) illustrates the free surface and inlet control flow in a culvert (Schall et al., 2012).

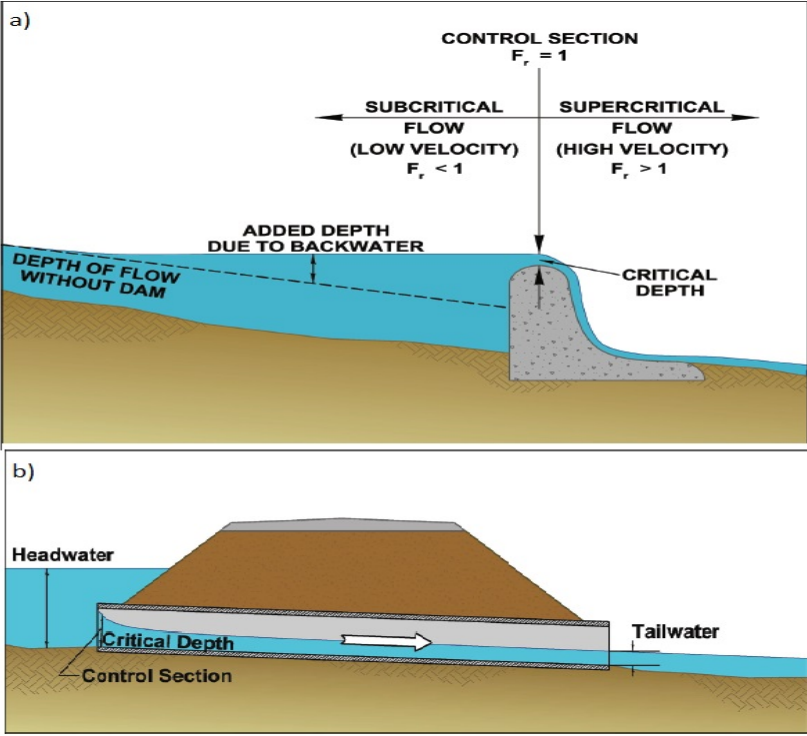


Figure 2.2 (a) Flow conditions illustrated with the help of a small dam. (b) Free surface and inlet control flow in a culvert (Schall et al., 2012)

2.1.3 Types of Flow Control

The two basic types of flow control are inlet and outlet control. These control types are classified according to the location of the control section. Since the location of the control section depends on the characterization of pressure, subcritical and supercritical flow regimes, types of flow control are also dependent of these factors. The capacity of a culvert depends upon a different combination of factors for each type control.

Inlet Control

A culvert is considered to be operating under inlet control, when the culvert barrel is capable to convey more flow than the inlet will accept (Schall et al., 2012). Due to this capability, a culvert flowing in inlet control has shallow and high velocity flow, categorized as free surface flow, and thus not flowing full through its entire length. Figure 2.2b illustrates an example of culvert operating under inlet control. Under inlet control, the control section is located just inside the entrance, with critical depth occurring at or near this section. The flow regime upstream control section is subcritical and changes to supercritical immediately downstream of the control section (Schall et al., 2012).

For culverts operating under inlet control, the flow patterns at the entrance may be three dimensional with vortices or other unpredictable features. A number of different factors can influence these patterns, the most important of which are inlet properties like; inlet geometry, wingwalls configurations, culvert shape and degree of bevelling (Creamer, 2007). In the in inlet control, the control section is located at the entrance and only the inlet properties and headwater affect the capacity of the culvert. Hydraulic characteristics of culvert downstream control section and tailwater do not have any effect on the culvert capacity (Schall et al., 2012).

Culverts can operate under inlet control, both in the low headwater conditions (unsubmerged inlet) and high headwater conditions (submerged inlet). When unsubmerged, the entrance operates as a weir. *“A weir is a flow control cross-section where the discharge and depth of water are related to one another through some predictable relationship”* (Creamer, 2007). When submerged the entrance operates as an orifice. *“An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section”* (Schall et al., 2012). Figure 2.3 illustrates the difference between unsubmerged and submerged conditions.

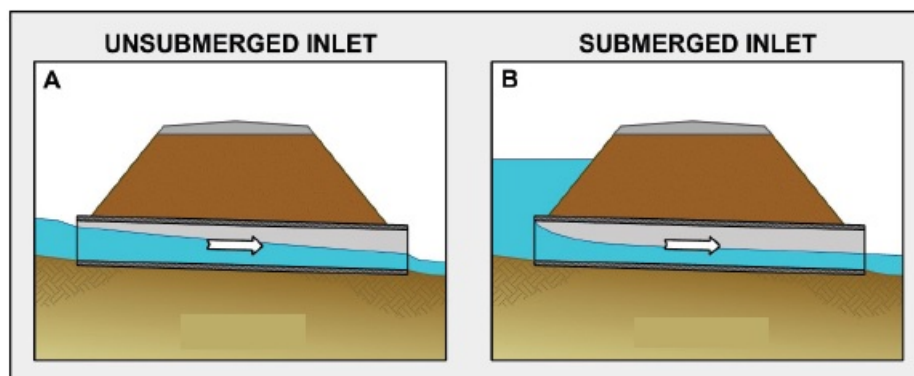


Figure 2.3 (A) Culvert operating under inlet control with the unsubmerged inlet. (B) Culvert operating under inlet control with the inlet submerged (Schall et al., 2012).

Different equations are used, to determine the headwater under inlet control for unsubmerged and submerged conditions. These equations are further explained in section 2.2.

Outlet Control

A culvert is considered to flow under outlet control when the culvert barrel is not capable of conveying as high flow as the inlet may allow. Under outlet control, the culvert barrel flows either full with pressure flow or partly full with subcritical free surface flow. In both cases, the control section is located at barrel exit or further downstream. Figure 2.4 represents two typical outlet flow conditions.

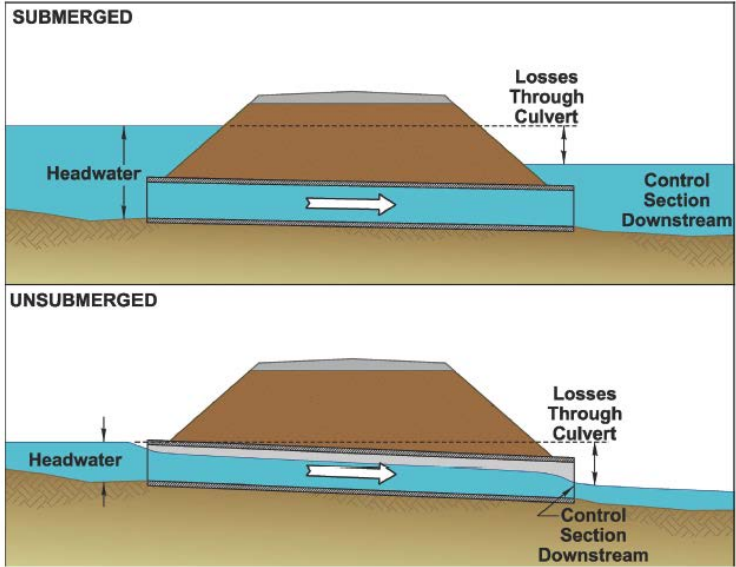


Figure 2.4 Culvert barrel flowing under outlet control in submerged and unsubmerged conditions (Schall et al., 2012).

Since in outlet-controlled flow the control section is located at barrel outlet or downstream outlet, all of the geometric and hydraulic characteristics of the culvert affect its performance. In addition to all the factors that influence culvert performance in inlet control flow, these characteristics include elevation of tailwater and the characteristics of culvert barrel (roughness, area, shape length and slope) (Schall et al., 2012). Table 2.1 summarizes the factors that influences the flow under inlet and outlet control.

Table 2.1 Factors influencing the culvert performance (Schall et al., 2012)

Factor	Inlet Control	Outlet Control
Headwater	X	X
Area	X	X
Shape	X	X
Inlet Configuration	X	X
Barrel Roughness	-	X
Barrel Length	-	X
Barrel Slope	X	X
Tailwater	-	X

Note: For inlet control the area and shape factors relate to the inlet area and shape. For outlet control they relate to the barrel area and shape.

For outlet control, the flow calculations are obtained with the help of energy balance. Culvert flowing full is a good example for the describing of such calculations. The amount of energy required to carry the flow through the culvert barrel is equivalent to the energy loss due to the entrance, the friction in the culvert, and the culvert exit. Losses due to the bend, junction and grates are also included if the culvert system possess these parts. Figure 2.5 shows how these losses affect the energy grade line (EGL) and hydraulic grade line (HGL), when culvert is flowing full under outlet control. The total energy loss is shown by the difference of upstream and downstream energy grade lines (Schall et al., 2012).

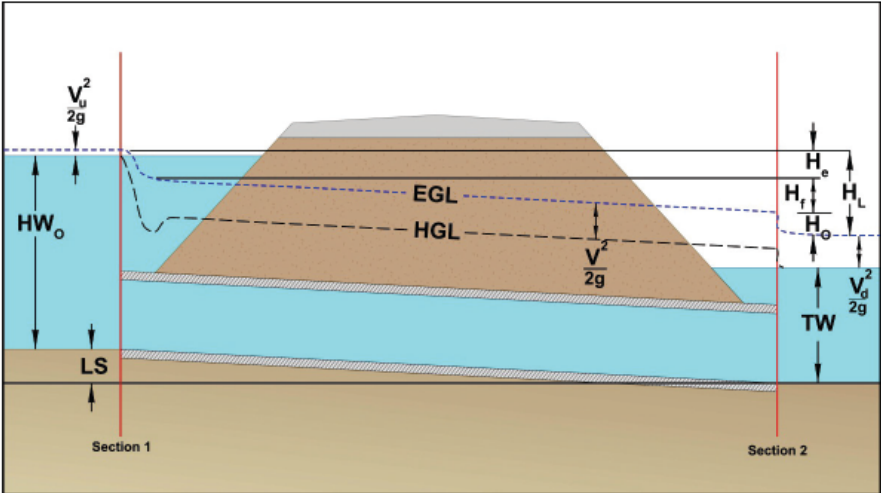


Figure 2.5 Flow calculation for a culvert flowing full (Schall et al., 2012).

By comparing the total energy on the upstream (section 1) and downstream (section 2) of the culvert barrel in figure 2.5 the equation 2.2 can be obtained (Schall et al., 2012).

$$HW_o + LS + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \tag{2.2}$$

In equation 2.2,

HW_o = Headwater

V_u = Approach velocity

TW = Tailwater

V_d = Downstream velocity

H_L = Sum of all the head losses through the culvert

LS = Drop though culvert

2.1.4 Performance curves

A Performance curve is a graphical representation of headwater HW vs flow discharge Q for a specific culvert. An example of a typical performance curve is illustrated in figure 2.6. A graphical representation of culvert operation is very useful in evaluating the hydraulic capacity of a culvert for various headwaters. Performance curves can be used to determine the consequences of higher discharges at the site (Schall et al., 2012).

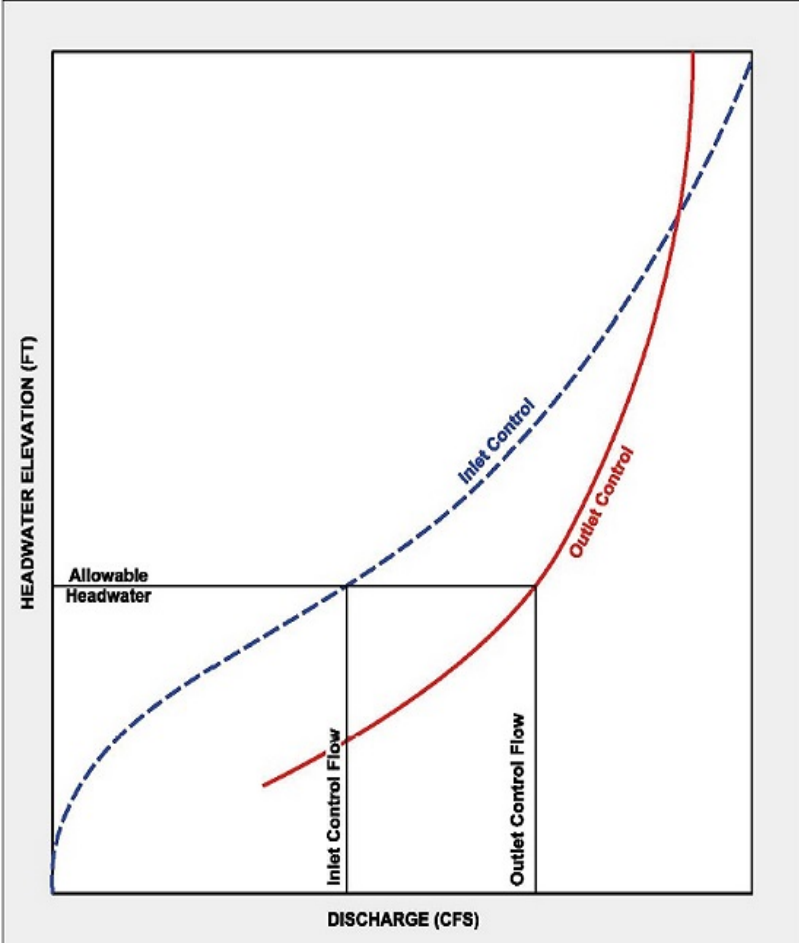


Figure 2.6 Culvert performance curve (Schall et al., 2012)

Both inlet and outlet control curves are given in the performance curve in figure 2.6. This is important because the dominant control at a given headwater is hard to predict. The control can shift from the inlet to outlet control or vice versa over a range of flow discharges. At the allowable or design headwater, the culvert always operates under inlet control.

If a performance curve is obtained by the model study, it can be used for the up-scaled models and real life situations by making it dimensionless. The headwater can be made dimensionless by dividing it on culvert diameter D, while discharge can be made dimensionless by equation 2.3. This equation was obtained by dimensional analysis using Froude scaling and Buckingham π theorem (Gotvassli, 2013).

$$Q^* = \frac{Q}{\sqrt{g}D^{2.5}} \tag{2.3}$$

However, the discharge in this model is distributed between two culverts, each of which has a different diameters and situated at different elevations. Therefore, the discharge cannot be distributed equally between the two culverts. As there are no discharge meters on each culvert and also the using performance curves from a separate system for each culvert could not give clear results, it was not possible to obtain discharge for each culvert. The calculations of discharge distributions from performance curves of separate system is explained in section 4.1.3.

As discharge for each culvert is known, it is not possible to make the results in this study dimensionless. Therefore, the results will be analysed in the model scale. However, the results in this study can be scaled up for further studies, using Froude similarity equations. Equation 2.4 can be used to scale up the discharge and equation 2.5 to scale up the headwater (McEnroe and Bartley, 1993).

$$HW_p = HW_m * \frac{D_p}{D_m} \quad 2.4$$

$$Q_p = Q_m * \left(\frac{D_p}{D_m}\right)^{\frac{5}{2}} \quad 2.5$$

As the scale of the model in this study is 1:10, $\frac{D_p}{D_m} = 10$.

2.2 Culvert design

Hydraulic Design of Highway Culverts by Federal Highway Administration (FHWA) of U.S. is a comprehensive culvert design publication. In addition to the guidelines for hydraulic design of the culverts, the publications also provides design considerations including hydrology, site data, site assessments, aquatic organism passage, and structural considerations (Schall et al., 2012).

This publication provides inlet control the headwater-discharge equations, which are widely used for the culvert design. The equations were obtained through a research work by FHWA at the National Bureau of Standards (NBS) laboratories starting in 1950s (Schall et al., 2012). Equation 2.6 and equation 2.7 apply to unsubmerged inlet, referred to as Form 1 and Form 2 equations, and equation 2.8 applies to submerged inlets.

(Form 1)

$$\frac{HW}{D} = \frac{Hc}{D} + K \left[\frac{Q}{AD^{0.5}} \right]^M - 0.5S \quad (2.6)$$

(Form 2)

$$\frac{HW}{D} = K \left[\frac{Q}{AD^{0.5}} \right]^M - 0.5S \quad (2.7)$$

$$\frac{HW}{D} = c \left[\frac{Q}{AD^{0.5}} \right]^M + Y - 0.5S \quad (2.8)$$

In the above equations HW is headwater; Hc is critical depth; D is culvert diameter; Q is culvert discharge; A is full cross-sectional area of culvert barrel; K, c and Y are empirical coefficients and M is empirical exponent, all of which vary with culvert inlet geometry; and S is culvert barrel slope (Haderlie and Tulis, 2008).

To make culvert design easier these equations are used to make nomographs for the culvert design. Nomographs are charts, which can be used to design culverts when two of the three parameters culvert diameter, design discharge, and headwater are known. A set of nomographs for different culvert types are given in *Hydraulic Design of Highway Culverts*. An example of a nomograph, and how it is used to find the headwater for specific discharge and culvert diameter is shown in figure 2.7.

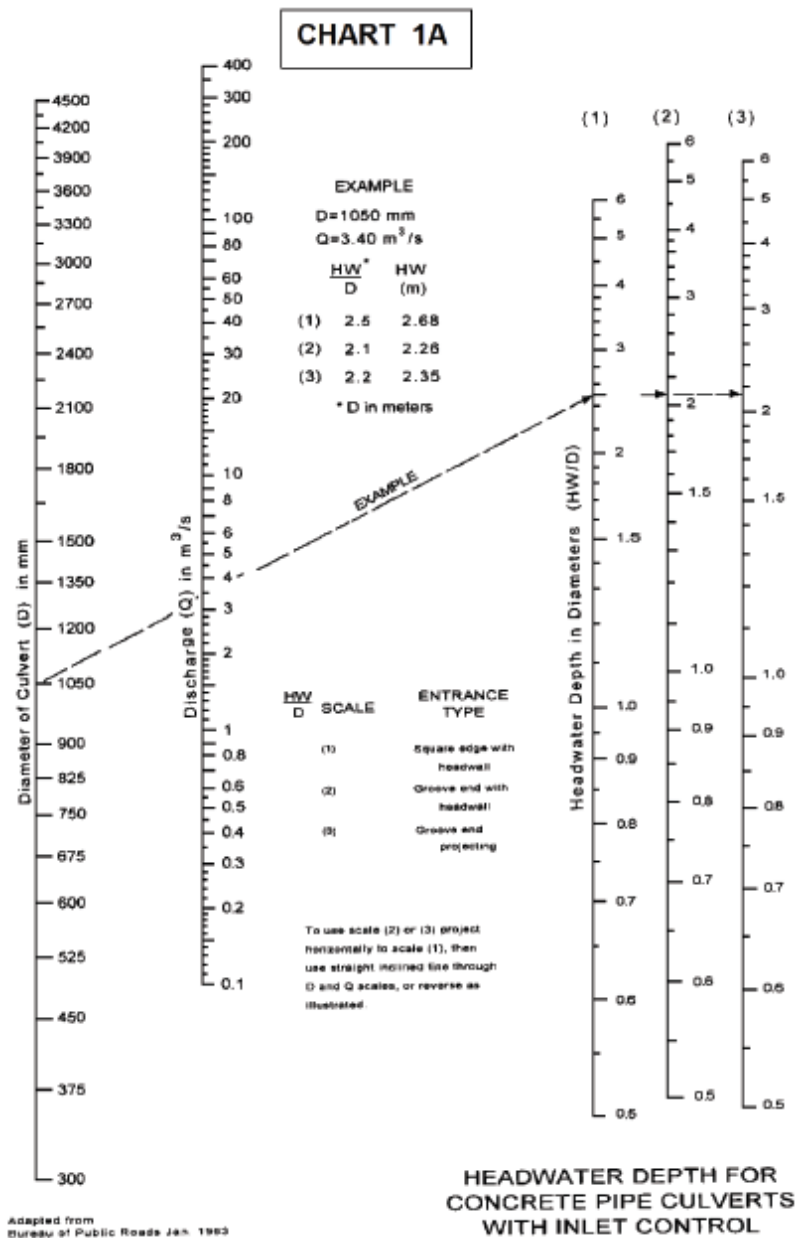


Figure 2.7 Example of a nomograph (Schall et al., 2012)

In Norway, the roads are designed in accordance to the manual *Håndbok 018 Vegbygging* published by The Norwegian Public Road Administration (NPRA). The manual provides guidelines for planning, dimensioning and building of roads. Design of culverts is also included with hydraulic and constructional considerations. According to this manual, all the circular culverts with length lesser than 15-20 meters should be design with inlet control flow (Vegvesen, 2011). Table 2.2 brought from this manual shows the capacity of culverts under inlet control and with headwater to diameter ratio $HW/D = 1$.

Table 2.2 Hydraulic capacity (l/s) for culverts with inlet control and HW/D =1 (Vegvesen, 2011)

Inn-løps utforming	Diameter (mm)				
	300	400	500	600	800
A	67	135	232	361	726
B	65	132	228	357	723
C	57	117	204	320	652
	1000	1200	1400	1600	
A	1247	1940	2818	3895	
B	1250	1954	2851	3956	
C	1133	1780	2607	3628	

A, B and C in the table represent Wingwalls, cut and projecting inlet respectively. According to the table wingwalls gives better capacity for diameters lesser than 1 meter, while cut gives a higher capacity for larger diameters. However, the difference between their capacities is not very significant for all the diameters. Projecting inlet give lower capacity than both the other two inlets for all the diameters.

2.3 Sedimentation problem in culverts

Usually culverts are constructed with relative mild slopes to avoid supercritical flow upstream of the culvert inlet. Consequence of a mild slope is increased probability of sediment deposition near the culvert inlet. Sediment accumulation near and inside the culvert barrel decreases its capacity and may make the culvert unable to pass its design discharge. Sediment deposition at culvert is influenced by many factors including size and characteristics of the sediments, the hydraulic characteristics generated under different hydrology events, culverts geometry design, channel transition design and vegetation (Ho, 2010).

Multibarrel culverts are exposed to sediment deposition, because the flow is often not distributed equally between the each barrel, which may make one of the barrels more susceptible to sediment deposition. Most culvert design guidelines provide specifications only for the clear water conditions. The customary design assumption taking sediment in consideration is that sediment might deposit at a normal flow condition and flushed out at storm flow event (Ho, 2010).

3 Experimental Setup

This chapter will present the setup of the physical culvert model and the procedure of different types of experiments.

3.1 Model Setup

The model consists of an upstream collecting reservoir, an approach channel with a sediment-adding vibrator, a channel expansion section, and a multi-barrel culvert system. The reservoir collects the water from the water pump system of the laboratory. The approach channel leads the water from the reservoir to the expansion section, and it represents a steep river where the flow is always supercritical. Its slope is adjustable. In this master thesis, the slope of the approach channel is kept to 1:9 for all the experiments. On the top of the approach channel, a sediment-adding vibrator is fixed. It is used to add sediment gradually and continuously during the sediment experiments. Before the water passes the culvert system, it runs through the expansion section. The depth of the water in the expansion section is called headwater HW and it is the main variable, which will be measured in the experiments. A close view of the expansion section is shown in figure 3.4. The multi-barrel culvert system in the model consists of two culvert barrels, a main culvert, and a reserve culvert. The main culvert has a diameter of 100mm and it is built on the centre line of the model in front of the approach channel. The reserve culvert has a diameter of 60 mm, which is built, with a centre-to-centre distance of 420 mm from the main culvert, and an elevation of 40 mm from the floor of the expansion section. Table 3.1 and figure 3.1 present the technical specification of model. Figure 3.3 shows a whole picture of the model. The model is scaled on the bases of the Froude similarity with a scale of 1:10.

Table 3.1 Technical specifications of the model

Components of the model	Physical dimensions				
	Length <i>l</i> [mm]	Width <i>w</i> [mm]	Height <i>h</i> [mm]	Slope <i>S</i>	Diameter <i>D</i> [mm]
Collecting reservoir (<i>cr</i>)	785	535	420		
Approach channel (<i>a</i>)	2400	230	300		
Expansion section (<i>exp</i>)	876	1100	300	2 %	
Main culvert barrel (<i>m</i>)				2 %	100
Reserve culvert barrel (<i>r</i>)				2 %	60
Energy dissipater blocks	20	20	20		

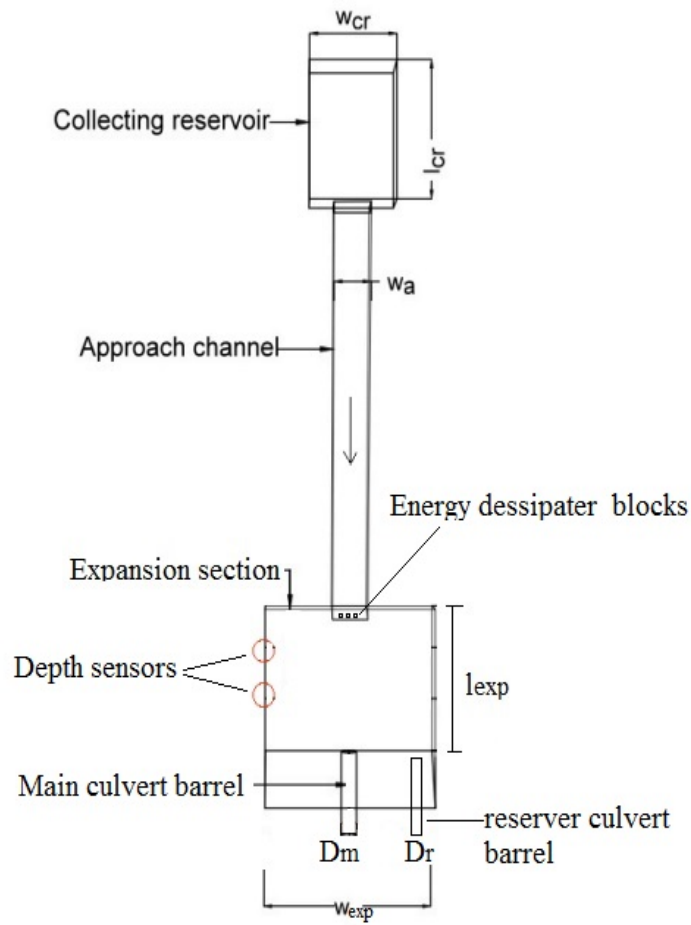


Figure 3.1 Top view of the model (modified from (Gotvassli, 2013))

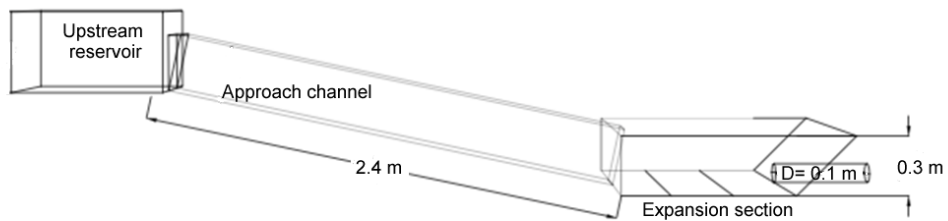


Figure 3.2 Side view of the model (Aberle et al., 2014)



Figure 3.3 A Picture of the whole culvert model

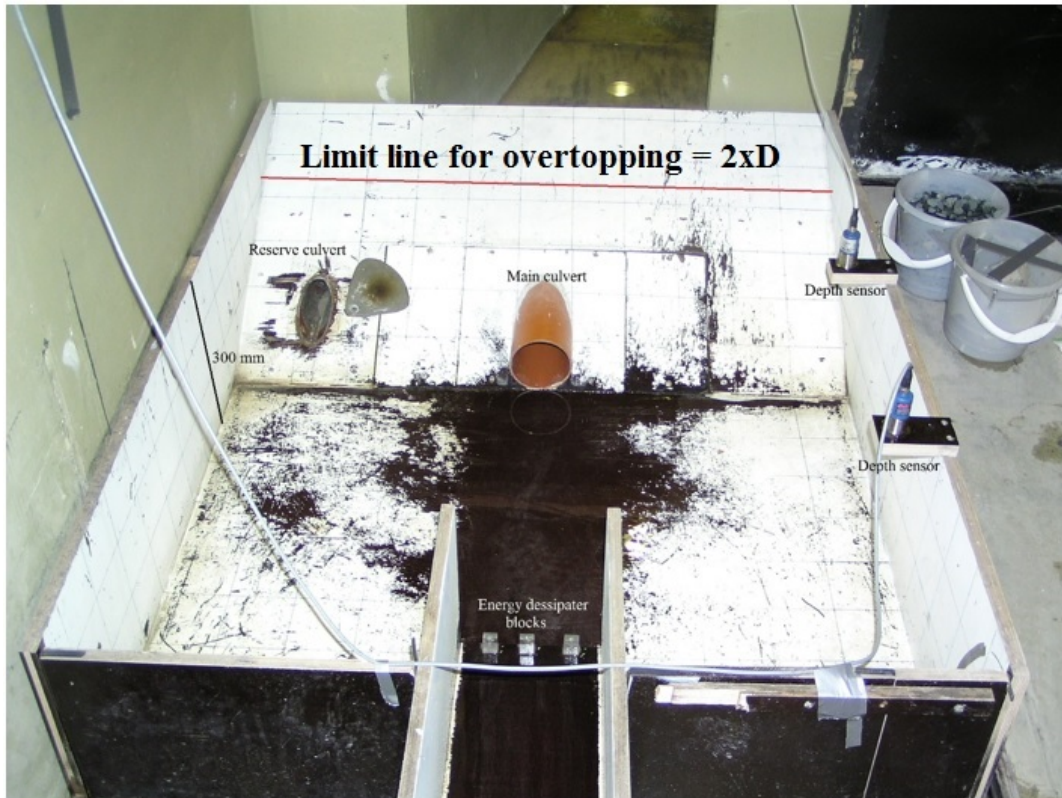


Figure 3.4 A Close view of expansion section

Three energy dissipater blocks are mounted at transition of the approach channel and expansion section. The background for these blocks was the unstable flow condition caused by the oscillating jet that occurred in the transition of the approach channel and the expansion section, in the previous study on the model (Gotvassli, 2013). The dimensions and location of the energy dissipaters are shown in table 3.1 and figure 3.1 respectively.

Types of inlet

The model is designed such that the inlet types of the main culvert can easily be changed. Three different shapes are tested in this thesis. These inlet shapes are A) Wingwalls inlet, B) Cut inlet, and C) Projecting inlet. All three inlet shapes are shown in figure 3.5.

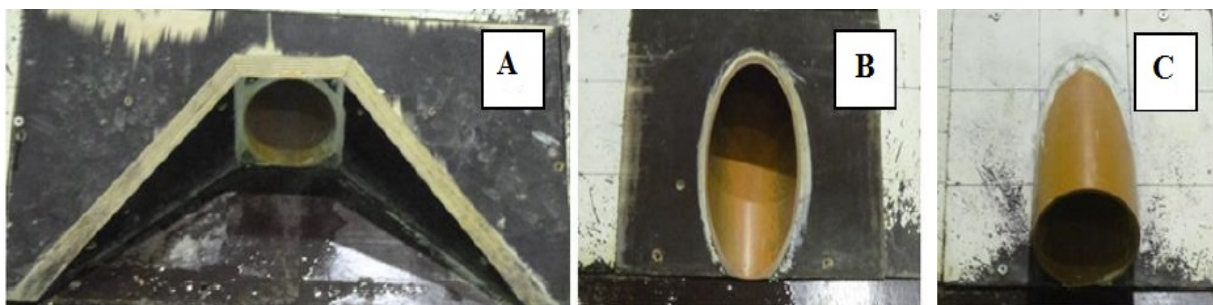


Figure 3.5 Types of inlet A) Wingwalls inlet, B) Cut inlet and C) Projecting inlet.

Wingwalls inlet has a 45-degree wingwalls. Cut inlet is an inlet type, which is mitred alongside the slope of the embankment, which is 1:2. The projecting inlet is a full pipe, which sticks out of the embankment.

The reserve culvert was designed with a cut inlet. The reason for the choice of cut inlet is recommended by both (Gotvassli, 2013) and NPRA guidelines (Vegvesen, 2011). According to them, the cut inlet is the best inlet shape after the wingwalls. Because of the limitations of the model, it was not possible to design a wingwalls inlet shape for the reserve culvert.

3.2 Sensors and measurements

The discharge Q in the experiments was measured by a Siemens Sitran FM Magflo MAG500 discharge meter, which is installed in the supply pipe to the collecting reservoir. The headwater depth in the expansion section was measured by the two Microsonic mic+ ultrasonic sensors, which are installed on the right wall of the expansion section. The headwater results for each experiment was obtained by averaging the readings of these two sensors over the whole sampling time of the experiment. The depth sensors could give minute depth values also when there was no discharge running. Therefore, measurements were also taken at zero discharges in the start of each experiment and then subtracted from the higher discharges.

Experiments were started at a discharge of 2 l/s, which was increased stepwise by 2 l/s increments for the next experiment. The discharge was increased until the water depth in the expansion channel exceeded the allowable headwater, or a pressure flow was observed at the outlet of barrel, indicating outlet control. The allowable headwater or overtopping limit is two times culvert diameter. The limit for overtopping was defined in conversation with Harald Norem from NPRA, in the previous study (Gotvassli, 2013). Overtopping limit line is shown in figure 3.4.

Different sampling times were chosen for clear water, gradual sediment feeding and all at once feeding experiments. The procedure of each experiment is explained in the next chapters. Sampling time for all clear water test was 3 minutes at each discharge. For gradual feeding experiments the total sampling time was 20 minutes, 15 minutes with sediment fed water and 5 minutes with clear water. The last five minutes called test was run with only clear water to analyse the effect of sediment deposition in the expansion section. The total sampling time for all at once feeding experiments was 16 minutes, 1 minute before sediment addition and 15 minutes after sediment addition.

A weighting scale was used to find the amount of sediment deposition at each discharge in the expansion section. Pictures were taken to illustrate the pattern of the sediment deposition. The maximum width of the sedimentation was found using the grid painted on the embankment in the model. Each grid is 10 times 10 cm. Maximum width of the sediment deposition W_{dep} is illustrated in figure 3.6.

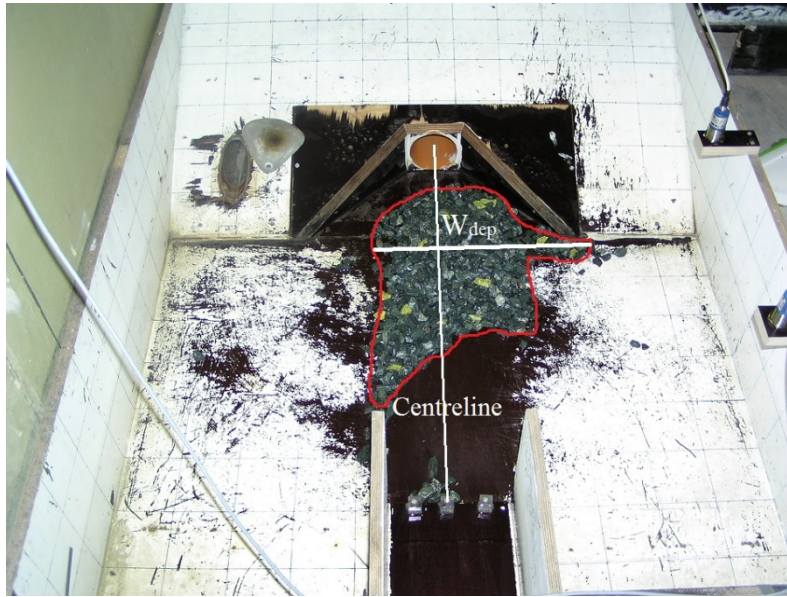


Figure 3.6 Maximum width of sediment deposition

3.3 Clear Water Experiments

To find the effect of the inlet shape on the culvert hydraulics and capacity, the experiments were run with only clear water first. Experiments were conducted for each inlet shape in combination with the reserve culvert, and with reserve culvert closed. One experiment was also conducted only for reserve culvert. In this case, the main culvert was kept closed to simulate a situation where the main culvert is blocked. A full list of the experiments carried out with clear water is given in table 3.2.

Table 3.2 List of experiments carried out with clear water

Barrel combinations	Inlet types		
	Cut	Projecting	Wingwalls
Only main culvert	X	X	X
Main culvert + Reserve Culvert	X	X	X
Reserve Culvert	<i>In this experiment, the main culvert was kept closed.</i>		

3.5 Sediment Experiments

Experiments with sediments were carried out to determine the effect of the sediment on capacity and hydraulics of the culvert. For these experiments, sediment had to be fed to the upstream section of the approach channel. This was approached with two feeding strategies; gradual feeding and all at once feeding. In the gradual feeding, the sediments were fed with a low feeding rate, simulating a stream with continuous sediment transport. In the all at once feeding, the sediments were fed to the approach channel all at once, simulating a landslide situation. The vibrating machine on the approach channel was used for the gradual feeding and a bucket was used to add the sediments all at once.

For each inlet geometry, continuous experiments were conducted with two different weights and two different grain sizes, to determine the effect of amount of sediment and the effect of size of sediment, respectively. 5 kg and 7 kg are the two weights tested, with grain sizes of diameter 8-16 mm and diameters 16-32 mm, are the two grain fractions tested. These quantities were also used in the previous studies on this model (Gotvassli, 2013) and (Hendler, 2014). All at once feeding experiments were conducted only with 5 kilograms of 8-16 mm sediments. Table 3.3 presents a list of all types of experiments conducted with the sediment fed water.

Table 3.3 List of experiments carried with sediment fed water

Parameters	Inlet Types		
	Cut	Projecting	Wingwalls
Sediment size [mm]			
8 -16	X	X	X
16 - 32	X	X	X
Sediment amount [Kg]			
5	X	X	X
7	X	X	X
Feeding strategies			
Gradual feeding	X	X	X
Sudden feeding	X	X	X

4 Results

In this chapter, results from all conducted experiments will be presented. The results from experiments conducted with different parameters are compared against each other to determine their effect on the culvert capacity and its hydraulics. As there was no sensors to determine the discharge in each of main and reserve culvert, it was not possible to make the results dimensionless. Therefore, the results are analysed dimensional, in the model scale. However to make the reader able to compare the results with the real life situation and scaled up models, the discharge increments are scaled up according to Froude similarity in table 4.1 using equation 2.5. Headwater or other model lengths can be scaled up by using equation 2.4 or simply by multiplying by 10.

Table 4.1 Discharges scaled up according to the Froude similarity.

Model discharge	Q_m [l/s]	2	4	6	8	10	12
Prototype Discharge	Q_p [l/s]	632	1265	1897	2530	3162	3795
Prototype Discharge	Q_p [m ³ /s]	0,632	1,265	1,897	2,530	3,162	3,795

4.1 Results of Clear Water Experiments

Clear water test were conducted to determine the effect of the inlet shape on hydraulics and capacity of the multi barrel system. Visual observations showed that hydraulics in the model changed for each discharge increment. Due to the presence of energy dissipater blocks at the transition of approach channel and the expansion section, the hydraulic jump occurred for all the discharges. Hydraulic jump led to a water stream of a higher surface and some reduced velocity and energy in the expansion section. However, the extent of energy and velocity reduction was not very large, and thus a flow jet with a high velocity and energy was always flowing towards the barrel. When unsubmerged, the hydraulic behaviour of the flow for each inlet type was different, but in submerged conditions, the flow in the expansion section was characterized with water circulations and surface waves for all of the inlet types. In all the experiments at 10 l/s, the surface waves were large enough to touch the overtopping line, while at 12 l/s they totally overtopped the overtopping line, even though the results at these discharges do not show overtopping headwater.

4.1.1 Effect of inlet shape

Figure 4.1 presents the performance curves for all the three inlet shapes, obtained by clear water experiments. Based on the figure 4.1 cut and wingwalls inlet represents almost similar results for most of the discharges except 6 l/s and 12 l/s. At 6 l/s, headwater for wingwalls inlet is 18 percent higher than the headwater for cut inlet. At 12 l/s cut inlets gives 13 percent higher headwater than wingwalls. At 8 l/s and higher discharges, the projecting inlet gives lower headwater results and thus a higher capacity, but the results are not comparable with cut and wingwalls inlet, since at these discharges the barrel with projecting inlet operates under pressure flow, and thus conveys more flow than free surface flow. The pressure flow at these discharges was determined by visual observation of the outlet condition of the barrel. Figure 4.5 shows the outlet condition of the barrel for each discharge increment in clear water experiments for all the three inlet shapes.

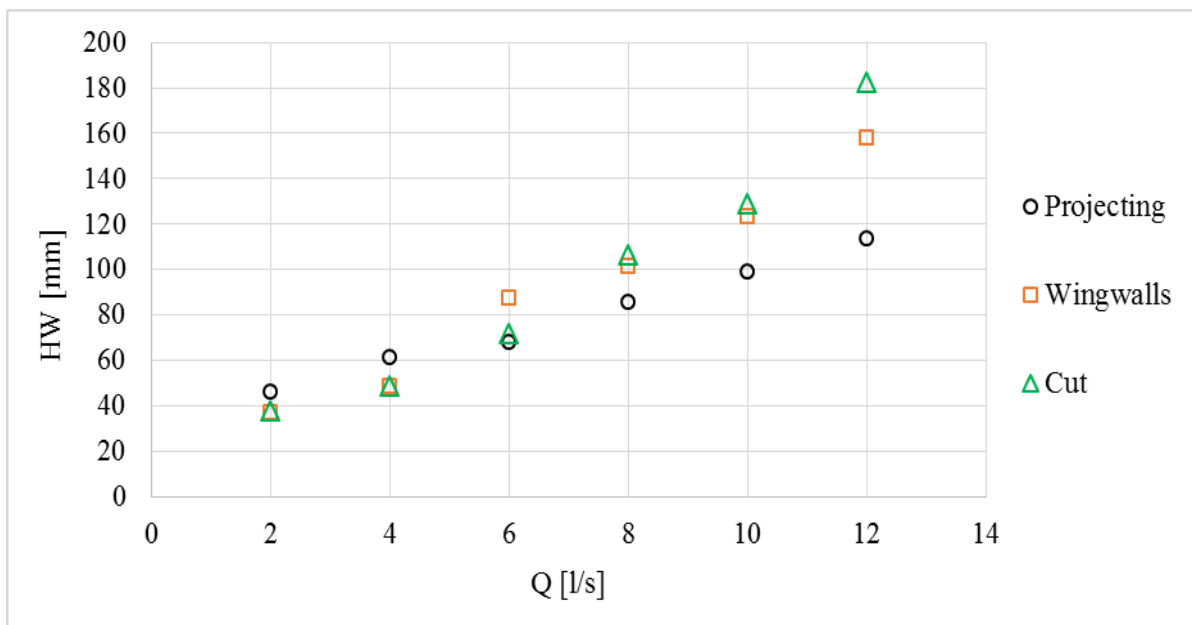


Figure 4.1 Performance curves showing the effect of the inlet shape on the capacity of the culvert in clear water condition.

Beside the different headwater results, each inlet shape represented different hydraulic behaviour in the expansion and culvert barrel. For the projecting inlet, the hydraulics of the expansion section was characterized with surface waves, sidewise oscillation of the jet and water circulations, for the unsubmerged conditions. In this master thesis, sidewise oscillations is defined as the condition where the jet oscillated alternately on each side of barrel. Sidewise oscillations and circulations are shown in figure 4.2. The size of sidewise oscillations in these experiments was not as large as the size of sidewise oscillations of jet in experiments without energy dissipater blocks (Gotvassli, 2013). For submerged conditions, the expansion section was only characterized with the surface waves.

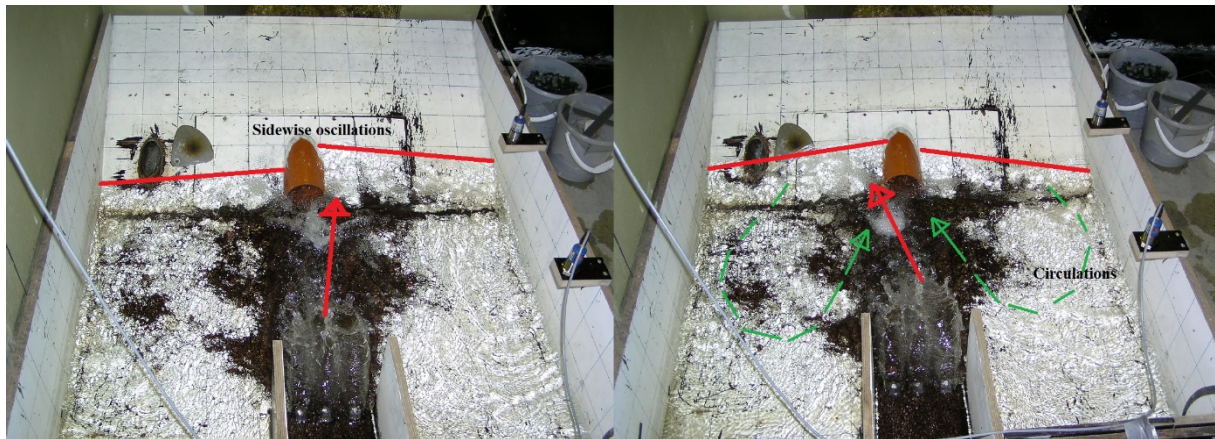


Figure 4.2 Illustration of sidewise oscillations of the flow jet and water circulations.

Sidewise oscillations of the water jet were not very visible for the cut inlet, however the jet in unsubmerged conditions gave a higher water level over the inlet. This is shown in figure 4.3. Water circulations also occurred in unsubmerged conditions for cut inlet.

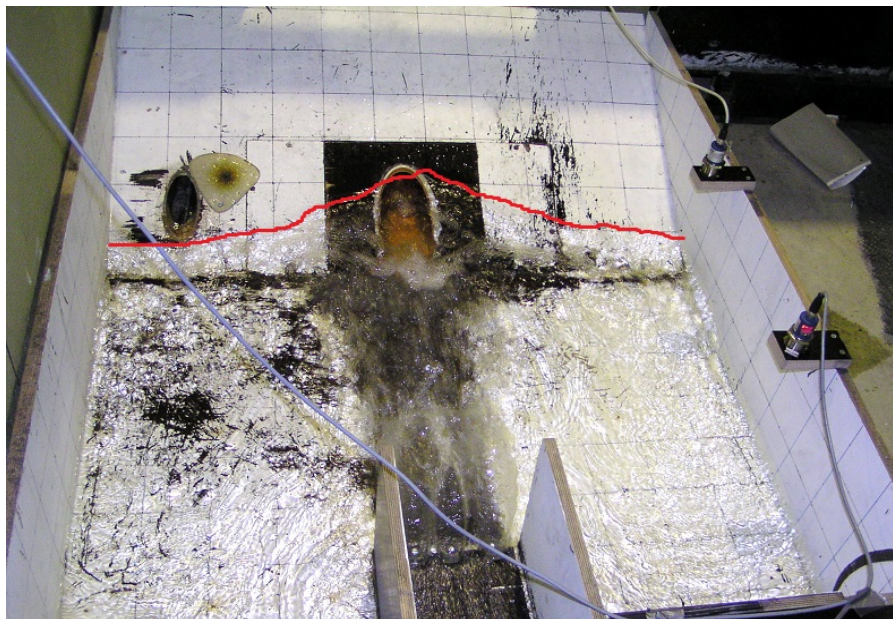


Figure 4.3 Behaviour of the jet in flow conditions for the cut inlet.

Wingwalls inlet gave the most stable flow conditions of all the three types of the inlet shape, under unsubmerged conditions. There was no sidewise oscillation of the flow jet and the surface waves and the circulations were very small. Figure 4.4 represents the unsubmerged flow conditions for wingwalls inlet.

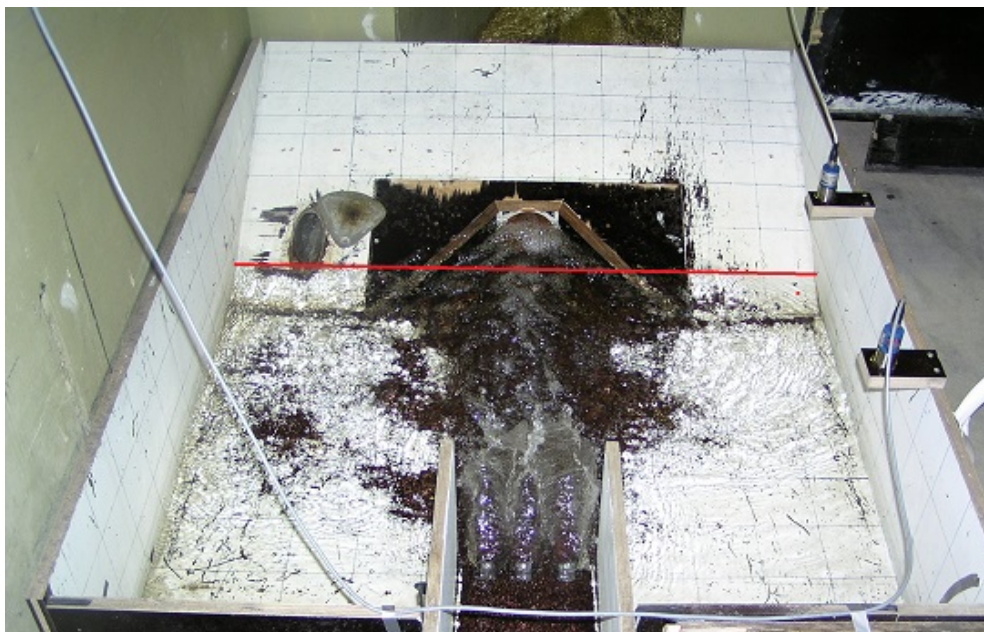


Figure 4.4 Flow condition in the expansion section for unsubmerged wingwalls inlet.

4.1.2 Outlet Condition

In each experiment, the condition of barrel outlet was visually observed to determine whether the flow in the barrel is inlet or outlet controlled. Figure 4.5 shows the outlet conditions for all the three inlet shapes and each discharge increment. In experiments with cut and wingwalls inlet, the barrel operates under inlet control for all the discharges. At 12 l/s, the flow in the barrel for both cut and wingwalls is very turbulent, and it can be misinterpreted with the pressure flow, but that is not true since there is free space and air in the barrel. For projecting inlet, the barrel operates with under inlet control for discharges up to 6 l/s. At 8 l/s, the barrel operates with a mixture of free surface and pressure flow. The transition between free and pressure flow at this discharge imitates a heartbeat pattern. At 10 l/s and 12 l/s, the barrel with projecting inlet operates with full pressure flow and thus outlet control, with no air in the barrel.

The reserve culvert starts to operate with pressure flow at 10 l/s for all the inlet types. The difference between the outlet conditions of clear water experiments and outlet condition of sediment fed experiments is minor and negligible. Thus, figure 4.5 can also be used to illustrate the outlet conditions for all types of sediment experiments.

In this thesis, visual observation of barrel outlet is chosen to determine the inlet and outlet control flow, instead of outlet limit curves used in the previous study (Gotvassli, 2013). The curves were not able to determine the outlet control flow, as an outlet control flow in the experiments conducted in this thesis gave lower headwater than the headwater in inlet control flow.

Outlet conditions of barrel with all three types of inlet

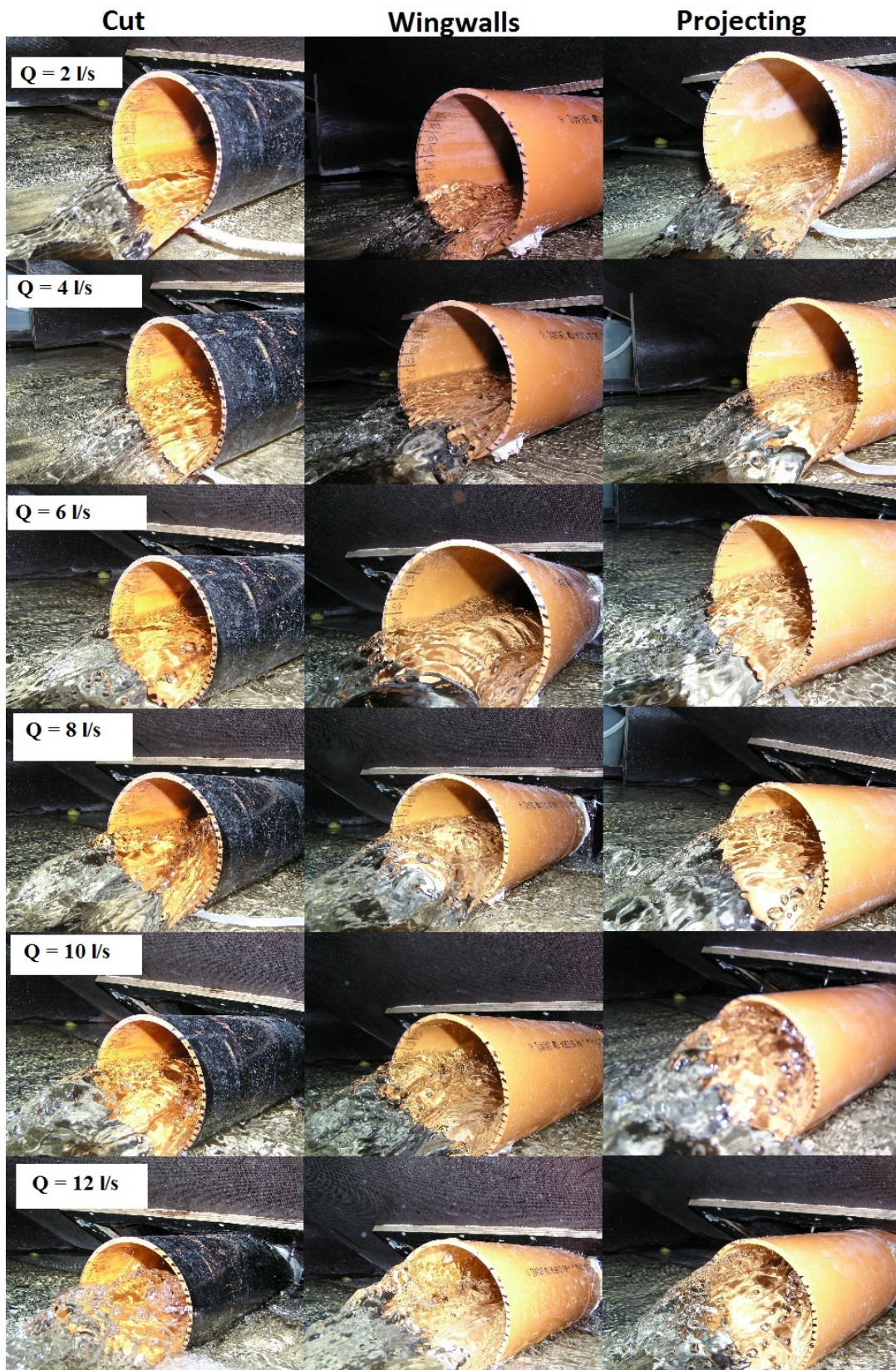


Figure 4.5 Outlet condition of the barrel for each discharge increment in clear water experiments conducted with cut, wingwalls and projecting inlet.

4.1.3 Capacity and effect of the reserve culvert

To determine the capacity of the reserve culvert and its effect on the hydraulics of the system, clear water experiments with only main culvert were also conducted. The results then were compared with the results of the multi-barrel system. Figure 4.6 gives the headwater results for wingwalls inlet operating with both single and multi-barrel system, and the difference between the two systems. The headwater difference between the two systems is the head of water the reserve culvert conveys out, in the multi barrel system. From the figure 4.6, it can be seen that the reserve culvert starts operating at 6 l/s and its impact increases for higher discharges. Similar figures for Cut and projecting inlet are given in the Appendix A.

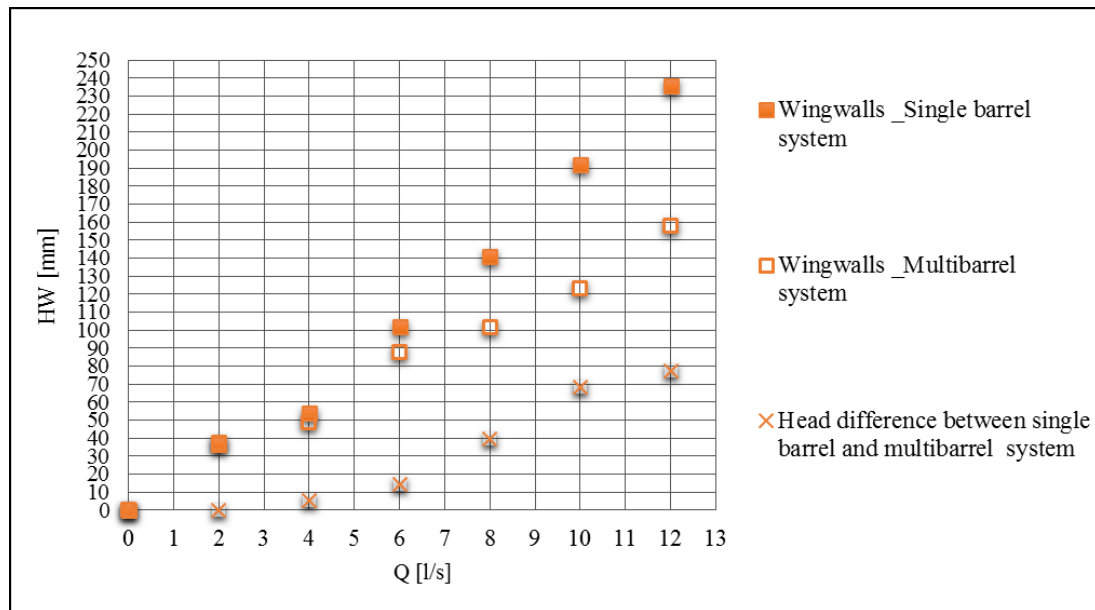


Figure 4.6 Headwater results of multibarrel system in comparison with single barrel system for experiments conducted with clear water and wingwalls.

The difference between the hydraulic behaviours of the single and multi-barrel system was not obvious except the headwater difference. Flow conditions in the expansion section was also characterized with the surface waves, circulations for all inlet types and sidewise oscillation of the flow jet for projecting inlet. Higher headwaters for single barrel system also imposed backpressure on the approach channel at the lower discharges.

Experiment for only reserve culvert was also conducted to determine its capacity in case of a blocked main culvert. The reserve culvert reached its capacity at a discharge between 3 l/s and 4 l/s. The headwater results for this experiment is given in the figure 4.7. In these experiments, the flow in the expansion section was very still and stable. The water in expansion section imposed backpressure on the approach channel, which moved the hydraulic jump upstream energy dissipater blocks. At 4 l/s, the hydraulic jump moved as long as 150 cm in the approach channel upstream of the energy dissipater blocks.

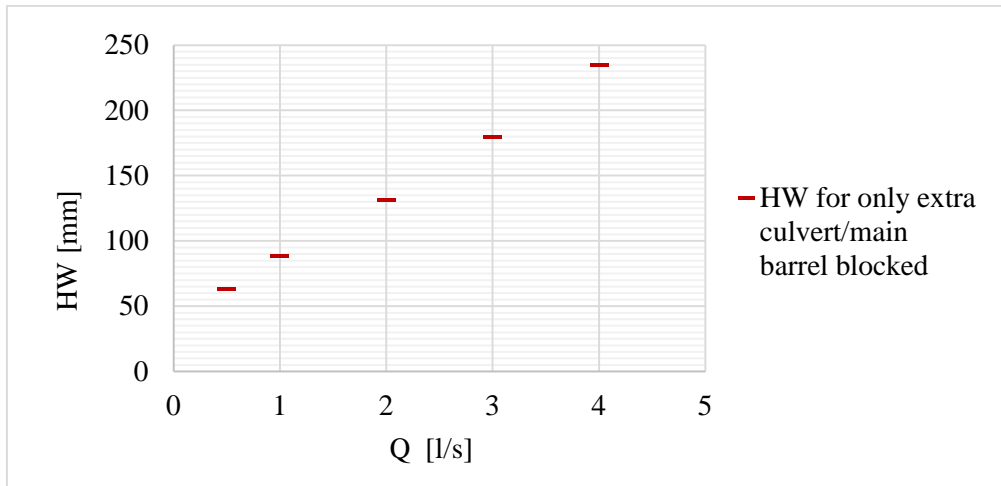


Figure 4.7 Performance curve of the reserve culvert when the main culvert was blocked.

To make the results of the experiments dimensionless it is necessary to determine the discharge at the main barrel and reserve barrel separately, while operating in multi barrel system. It is assumed that at a specific headwater the sum of discharges found from performance curves of single barrel system Q_{sb} and reserve culvert Q_{res} will give an equivalent discharge to that of multi barrel system Q_{mb} . The assumption is expressed in equation 4.1.

$$Q_{mb} = Q_{sb+res} = Q_{sb} + Q_{res} \quad 4.1$$

Figure 4.8 illustrates an example of discharge distribution calculation for wingwalls inlet graphically. Interpolation was used to find the values where there were no measurements taken.

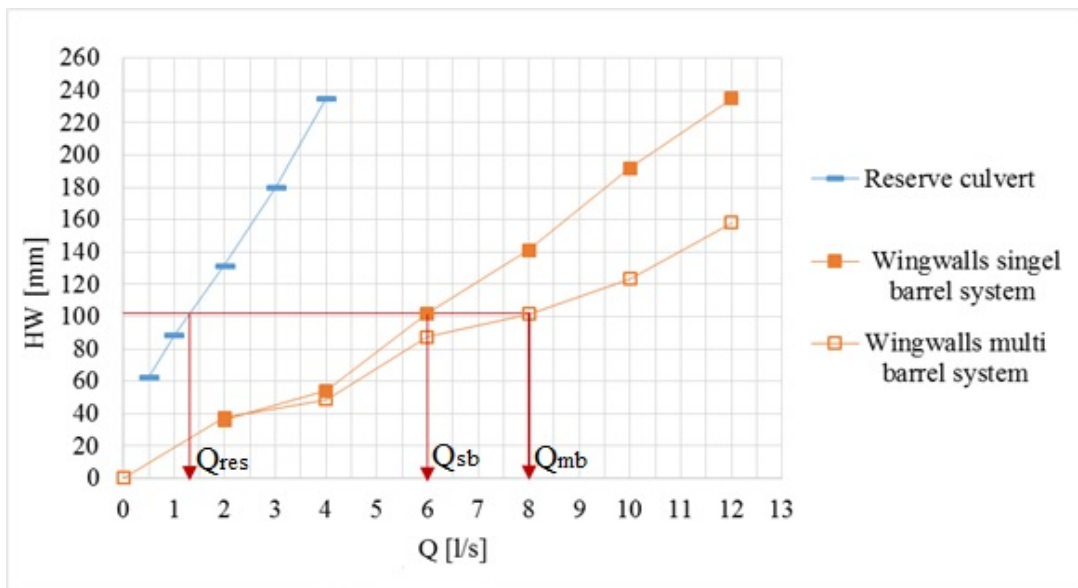


Figure 4.8 Calculation of discharge distribution between main and reserve barrel in the multibarrel system for wingwalls inlet.

However, the sum of the discharges from these two curves does not match up the total discharge in the multibarrel system. For example according to the results shown in figure 4.8, at a headwater HW of 102 mm the multibarrel system operates with $Q_{mb} = 8$ l/s, but the sum of the discharges from the single barrel system $Q_{sb} = 6$ l/s and reserve culvert $Q_{res} = 1.3$ l/s at this headwater is $Q_{sb+res} = 7.3$ l/s. This gives a discharge error $Q_{error} = 0.7$ l/s which is 9 percent lower than Q_{mb} . The discharge distribution between the two barrels and corresponding errors according to this calculation, for other headwaters in clear water experiments with wingwalls inlet is given in table 4.2.

Table 4.2 Discharge distribution between main and reserve barrel in the multibarrel system for wingwalls inlet.

Discharge multi-barrel system	Headwater	Discharge single-barrel system	Discharge reserve culvert	$Q_{sb} + Q_{res}$	$Q_{mb} - Q_{sb+res}$	Percent of Q_{mb}
Q_{mb} [l/s]	HW [mm]	Q_{sb} [l/s]	Q_{res} [l/s]	Q_{sb+res} [l/s]	Q_{error} [l/s]	Q_{error} [%]
2	37	2,0	0,0	2,0	0,0	0,0
4	49	3,5	0,3	3,8	0,3	6,3
6	88	5,4	1,0	6,4	-0,4	-6,7
8	102	6,0	1,3	7,3	0,7	8,8
10	123	7,1	1,8	8,9	1,1	11,0
12	158	8,6	2,5	11,1	0,9	7,5

The errors in the discharge distribution from the separate curves can be related to the difference in hydraulic condition of the expansion section and the velocity of the jet flow, in each system. For example, at a headwater HW of 102mm the flow in the expansion section is very still for the system with only reserve culvert open and the discharge Q_{res} is only 1.3 l/s. For the same HW the flow condition is dominated by the jet flow for both single and multi barrel systems. Flow conditions in all three systems are given in figure 4.9. The difference here is that the multi barrel system is operating with a higher discharge for the same headwater, and thus the jet flow has a higher velocity towards the inlet. The higher velocity in the multi-barrel system may give a higher discharge through the main barrel than what the single-barrel system represents. Assuming the entire flow pass through a cross section area of 10 by 30 mm (height x width) in front of the culvert inlet, gives a jet velocity of $v_{mb} = 270$ mm/s for multibarrel system and $v_{sb} = 200$ mm/s. The argument of the jet velocity can also be supported by the headwater result from experiments conducted without energy dissipaters (Gotvassli, 2013) . At those experiments, the headwater results at corresponding discharges were lower than the present results, meaning a jet of higher intensity (velocity) which increased the capacity of the culvert.



Figure 4.9 Flow conditions in the expansion section for system operating with a) only reserve barrel, b) multibarrel and c) only main culvert.

Similar calculations for the cut and projecting inlet give a maximum $Q_{\text{error}} = 20\%$ and $Q_{\text{error}} = 38\%$ respectively. Due to these high errors, it was considered not to use the distribution curves for making the results dimensionless. Therefore, the results were analysed dimensional in the model scale.

4.2 Results of Sediment Experiments

Results of each sediment experiments listed in table 3.3 are compared with the results of clear water experiments to determine how each parameter influences the capacity and hydraulic of the multibarrel culvert system. In addition to headwater results the amount of sediment deposited in the expansion section, is also presented graphically for each experiment. Pictures taken during each experiment are presented in this section to illustrate the pattern of sediment deposition in each experiment.

4.2.1 Effect of sediment addition

Results of both continuous and all at once feeding experiments for each inlet type are compared with the clear water results to determine the effect of sediment filled water on the capacity and hydraulics of multi barrel system. Only results from experiments conducted with 5kg and 8-16 mm sediments are used for this purpose.

In general, for all the three inlet types, the hydraulic conditions of the expansion section does not change a lot due to the sediment in the water. However, in unsubmerged conditions the oscillations and surface waves reduced to some extent after some amount of sediments is deposited in the expansion section. Especially during the all at once experiments where all the sediments deposited just downstream of the energy dissipater blocks, the reduction in oscillations and surface waves was more visible.

For all the three inlet types, once deposited sediments were quite stable at their position without a lot of movement. Only a few sediments went through the culvert during the test time, in gradual feeding experiments.

Wingwalls Inlet

Figure 4.10 shows that except at 6 l/s, both continuous feeding and all at once feeding experiments gives higher headwater results than clear water experiments. The maximum headwater difference between continuous feeding experiment and clear water experiment is 24 percent of clear water head at 2 l/s. For all at once feeding experiment, it is 36 percent at 2 l/s.

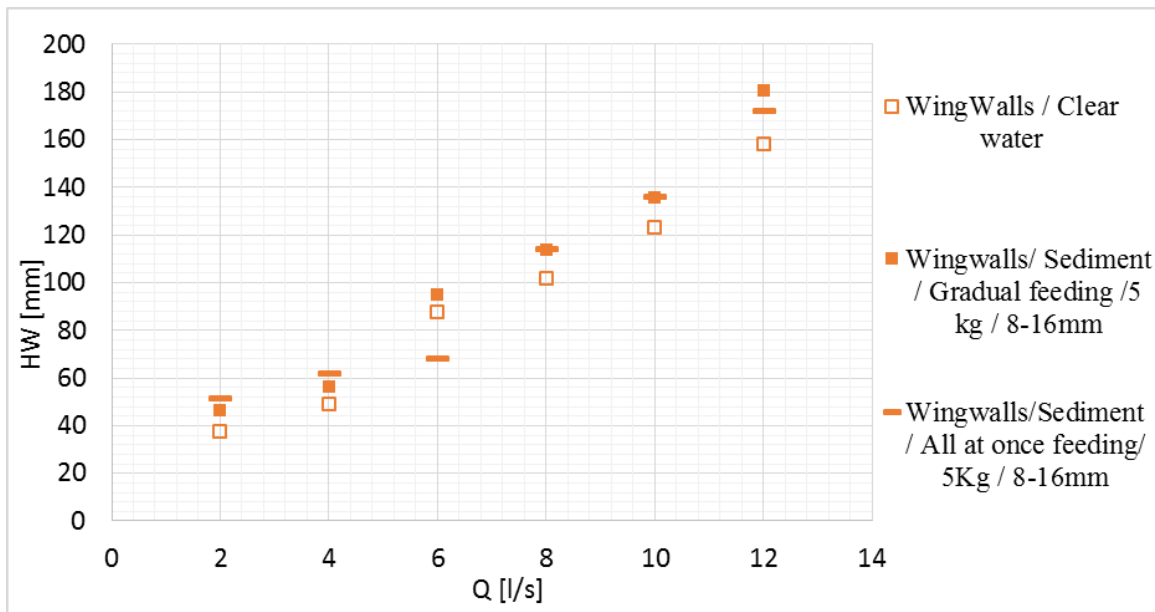


Figure 4.10 Headwater results of clear water, gradual feeding and all at once feeding experiments conducted with wingwalls inlet.

At 6 l/s in all at once feeding experiment the headwater is about 22 percent lower than the headwater in clear water experiment. Figure 4.11, shows that while at other discharge the headwater elevates when the sediments reach the expansion channel, it declines at 6 l/s.

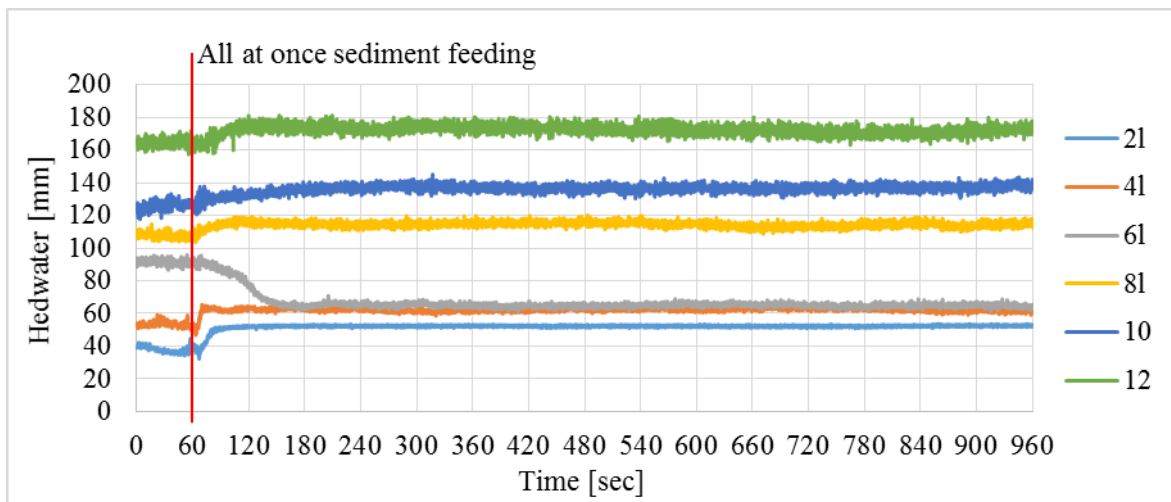


Figure 4.11 Headwater over the whole time length of the 5kg all at once experiments conducted with wingwalls inlet.

The reason for this behaviour is not very obvious, but it can be related to the pattern of the sediment deposition in expansion channel. At 6 l/s similar behaviour and similar sediment deposition pattern in the expansion section, was also observed for all at once experiments with projecting and cut inlet, Sediments in this case were deposited right after the energy dissipater block. At this position, the sediments possibly form a smooth transition between the approach channel and expansion section and thus helping the jet regime to flow towards the culvert inlet with more control and high energy.

For wingwalls inlet, the sediment transport was very low in both gradual feeding experiments and all at once feeding experiments. More than 70 percent of 5 kg sediments deposited in the expansion section at each discharge increment in gradual feeding experiment. Figure shows 4.12 the amount of sediment deposition at each discharge in 5 kg gradual feeding experiments for all three types of inlets.

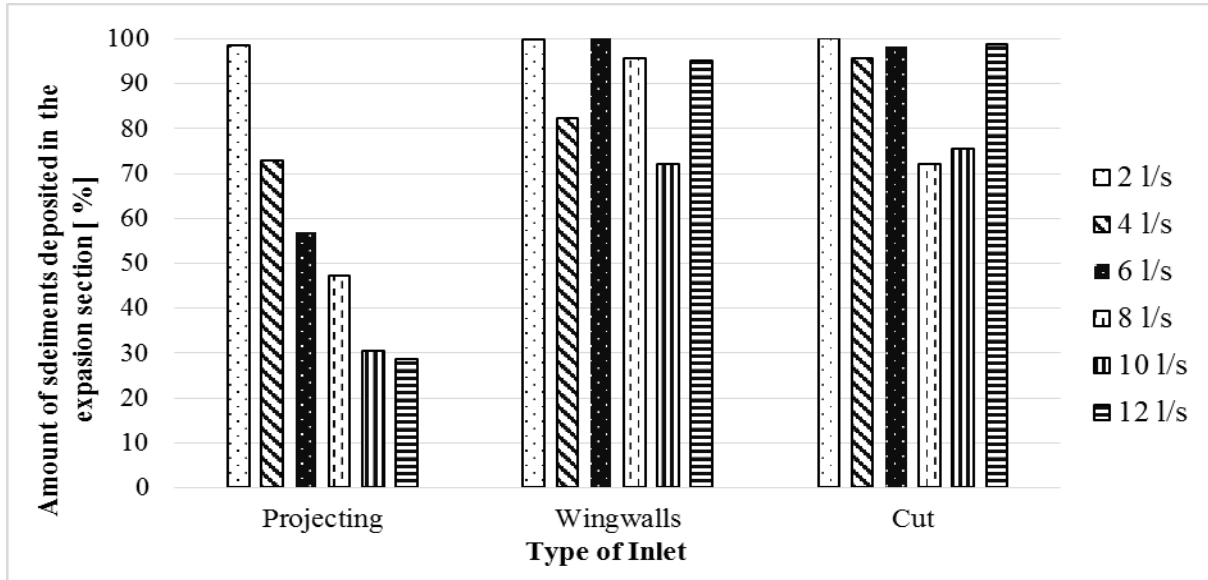


Figure 4.12 Amount of sediment deposited in the expansion section in 5kg 8-16mm gradual feeding experiments conducted with all the three inlet types.

Sediment deposition increased to above 90 percent at each discharge increment, in all at once feeding experiments for wingwalls inlet. The amount of sediment deposition at each discharge increment in these experiments is given in figure 4.13.

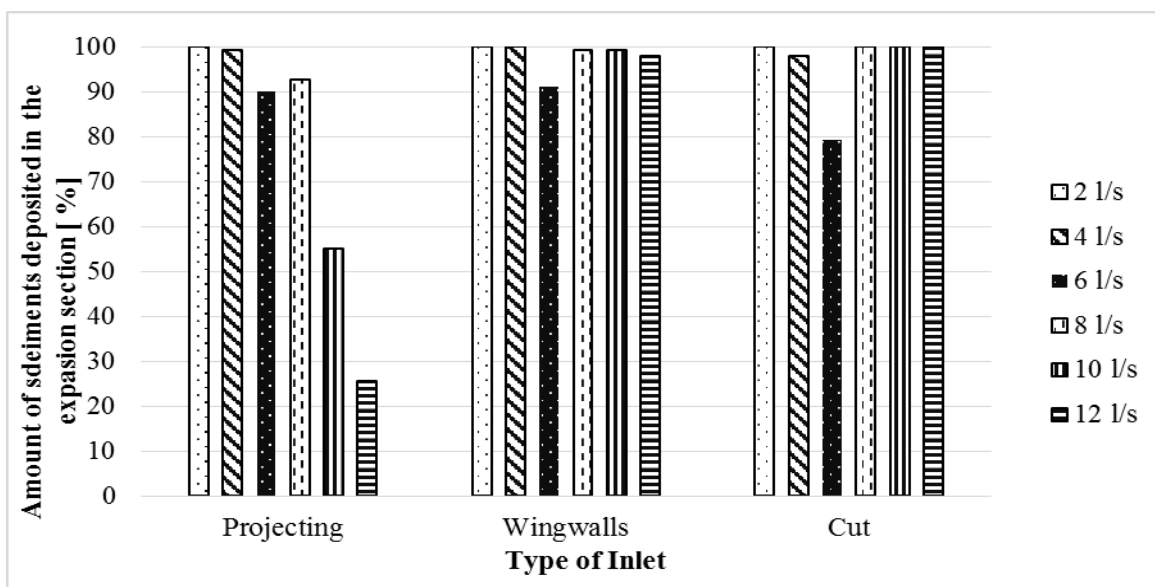


Figure 4.13 Amount of sediment deposited in the expansion section in 5kg 8-16mm all at once feeding experiments conducted with all the three inlet types.

In gradual feeding experiments sediment deposition always started about 80 to 150 cm upstream of the inlet between the wingwalls and moved towards the approach channel as more sediments reach the expansion section. Sediments did not spread a lot from the centreline. The maximum width of the sediment deposition was 55 cm, with 35 cm on right side and 20 cm on the left side of the centreline, at 10 l/s. No sediment was deposited inside the barrel. Figure 4.14 shows the sediment deposition pattern at each discharge, in gradual feeding experiments for wingwalls inlet.

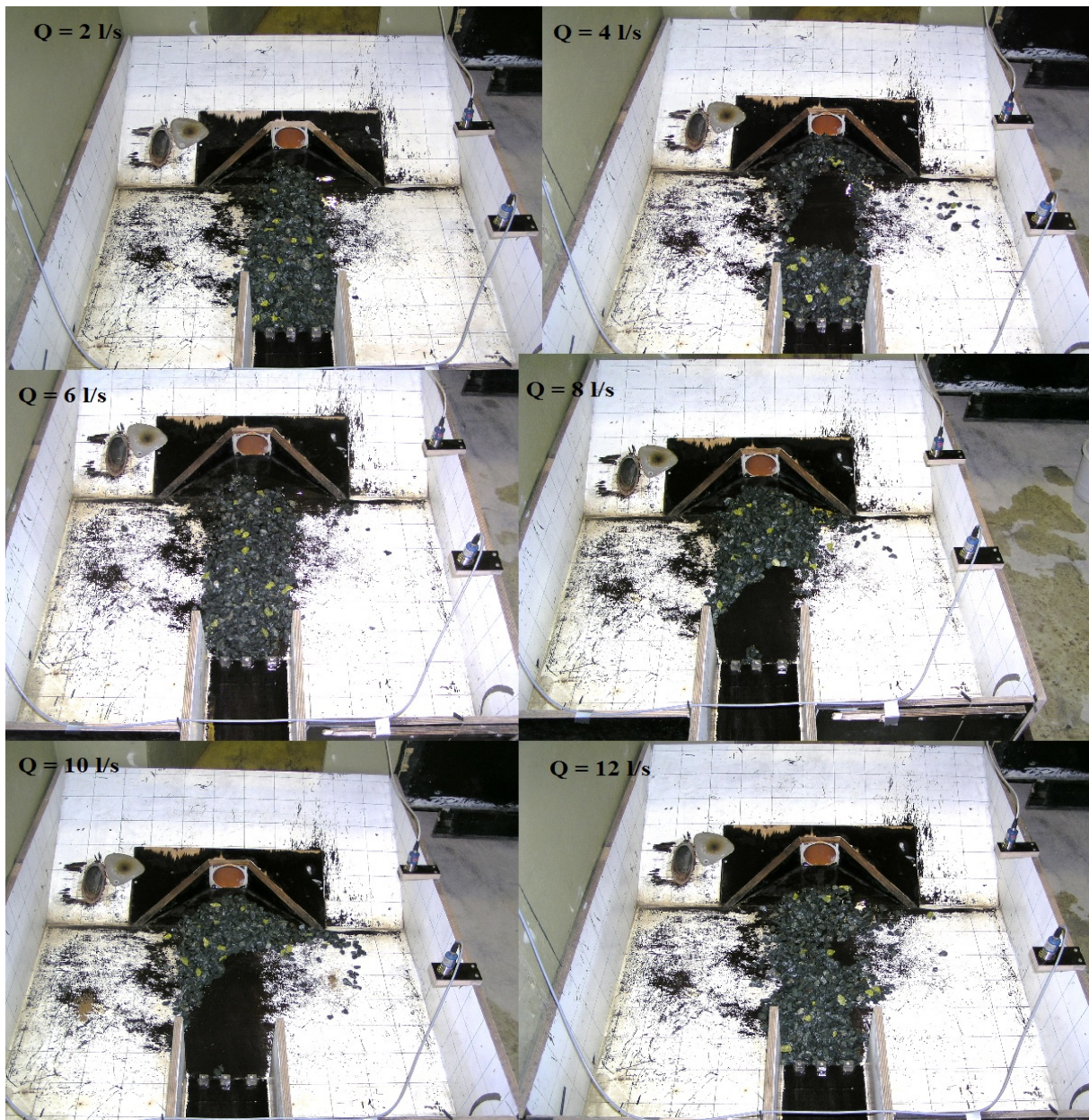


Figure 4.14 Sediment deposition pattern at each discharge, in 5kg gradual feeding experiments conducted with wingwalls inlet.

In all at once experiments for wingwalls, on reaching the expansion section, sediments deposited right after the energy dissipater blocks at all the discharges. The maximum width of the deposition at any discharge was not more than 40 cm, with 20 cm on each side of the centreline. No sediment was deposited inside the barrel. Figure 4.15 shows deposition pattern for each discharge in all at once experiments for wingwalls inlet.

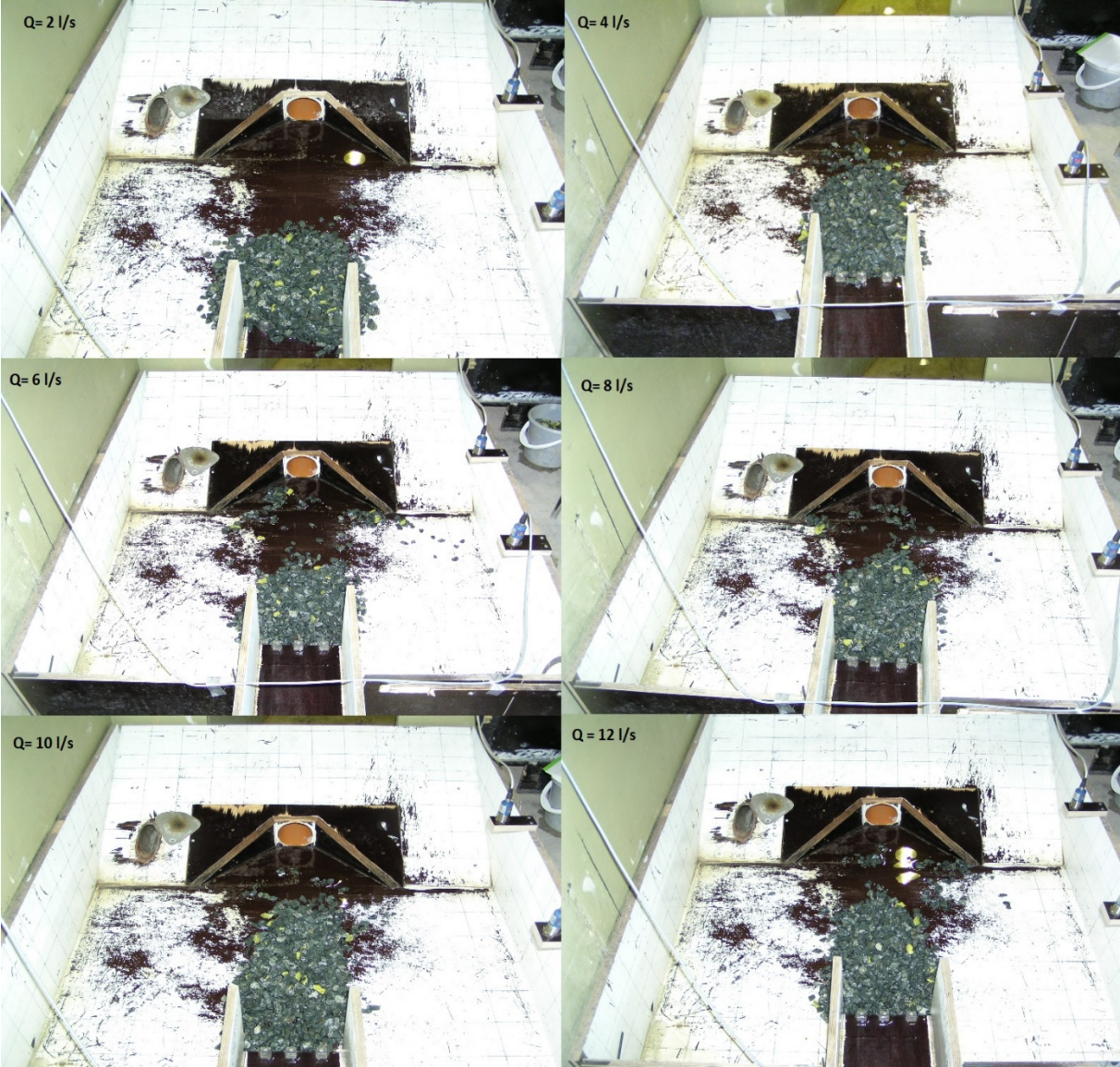


Figure 4.15 Sediment deposition pattern at each discharge, in 5kg all at once feeding experiments conducted with wingwalls inlet.

Cut inlet

For cut inlet, at all discharges, gradual feeding method gives higher headwater results than experiments with only clear water. All at once feeding methods gives higher headwater results than both clear water and gradual feeding method, at all discharges except at 6 l/s. Figure 4.16 gives the headwater result in all three types of experiments, for cut inlet. At 6 l/s in all at once experiment a declining down behaviour of headwater, shown in figure 4.16, happens also for cut inlet.

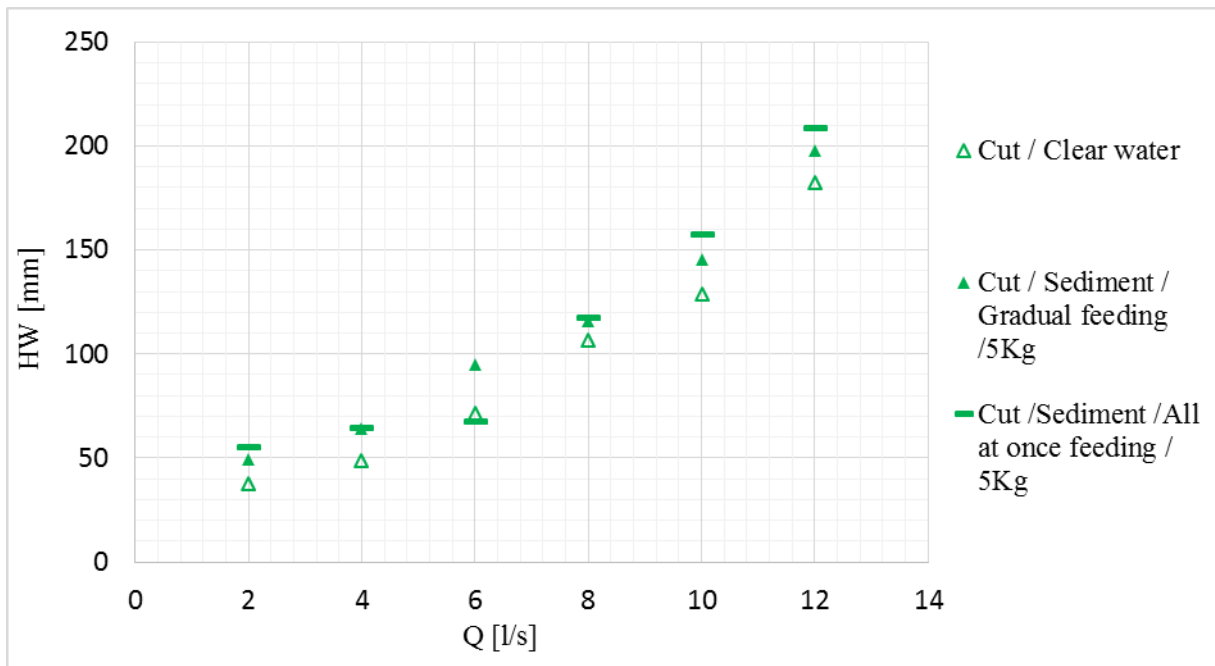


Figure 4.16 Headwater over the whole time length of the 5kg 8-16 mm all at once experiments conducted with cut inlet.

In gradual feeding experiments, the maximum headwater elevation is 32 percent higher than headwater in clear water experiment, at 6 l/s. In all at once experiments, the maximum elevation is 45 percent at 2 l/s.

Sediment transport through barrel for cut inlet was very low in both gradual and all at once feeding experiments. The maximum amount of sediment transported through the barrel in gradual feeding experiment was only 28 percent of 5 kg at 8 l/s. In all at once experiment the maximum amount of sediment transported through the barrel was only 20 percent, at 6 l/s. the amount of sediment deposition in the expansion section at each discharge for gradual feeding and all at once feeding experiments for cut inlet is given in figure 4.12 and figure 4.13 respectively.

Also for cut inlet, at 10 l/s and lower discharges, the sediment deposition in gradual feeding experiments started very close to the inlet and moved towards the approach channel. Some sediments even deposited inside the inlet end of the barrel, but the flow was not able to transport them out of the barrel. At 12 l/s a high headwater put backpressure on the approach channel, which caused the hydraulic jump to move 50 to 60 cm upstream of the energy dissipater blocks. Due to the backpressure, most of the sediments were not able to move further than just downstream of the energy dissipater blocks. 10 l/s gave the maximum deposition width, which was 50 cm, with 35 cm on right side of the centreline and 15 cm on the left side of the centreline. Figure 4.17 shows deposition pattern at each discharge in gradual feeding experiments for cut inlet.

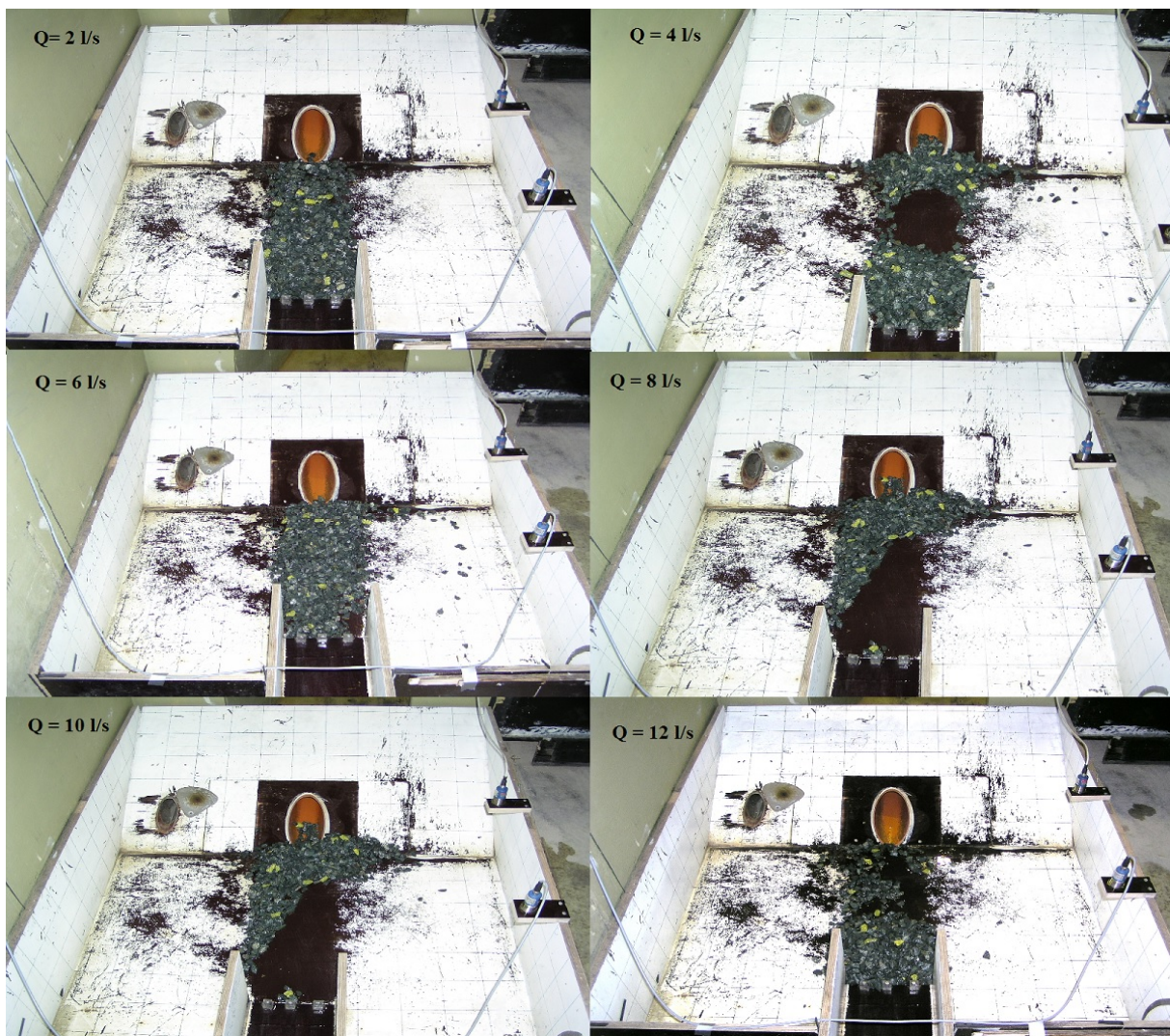


Figure 4.17 Sediment deposition pattern at each discharge, in 5kg gradual feeding experiments conducted with cut inlet.

In all at once experiments for cut inlet, the sediment slide deposited just after the energy dissipater blocks for 10 l/s and lower discharges. Due to the high headwater and backpressure on approach channel, at 12 l/s most part of the sediment slide deposited on the energy dissipater blocks and did not move further towards the inlet through the entire time length of the experiment. The maximum deposition width was 50 cm at 6 l/s, with 30 cm on right side and 20 cm on left side of the centreline. The deposition pattern for each discharge in these experiments is given in figure 4.18.

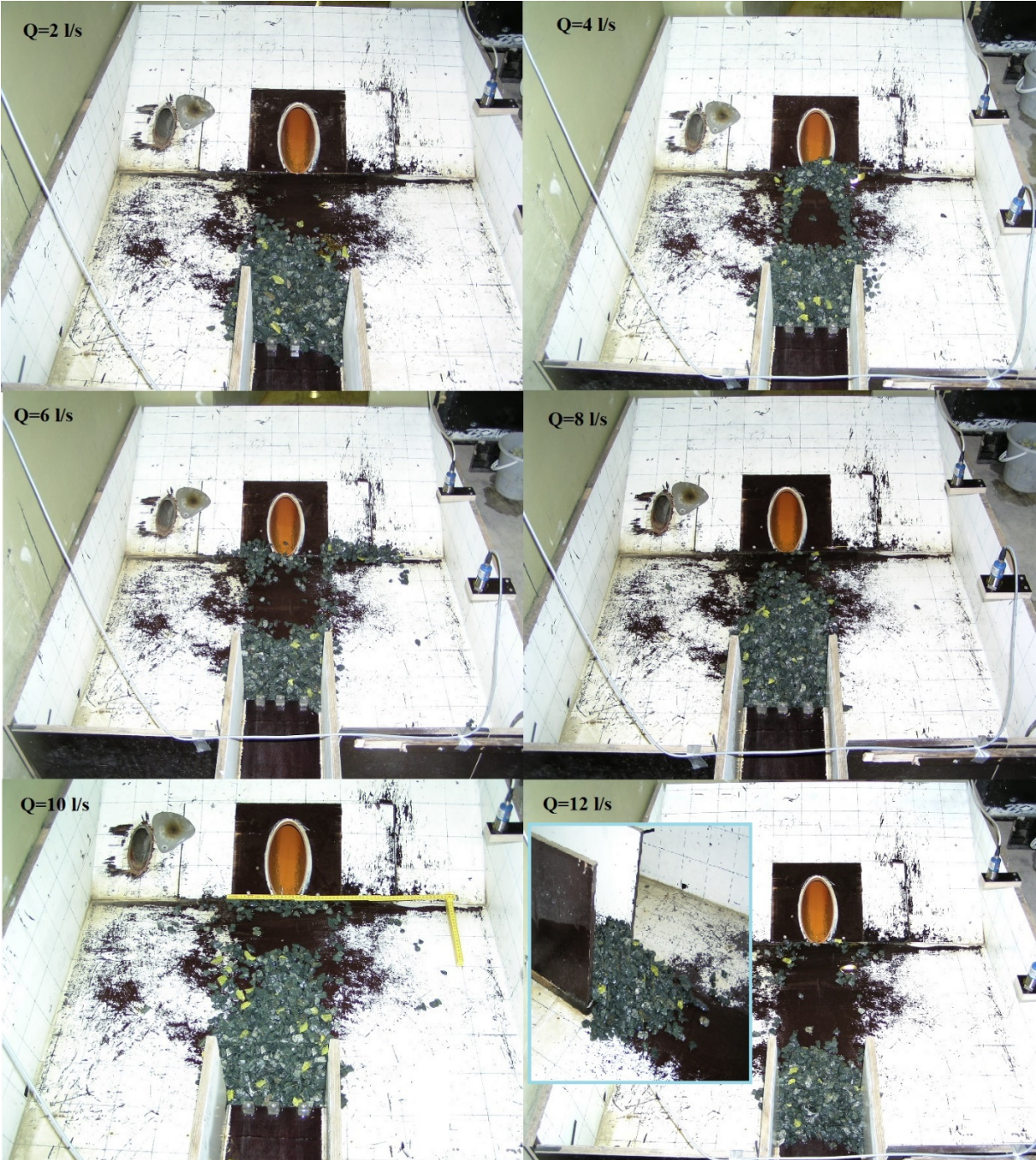


Figure 4.18 Sediment deposition pattern at each discharge, in 5kg all at once feeding experiments conducted with cut inlet.

Projecting inlet

Figure 4.19 shows the results of the sediment experiments in comparison with the results of clear water experiments for the projecting inlet. Both gradual feeding and sudden feeding methods gave higher headwater results than the clear water results for most of the discharges, although the difference is not very significant. The maximum headwater difference between the gradual feeding method and the clear water experiments is 19 percent of headwater in clear water experiment at 8 l/s, while for sudden feeding method it is 10 percent, at 2 l/s. At 12 l/s the results for all three types of experiments for projecting inlet is almost the same.

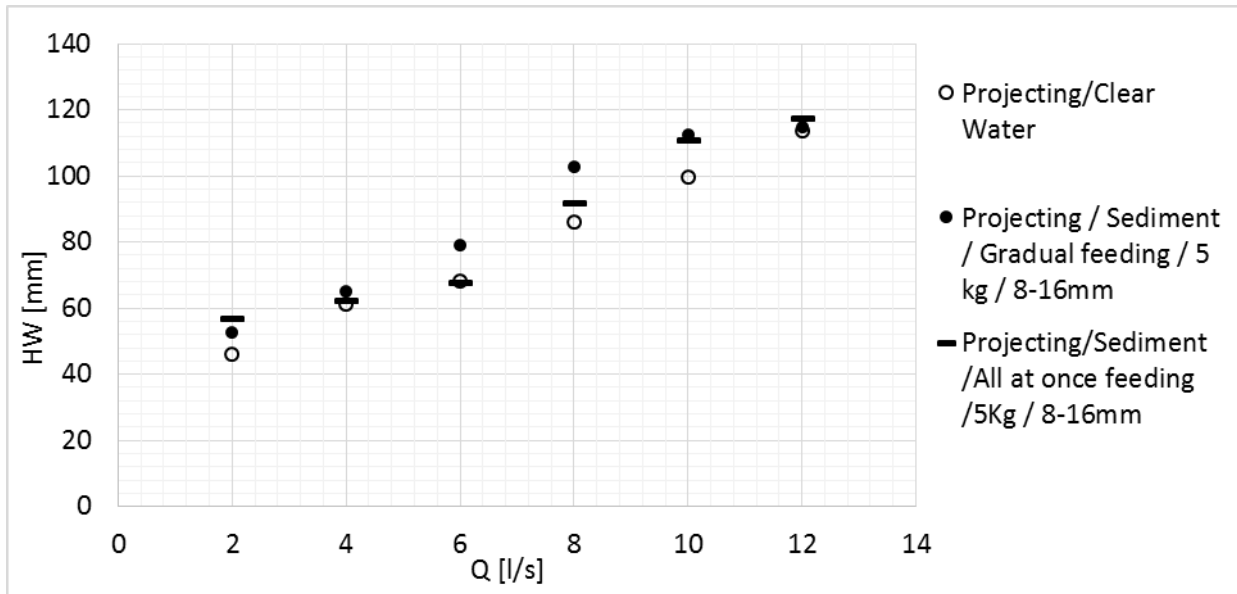


Figure 4.19 Headwater results of clear water, gradual feeding and all at once feeding experiments conducted with projecting inlet.

In continuous feeding experiments, almost all the sediments deposited in the expansion channel at 2 l/s, but the sediment transport through the culvert increased for higher discharges. For projecting inlet, the sediment transported all the time while the feeding was on. Figure 4.12 shows the amount of sediments deposited in the expansion section. Sediment deposition always started very close to the inlet and then prolonged towards the approach channel. Figure 4.20 shows the sediment deposition pattern for each discharge increment in gradual feeding experiments for projecting inlet.

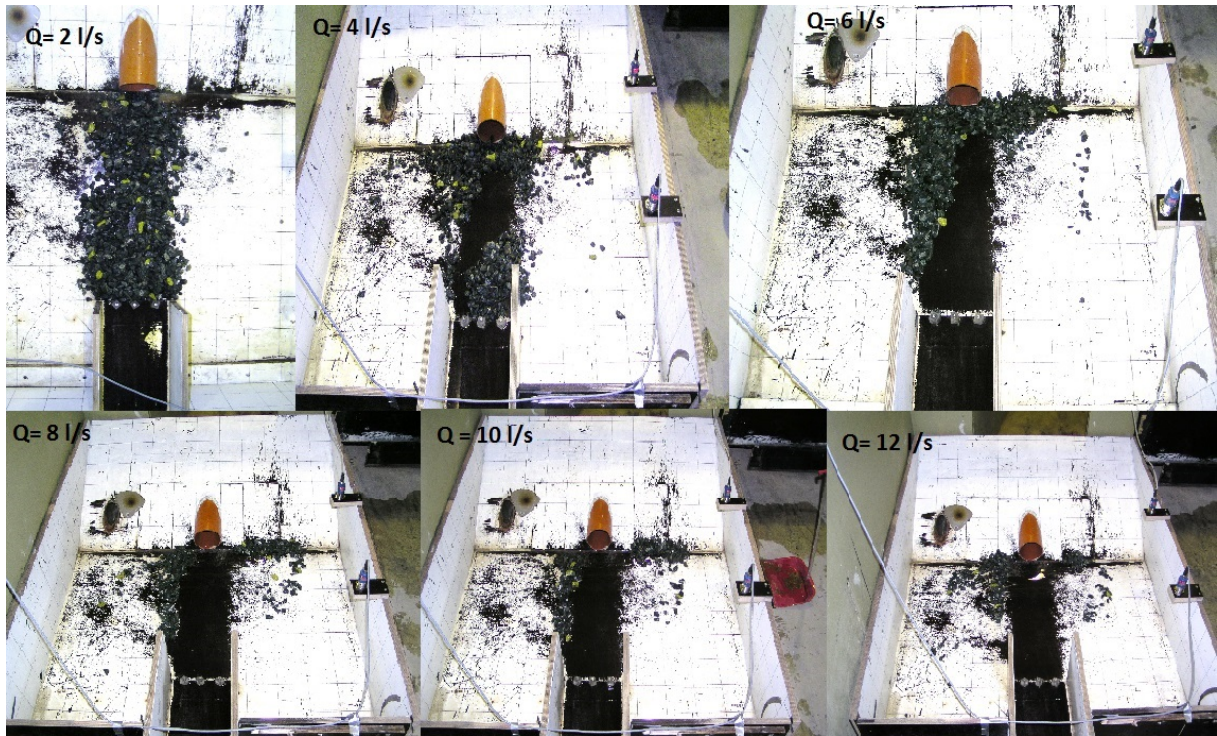


Figure 4.20 Sediment deposition pattern for 5kg 8-16 mm gradual feeding experiments conducted with projecting inlet.

In all at once feeding experiments, about 90 to 100 percent of sediments deposited in the expansion section at 8 l/s and lower discharges. At 10 l/s and 12 l/s sediment transport increased, and only 55 and 25 percent sediments deposited for each discharge respectively. Figure 4.13 shows the amount of sediment deposition at each discharge for projecting inlet in all at once feeding experiments.

After adding the sediment in the approach channel, all the sediments slid down towards the expansion section as a landslide and deposited just downstream side of the energy dissipater blocks at 2 l/s, and prolonged further downstream of the blocks for higher discharges. Figure 4.21 shows the sediment deposition pattern for at 6 l/s and higher discharges, during the all at once feeding experiments for projecting inlet.

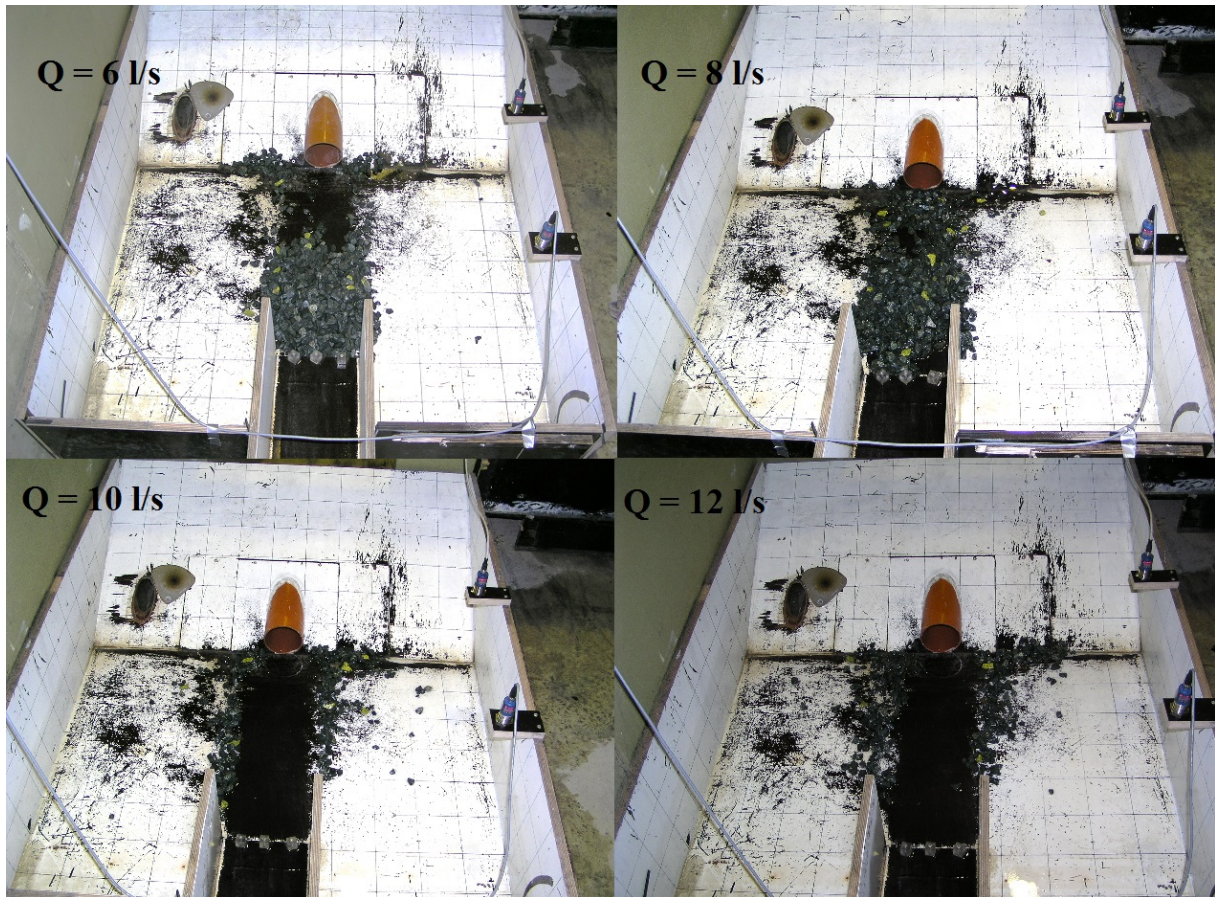


Figure 4.21 Sediment deposition pattern for 5kg 8-16 mm all at once feeding experiments conducted with projecting inlet.

4.2.2 Effect of amount of sediment

Headwater result of gradual feeding experiments conducted with 7 kg, 5 kg 8-16 mm sediments and only clear water are compared to determine the effect of amount of sediments on the capacity and hydraulics of the multi-barrel culvert system. Comparison of the results are shown in figure 4.22, figure 4.23 and figure 4.25 for cut inlet, wingwalls inlet and projecting inlet respectively.

Headwater results of the gradual feeding experiments conducted with cut inlet shows that the increased amount of the sediments elevates the headwater, but the elevation is not very significant at most of the discharges. At all the discharges, the difference between the headwater results of 7 kg and 5kg experiments is very small. The maximum headwater elevation due the increased amount of the sediments is 17 mm, which occurs at 12 l/s. This elevation is only 8,5 percent higher than headwater at the same discharge in 5 kg experiment.

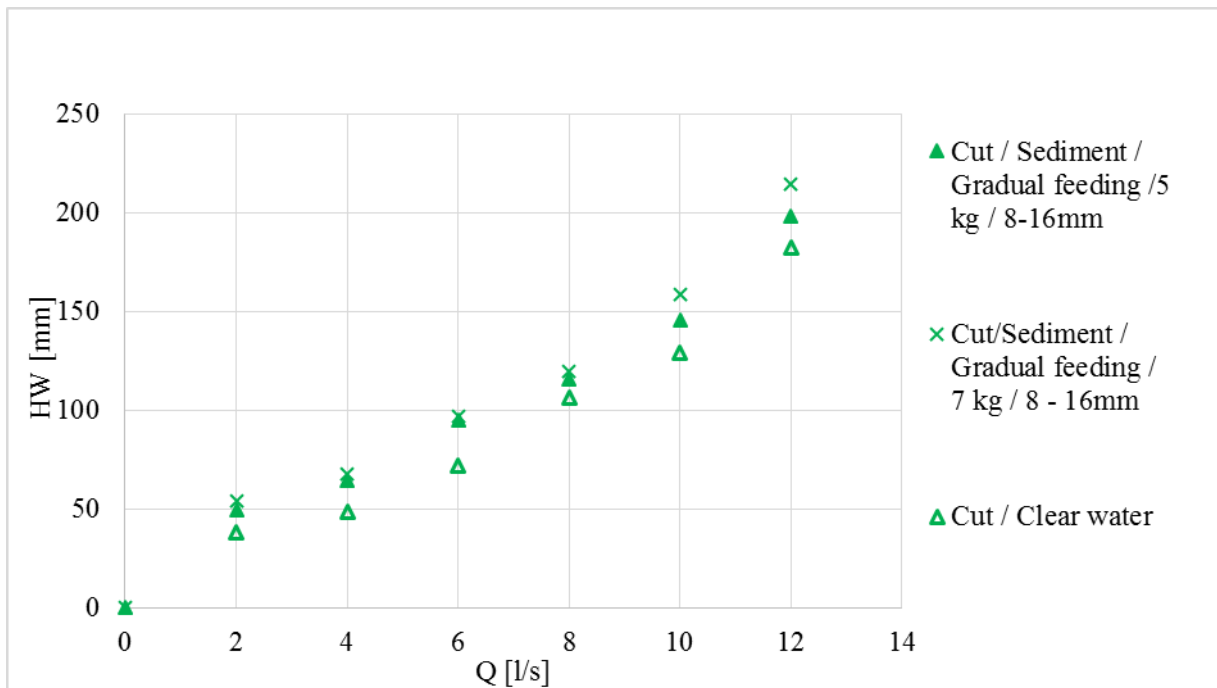


Figure 4.22 Comparison of headwater results of gradual feeding experiments conduct with 7 kg 8-16 mm, 5kg 8-16mm sediments and only clear water, for cut inlet.

The difference between the headwater results of 7 kg and 5 kg experiment conducted with wingwalls is also very small. However, at 6 l/s and higher discharges, experiments conducted with 7 kg gave lower headwater results than those conducted with 5 kg. At 12 l/s, 7 kg experiment gave 8,6 percent lower headwater than 5 kg experiment.

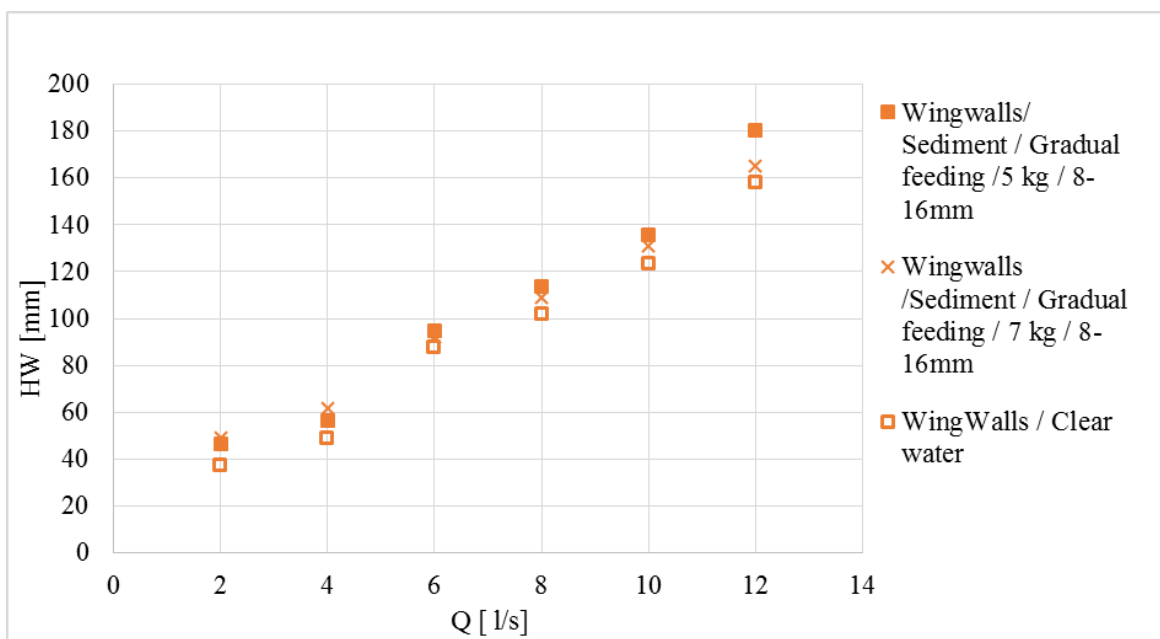


Figure 4.23 Comparison of headwater results of gradual feeding experiments conduct with 7 kg 8-16 mm, 5kg 8-16mm sediments and only clear water, for wingwalls inlet.

Sediment transport through the barrel did not increase very significantly due to increased amount of the sediments, for cut and wingwalls inlet. At some discharges, the sediment transport was even lower than the sediment transport in 5 kg experiments. The amount of sediments deposited in gradual experiments conducted with 7 kg sediments for cut and wingwalls inlet is given figure 4.24. No big difference was also observed in the pattern of sediment deposition in experiments with the two amounts of the sediment.

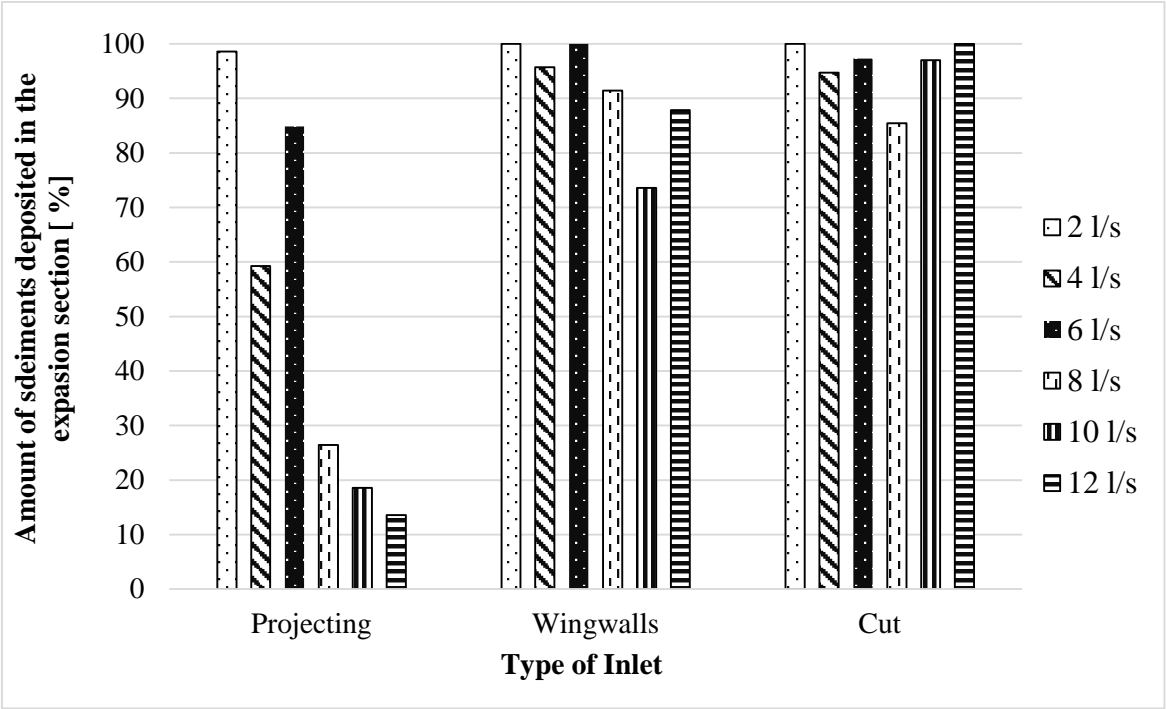


Figure 4.24 Amount of sediments deposited in the expansion section during the gradual feeding experiments conducted with 7 kg sediments for all the three inlet types.

For projecting inlet, the headwater results for 7 kg gradual feeding experiments are either lower than 5 kg experiments or the difference between them is very small at most of the discharges, except at 6 l/s. At this discharge, the headwater in 7 kg experiment is 20 percent higher than the headwater in 5 kg experiments. Higher headwater only at 6 l/s can be related to the increased amount of the sediment deposition and different deposition pattern at this discharge.

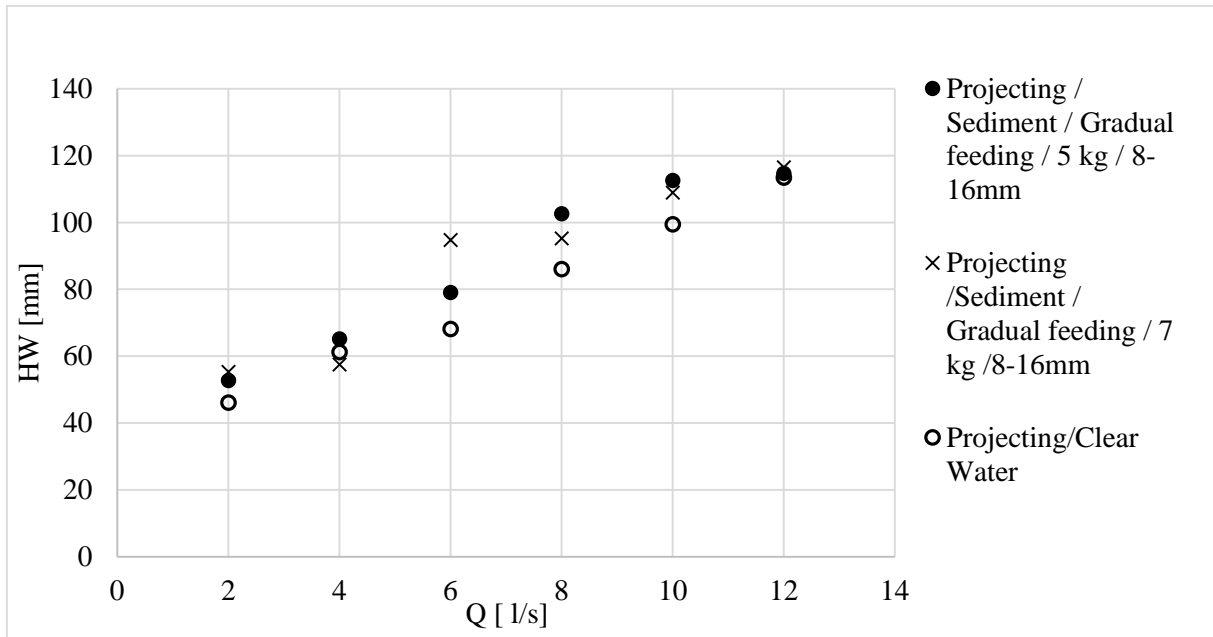


Figure 4.25 Comparison of headwater results of gradual feeding experiments conduct with 7 kg 8-16 mm, 5kg 8-16mm sediments and only clear water, for cut inlet.

In 7 kg sediments, the amount of sediment deposition in expansion section for all the discharges except 2 l/s and 6 l/s is almost the same or lower than the amount of sediment deposited in 5 kg experiments. Amount of sediment deposition for each discharge in 7 kg gradual feeding experiment for projecting inlet is given in figure 4.24. Sediments in the experiments with these two amounts deposited almost with the same pattern in the expansion section at all discharges except 6 l/s. Figure 4.26 shows the difference between deposition pattern for the two amounts at 6 l/s.

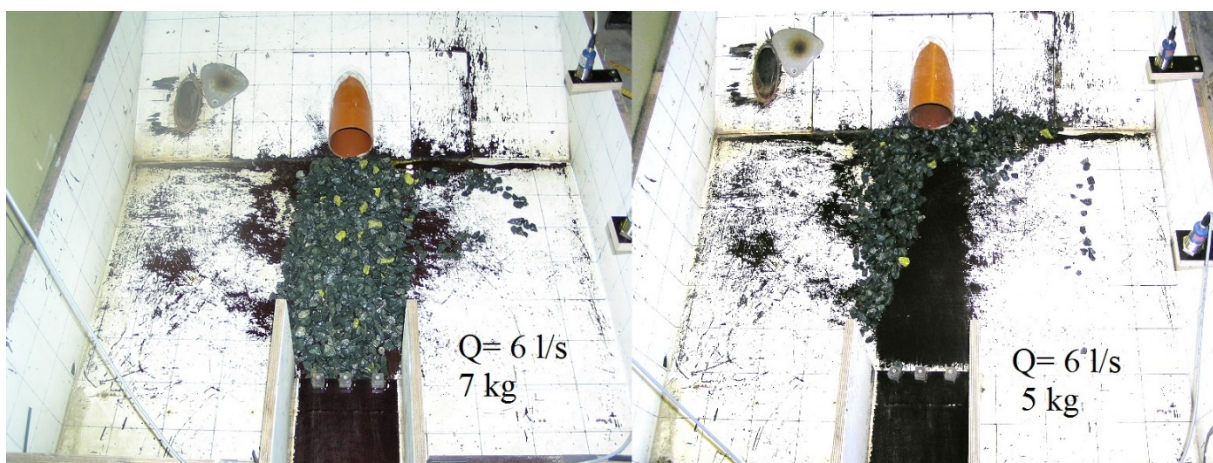


Figure 4.26 Difference between pattern of sediment deposition between 7 kg and 5 kg gradual feeding experiments for projecting inlet at 6 l/s.

4.2.3 Effect of size of sediment

Headwater results of the gradual feeding experiments conducted with the larger sediment size 16-32 mm are compared with the results of those conducted with 8-16 mm, to determine how the size of the sediment affects the capacity and hydraulics of the culvert. The results are also compared with the clear water results.

Comparison of the headwater results obtained from the experiments with the two sediment sizes are shown in figure 4.27 and figure 4.28 for wingwalls and cut inlet respectively. For these two inlet types, the difference in sediment size does not show any big difference in the headwater results. Headwater results in 16-32 mm experiments are also higher than headwaters in clear water experiments, and follow same trend as headwaters obtained with 8-16 mm.

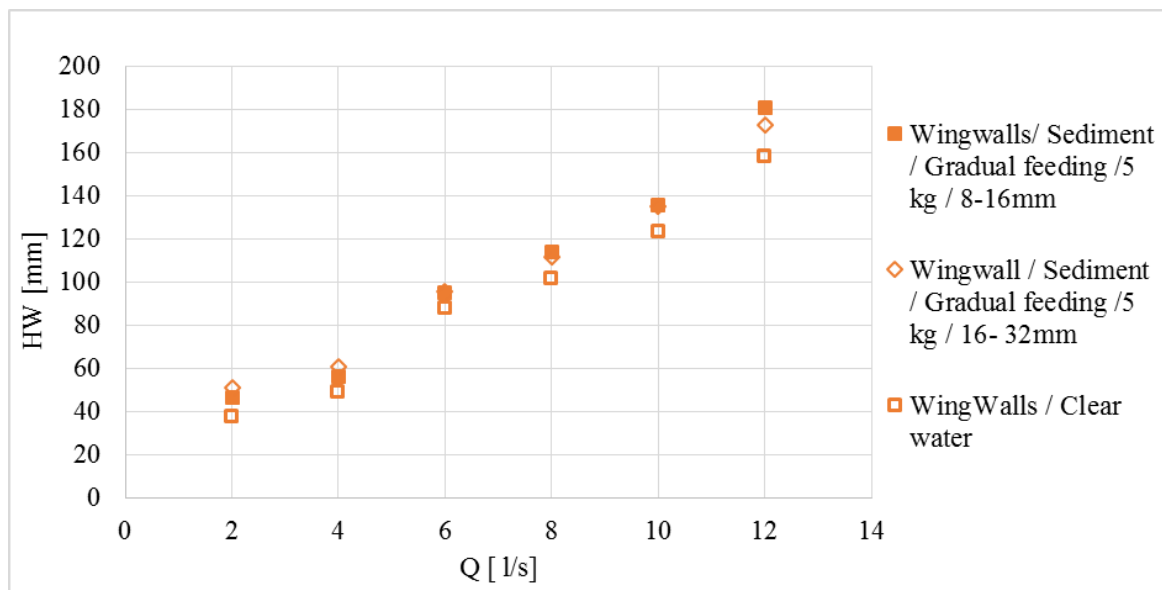


Figure 4.27 Comparison of headwater results obtained from 5 kg gradual feeding experiments conducted with two different sediment sizes and only clear water for wingwalls inlet.

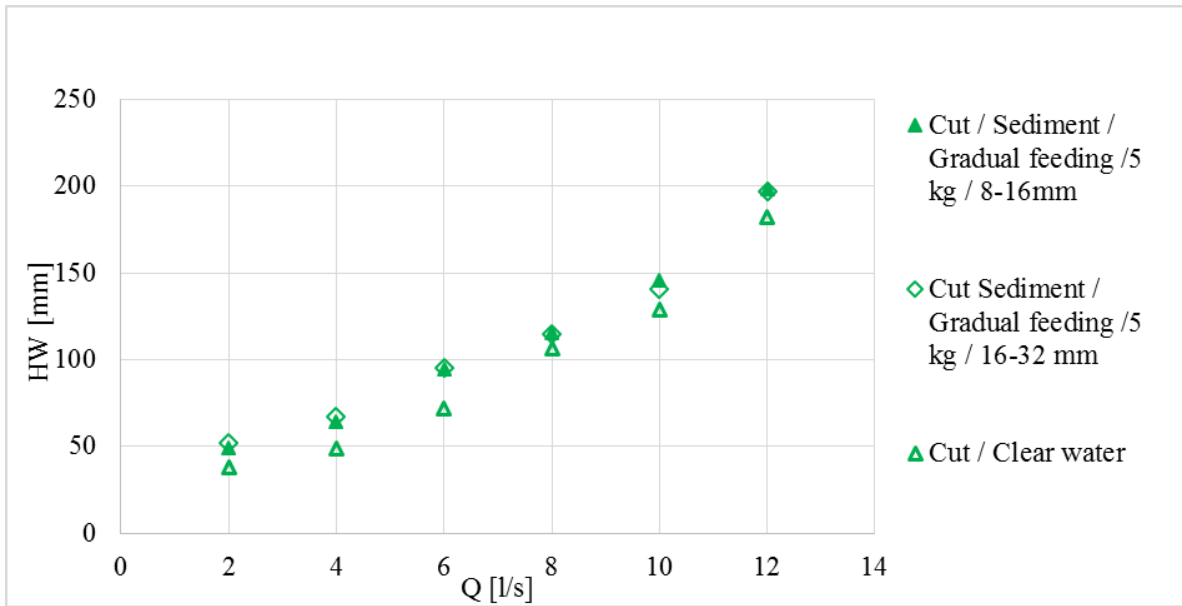


Figure 4.28 Comparison of headwater results obtained from 5 kg gradual feeding experiments conducted with two different sediment sizes and only clear water for cut inlet.

Similarly, for cut and wingwalls inlet, at all the discharges there was also no big difference in the amount and pattern of sediment deposition between the two different sediment sizes. Only at 2 l/s in experiments with 16-32 mm sediments, some sediments were stuck in the energy dissipater blocks, which was not the case for experiments with 8-16 mm sediments. Figure 4.29 gives the amount of sediment deposited in the expansion section in the experiments conducted with 16-32 mm sediments. Sediment deposition patterns at each discharge in these experiments are given in figure 4.32.

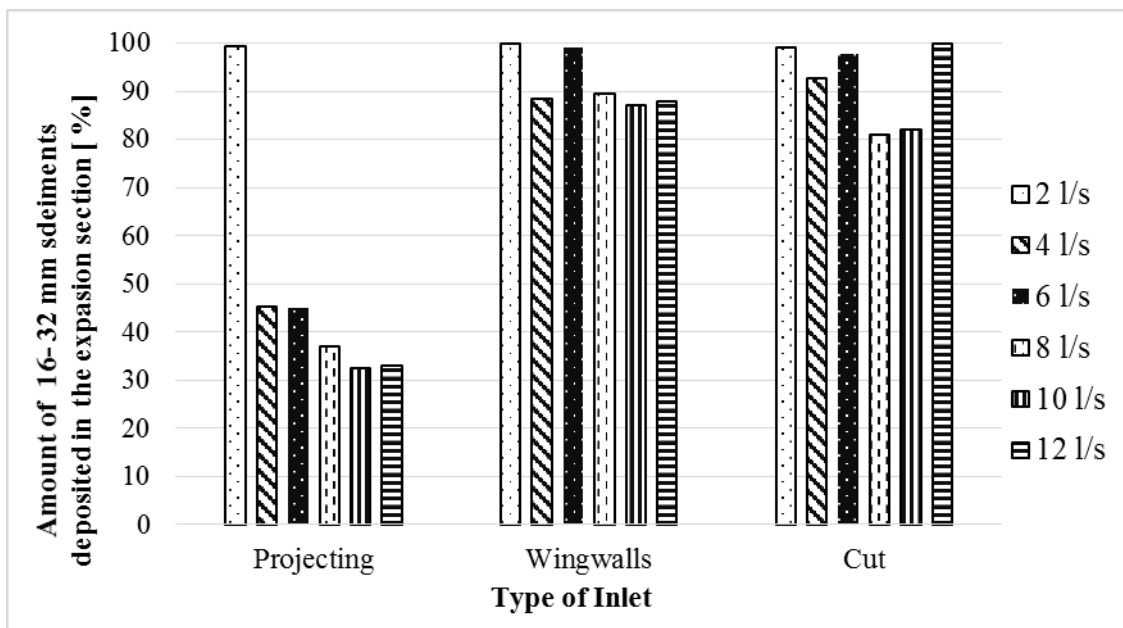


Figure 4.29 Amount of sediments deposited in the expansion section during the gradual feeding experiments conducted with 5 kg 16-32 mm sediments for all the three inlet types.

Figure 4.30 shows that the projecting inlet experiments with 16-32 mm give lower headwater results than experiments with 8-16 mm sediments at all the discharges except at 2 l/s. The lower headwaters for the larger sediments can be related to the way the flow transported the two sediment sizes out of the expansion section through the barrel. While the 16-32mm sediments were transported continuously out through the barrel, the 8-16mm sediments were first accumulated in front of the barrel and then after a while they were washed out through the barrel. Thus for 8-16 mm the headwater elevated and declined several times in the same experiment, but for 16-32 mm sediments the headwater could not elevate at all or elevated at the end when some sediments started accumulating in front of the inlet. This trend is better explained by comparing the headwater measurements over the whole length of the experiment for both of the sediment sizes. Figure 4.31 shows the headwater measurements over the time at 6 l/s for experiments with both of the sediment sizes.

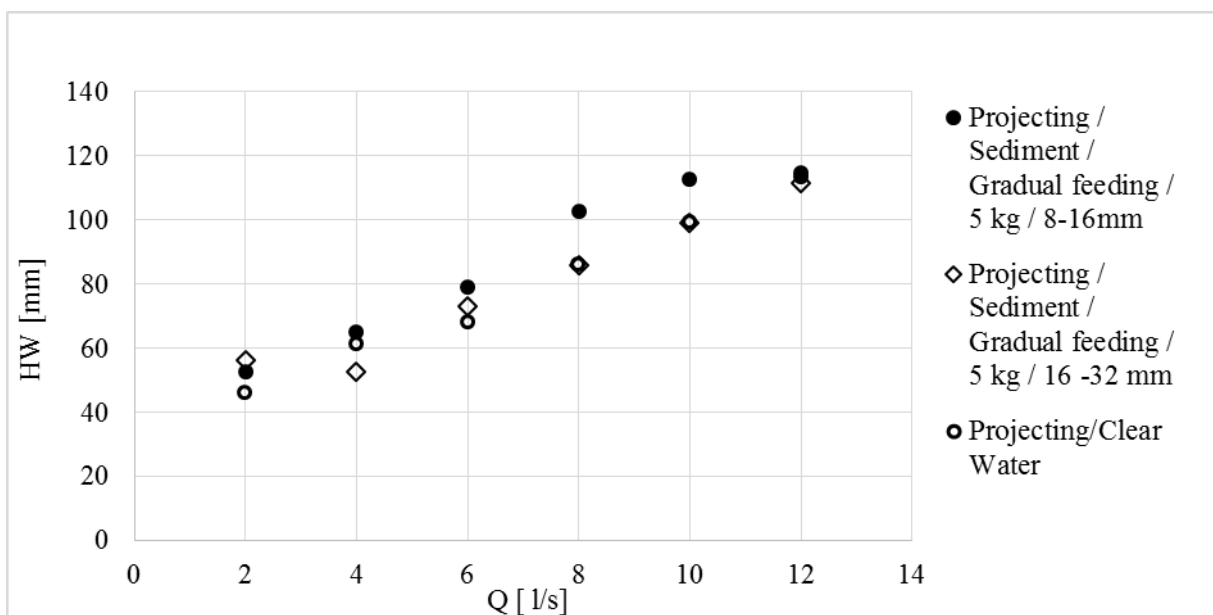


Figure 4.30 Comparison of headwater results obtained from 5 kg gradual feeding experiments conducted with two different sediment sizes and only clear water for the projecting inlet.

The maximums in figure 4.31 shows the headwater elevation due to the accumulation of the 8-16 mm sediments in front of the inlet, while the minimums represents the headwater decline due to the wash out of the sediments accumulated in front of the inlet. For 16-32 mm headwater elevates only when at the end some sediments accumulates in front of the inlet. Thus with several elevations the averaged headwater over the sampling time for experiments with 8-16mm is higher than the averaged headwater result for 16-32 mm sediments.

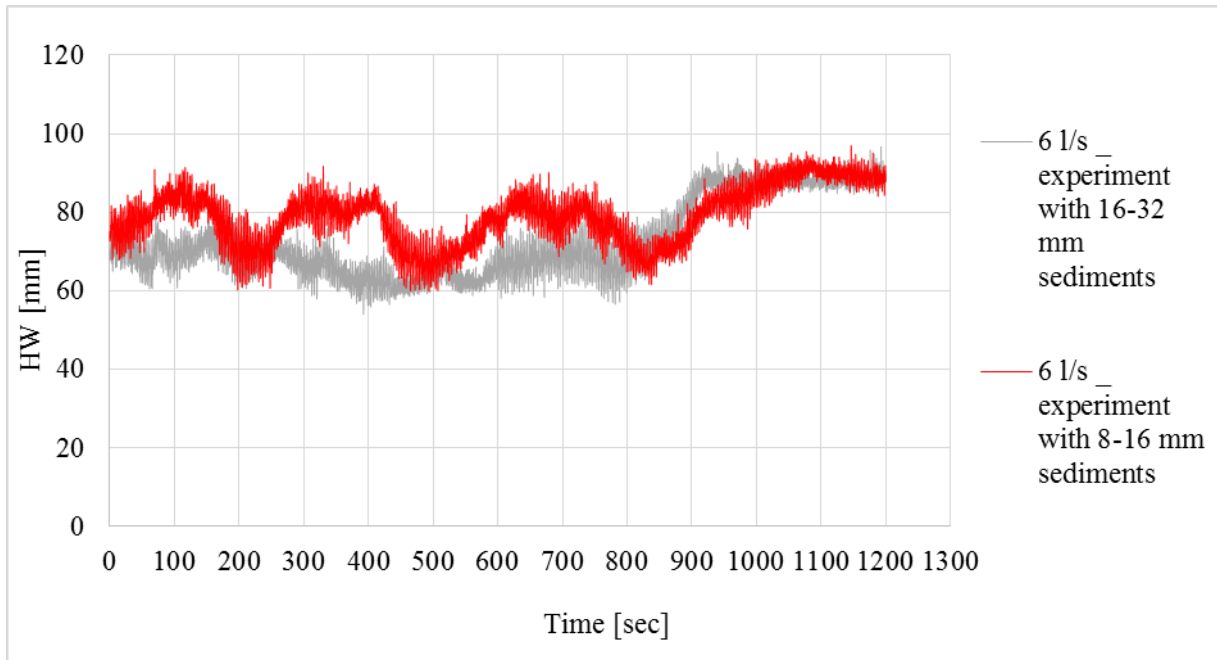


Figure 4.31 Headwater measurements over the sampling time, at 6 l/s for gradual feeding experiments conducted with the two different sediment size for projecting inlet.

The amount of sediment transport through the barrel at some of the discharges was increased in the experiments with the larger size. The amount of the larger sediments deposited in expansion section is given in figure 4.29. The finale deposition pattern of the 16-32mm sediments was also quite similar to the deposition pattern of the 8-16 mm sediments at all the discharges except at 4 l/s. At this discharge, no sediment was accumulated in front of the inlet. Discharge pattern of the larger sediment size is given in figure 4.32.

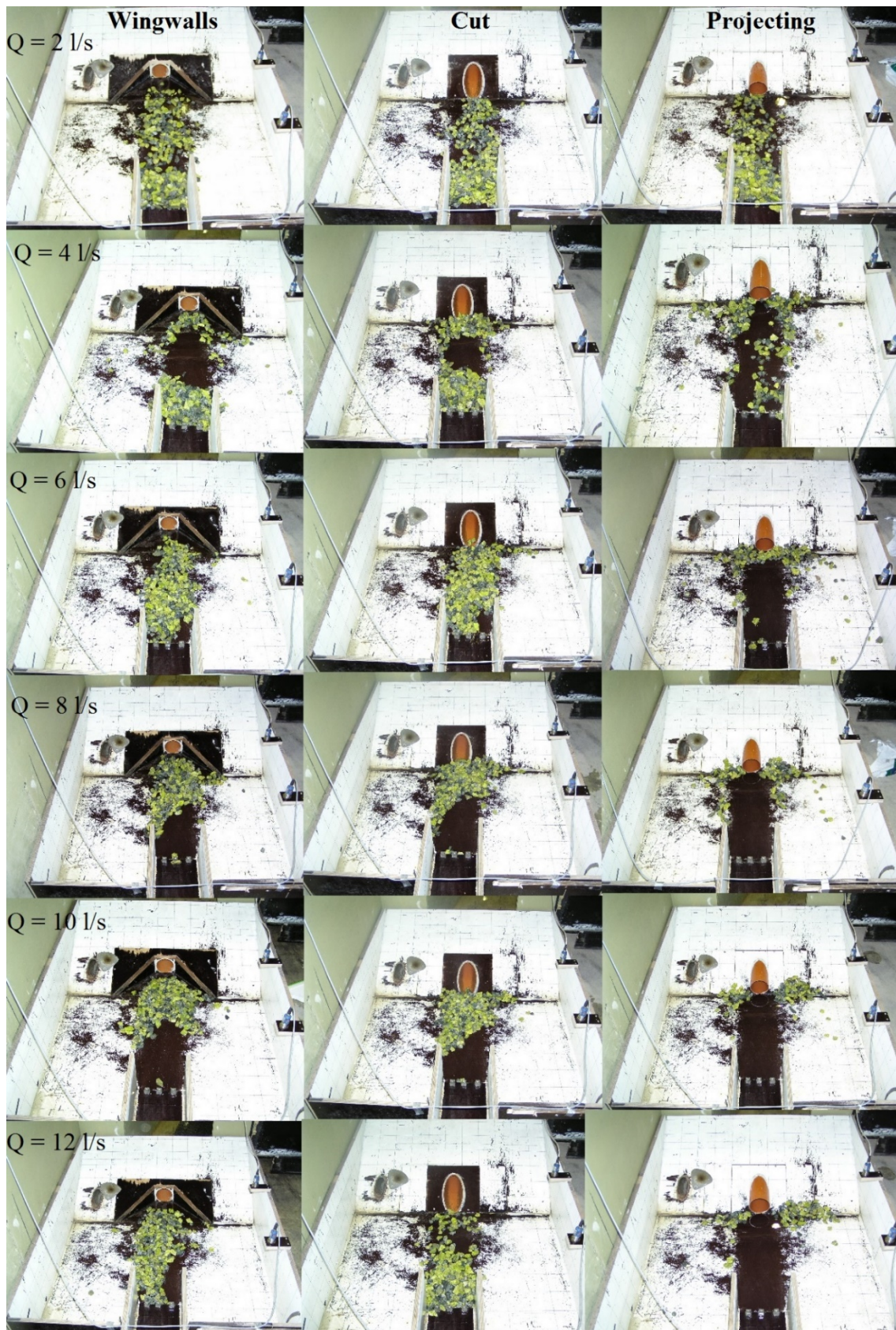


Figure 4.32 Sediment deposition pattern at each discharge, in 5kg 16 -32mm gradual feeding experiments conducted with all the three inlet types.

5 Discussion

In this section, the results are discussed in comparison with the previous studies on this model and guidelines.

Effect of inlet shape

Headwater results from both clear water and sediment experiments shows that the inlet shape is the most dominant parameter that affects the capacity and hydraulics of the culvert, and the sediment transport through the culvert. Clear water results shows that for unsubmerged conditions all the three inlet types operates with inlet control and the difference between the capacities is very small. For submerged conditions however, only the projecting inlet starts operating with a mixture of inlet and outlet control flow at 8 l/s and only outlet control at higher discharges. It thus means that, the barrel with projecting inlet reaches its maximum capacity under inlet condition at a discharge between 6 l/s and 8 l/s. Cut and wingwalls inlet operates with inlet control for all the discharges also in submerged conditions but due to the surface waves, that starts touching the overtopping limit at 10 l/s, and totally overtops it at 12 l/s, their maximum capacity can be concluded at a discharge between 8 l/s and 10 l/s. Similar to the table 2.2 from NPRA these results also shows that wingwalls and cut inlet is better than projecting inlet in terms of capacity. However, the results give higher capacity than the capacities given for each inlet type in table 2.2. If the capacity of projecting inlet is considered 7 l/s and the capacity of wingwalls and cut inlet is considered 9 l/s, table shows that the scaled up discharges of 7 l/s and 9 l/s is higher than the sum of capacities of 1000 mm and 600 mm diameter culverts in table 2.2.

Table 5.1 Comparison of capacity of multibarrel culvert system with the capacities of culverts in table 2.2 from NPRA

Capacity of the multibarrel system in the model			
		Projecting	Wingwalls and Cut
Model capacity discharge	Qm [l/s]	7	9
Scaled up capacity discharge	Qp [l/s]	2214	2846
Sum of capacities for 1000 mm and 600 mm culverts from NPRA table 2.2			
Projecting	Qp [l/s]	1453	
Wingwalls	Qp [l/s]		1608
Cut	Qp [l/s]		1607

The difference in hydraulic condition in the expansion section for each inlet shape can be related to factors like the distance of the barrel inlet from the approach channel and the width of the inlet. The smaller width of the projecting and cut inlet than the width of jet causes sidewise

oscillations and surface waves in unsubmerged conditions. The stable flow conditions for wingwalls inlet can be related to the longer distance of the barrel inlet from the approach channel, and the wings of the inlet. The distance of each inlet from approach channel is illustrated in figure 5.1.

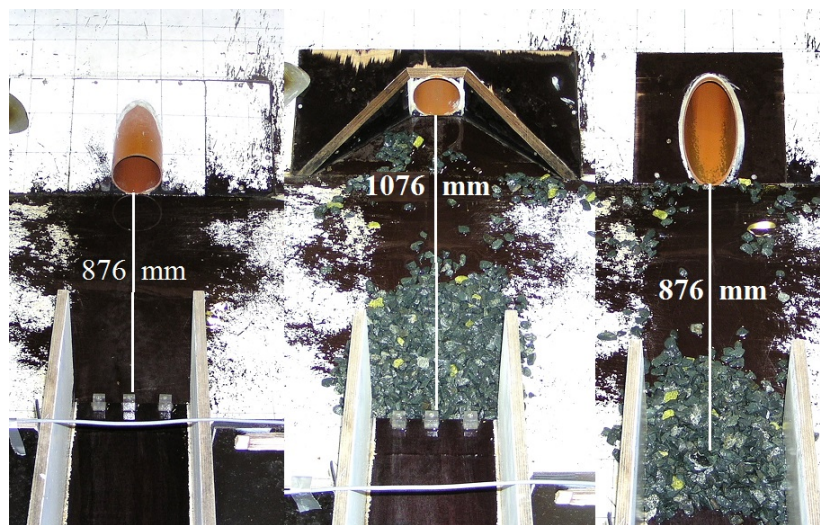


Figure 5.1 Distance of each inlet type from the approach channel (the sediments in this figure is of no consideration)

The longer the distance from the approach channel means a jet with lower velocity and increased expansion when it approaches the barrel. In addition to this, a wider the width of the wings than the width of the jet helps the jet to flow directly and smoothly into the barrel, under the unsubmerged conditions.

The hydraulic condition of the expansion section showed that surface waves under the submerged condition could be of big concern for culverts in steep streams. Surface waves could hit the overtopping line even if the headwater in the expansion section was 40 percent lower than the limit. For example, even though the headwater in clear water experiments for wingwalls was only about 120 mm at 10 l/s, the surface waves could hit the overtopping limit. Therefore, the capacity of the wingwalls and cut was decided by the overtopping limit not by flow condition in the barrel.

Effect of sediment

When the sediments approached the expansion section all at once, none of the three types of the inlet was able to transport them out at their maximum capacity discharge and lower discharges.

Cut and wingwalls inlet were also not able to transport more than 25 percent of the sediments out at any discharge, when the sediments reach the expansion section gradually. However, the projecting inlet showed some increased tendency to transport sediment for higher than 2 l/s discharges when the sediments approach the expansion section gradually. Sediment transport for projecting inlet increased almost linear with the discharge. The decrease in sediment

transport through the barrel in the present study can be related to the increased water level and flow jet of lower energy in the expansion section due to the energy dissipater block.

In the experiments conducted without energy dissipater blocks in the previous study by Ida Gotvassli (Gotvassli, 2013), wingwalls inlet was the best inlet type for sediment transport, followed by the cut inlet while projecting was the worst inlet type for the sediment transport. Figure 5.1 shows sediment deposition results from experiments without energy dissipater blocks (Gotvassli, 2013). Although the experiments are conducted with a slope of 1:5, the results can show that wingwalls is a better inlet type when the jet has high enough energy to move the sediments toward the culvert inlet. The results in the table shows also that sediment transport decreases when discharge and thus water level increases in the expansion section.

Table 5.2 Amount of sediment disposition in expansion section in experiments conducted without energy dissipater blocks. (Gotvassli, 2013)

B.2 Amount of sediments deposited in the basin for sediments added gradually, basin length 876 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
Gradually	Cut	2	4,76	0,26	5,01	5,09
		4	1,42	3,89	5,31	73,22
		6	3,25	1,62	4,88	33,30
		8	2,91	1,57	4,48	35,00
		10	4,13	0,97	5,10	18,99
		12	3,18	1,43	4,61	30,99
		14	3,05	1,48	4,53	32,62
	Projecting	16	2,67	2,18	4,85	44,98
		2	4,69	0,37	5,06	7,39
		4	2,52	2,54	5,06	50,20
		6	2,40	2,22	4,62	48,12
		8	2,86	2,30	5,16	44,55
		10	2,84	2,03	4,88	41,71
		12	2,41	2,19	4,59	47,60
	Wingwalls	14	2,48	2,16	4,64	46,51
		16	3,51	1,16	4,66	24,82
		2	4,23	0,40	4,64	8,71
		4	4,17	0,30	4,48	6,79
		6	4,39	0,26	4,65	5,61
		8	4,28	0,30	4,57	6,54
		10	4,20	0,56	4,75	11,68
12	4,30	0,59	4,89	12,11		
14	3,93	0,79	4,71	16,68		
16	4,12	0,74	4,87	15,23		
17	3,34	0,91	4,25	21,33		

In the present study, sediments deposited mostly on the centre line of the expansion section, while in the previous study (Gotvassli, 2013) sediment deposition for most of the experiments was very scattered. The difference between the sediment deposition patterns in these two studies is shown in figure 5.2.

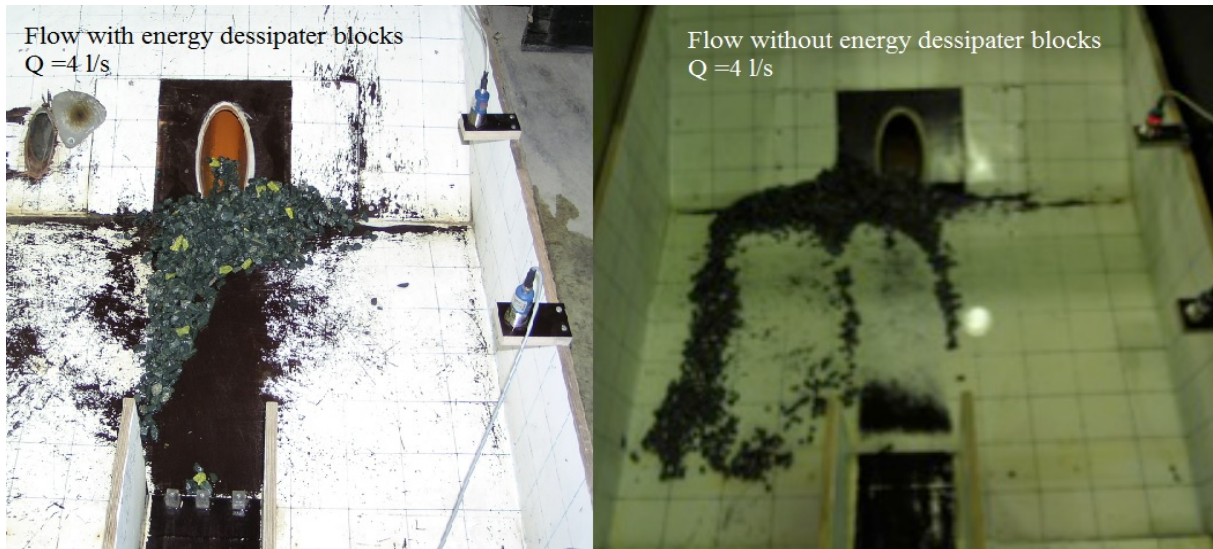


Figure 5.2 Difference between sediment deposition in the flow with and without energy dissipater blocks.

Although energy dissipater blocks reduce the energy of the flow, the difference in the sediment deposition pattern shows that they provide more control and stability to the flow. A low energy and stable flow is very important for the stability of the culvert and the embankment in which the culvert is installed. *Jet dominated flow conditions impose a threat to the culvert structure as the culvert is exposed to high kinetic energy. Such flow regime should be avoided using technical measures such as drop inlets or additional roughness elements triggering a hydraulic jump* (Aberle et al., 2014). High velocity flow may tend to scour away the embankment adjacent to the culvert. In many cases, a scour hole may also form upstream of the culvert floor because of acceleration of the flow as it leaves the natural channel and enters the culvert (Schall et al., 2012).

The result of sediment experiments shows that sediment does affect the capacity of the culvert, both when the sediment is fed gradually or all at once. In most of the experiments, the headwater in experiments with sediment was higher than the headwater in clear water experiments. However, the effect was not very significant that could give a lower maximum capacity discharge than those obtained in clear water experiments for the three inlet types. Therefore, the maximum capacity discharge for each inlet type in sediment experiments is also the same as maximum capacity discharge in experiments with clear water.

Closer investigation of the headwater over the entire sampling time length and the deposition amount and pattern of sediment experiments showed that headwater elevation is actually caused by the accumulation of the sediments in the expansion section, and most especially when the sediments accumulated near the inlet. In experiments where more sediments were transported out through the barrel, the headwater was lower than the headwater in experiments where most of the sediments accumulated in the expansion section. For example in gradual feeding experiments for projecting inlet at 6 l/s, it was 7 kg that gave higher amount of sediment deposition and higher headwater, but at 8 l/s it was 5 kg that gave higher amount of sediment deposition and higher headwater. This shows that even if an experiment was started with

increased amount of sediment, it was only the amount of the sediments accumulated in the expansion section that affected the capacity of the culvert.

The results show that, increased size of sediments does not have any effect on the capacity of any type of the inlet. For projecting inlet, the sediment transport through the barrel even increased when the gradual feeding experiments conducted with the larger sediments.

Effect of reserve barrel

By comparing the results of the multibarrel system with the results of single barrel system conducted with energy dissipater blocks (Hendler, 2014), the main function of the headwater was found to be the reduction of headwater. However, for an equal headwater, the hydraulics in the barrel and expansion section was different in each system. As the discharge in an equal headwater was higher in multibarrel system, the velocity of the flow towards the main barrel was higher than the velocity of flow in the single barrel system. Therefore as earlier discussed, lower head and higher velocity is important for sediment transport through the barrel.

The reserve culvert in the multibarrel system was not also able to give any different deposition pattern than that of single barrel system. In both systems, the sediments deposition was mostly on the centre line of the expansion section. This shows that having one of the barrels of the multibarrel system installed on a higher elevation than the flow line will help the sediment to flow only through the lower barrel. Sediment deposition in front of the higher elevation culvert will be minimized, as this one will only be operating in higher flows.

The Pattern of sediment deposition in each system is illustrated in figure 5.3.



Figure 5.3 Sediment deposition pattern in a) single barrel and b) multibarrel system.

Projecting inlet showed better sediment transport capability than wingwalls and cut inlet also in the single barrel study.

Adaptation of results for culvert design

The results obtained by experiments in this study could not provide a complete solution for how a multibarrel system should be designed to manage the sediment problem in steep streams. For a complete solution, the results of this study should be combined with those of previous studies. This is because a complete solution needs many factors to be considered together. These factors are the length and width of the expansion section, distance of the inlet from the energy dissipater, what kind of flow the expansion section should be provided with (i.e. flow with or without energy dissipater block). However, the results can help the culvert designer to find out

which type of inlet gives better capacity, flow condition and sediment transport, and at which discharge the flow overtops the overtopping limit. The result can also give an estimation for the amount and pattern of sediment deposition in the expansion section.

Uncertainties in the results

The results of experiments in a laboratory model will always include some uncertainties. The uncertainties can be due to the sensors, the model itself and other measurement apparatuses used in the experiments. In the present experiments, while changing the inlet geometries, the leakage sealing could be move or break, which caused some small leakages. Thus meaning some small amount of water could flow from the leakages, which gives some uncertainties in the headwater results. Changing the geometries was not possible without walking on the expansion section; the body weight might have possibly tilted the expansions section in small degrees on either side of the centre line. This could also cause the flow jet not to flow directly toward the culvert inlet. By looking over the sampling time length of some measurements, it was found that in some cases the measurement points were very low than the actual headwater. In other cases, even though the low points were removed, it still gave some uncertainty.

6 Conclusion

Summing up all the results and discussions it can be concluded that, inlet shape is the most dominant of all parameters that affects the culvert capacity and hydraulics under the sediment transport conditions. Different shapes of inlets can give different capacities, different hydraulics upstream and inside the culvert. This can further influence the capability of sediment transport. Considering only capacity and hydraulics upstream culvert, wingwalls inlet is the best culvert second by the cut inlet. These two inlet shapes does not differ a lot in their capacities but wingwalls gives the most stable flow conditions when unsubmerged. Projecting inlet gives lower capacity but it is capable of transporting more sediments out of the expansion section than wingwalls and cut inlet. However, the sediment transport is not just decided by the shape of inlet but also by the flow condition in the expansions section. A flow of low velocity and higher depth in the expansion section increases sediment deposition. Therefore, sediment transport theories should be involved while designing a culvert in streams with sediment transport. Energy dissipater blocks can give a stable flow condition in the expansion section but it reduces the intensity of the flow and increases its depth which causes the sediments to deposit before approaching the culvert inlet. Higher depths give surface waves when the inlet is submerged which is of big concern in designing culverts in steep streams.

Sediment affects the capacity of the culvert by elevating the headwater upstream the culvert. However, elevation comes only as result of the amount and pattern of sediment deposition. Larger amount of sediment deposition and deposition near the inlet elevates the headwater in comparison to no sediment deposition in the expansion section. Even the size of the sediment does not matter until they accumulate in front of the inlet.

Having one of the barrels (reserve barrel) in the multibarrel system installed on higher elevation and with a distance from the main barrel helps the sediments to flow through the main barrel only. In this case the reserve barrel functions to reduce the headwater in high flows and will never get blocked by sediments. In multibarrel system, the flow towards the main barrel has a higher velocity as the discharge in this system is high and water depth is low. This can help the sediments to transport more frequently.

As culvert design requires many parameters to be considered, the results of only this thesis are not able to give a complete solution for culvert design in steep streams under the consideration of sediment transport. However, by combining these results with the results of other parameters and further work will give a complete design solution.

7 Further work

Under the light of this thesis, the following further works are found to be necessary for the competition of design guidelines under sediment transport:

1. Varying the distance between the culvert inlet and energy dissipater blocks. The results will help find the suitable distance which enables the sediments transport out of the expansion section. A similar work has been done by Sissel Alne Amundsen (Amundsen, 2005). However, the inlets shapes and discharges are not varied.
2. Varying the position and elevation of reserve barrel to determine its effect on the capacity of main culvert, sediment deposition and amount. Discharge sensors on each barrel will be beneficial better results and analysis of each barrel in the system.

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A. – Comparison of Headwater in multibarrel and single barrel system

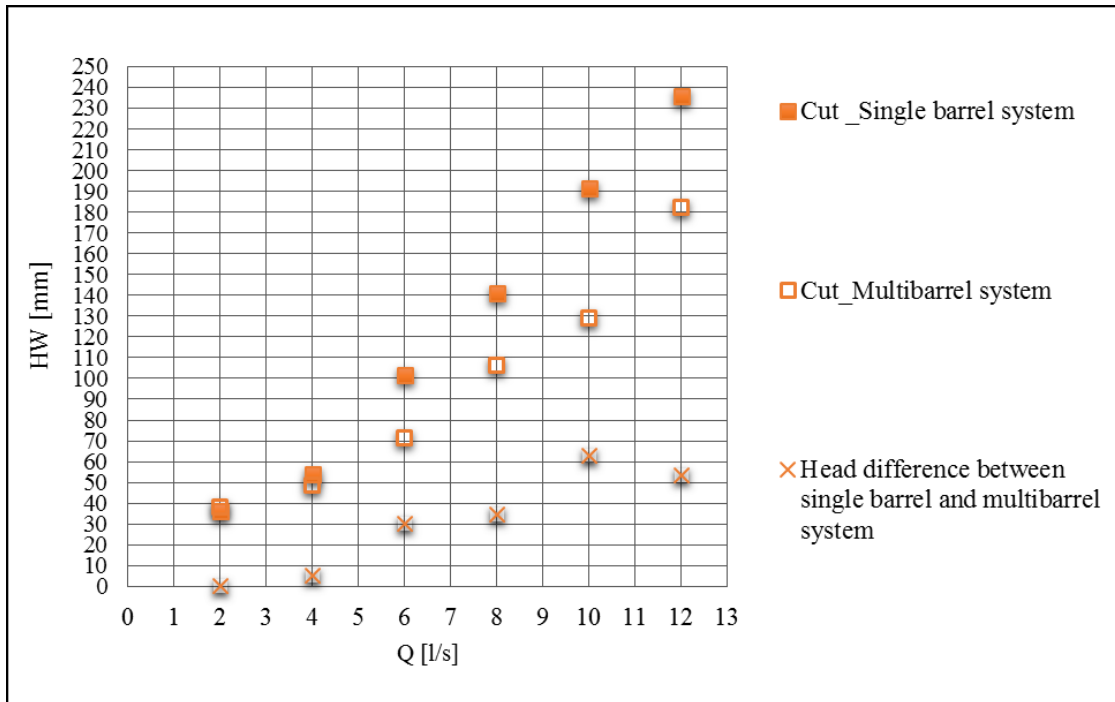


Figure A.1 Headwater results of multibarrel system in comparison with single barrel system for experiments conducted with clear water and cut inlet.

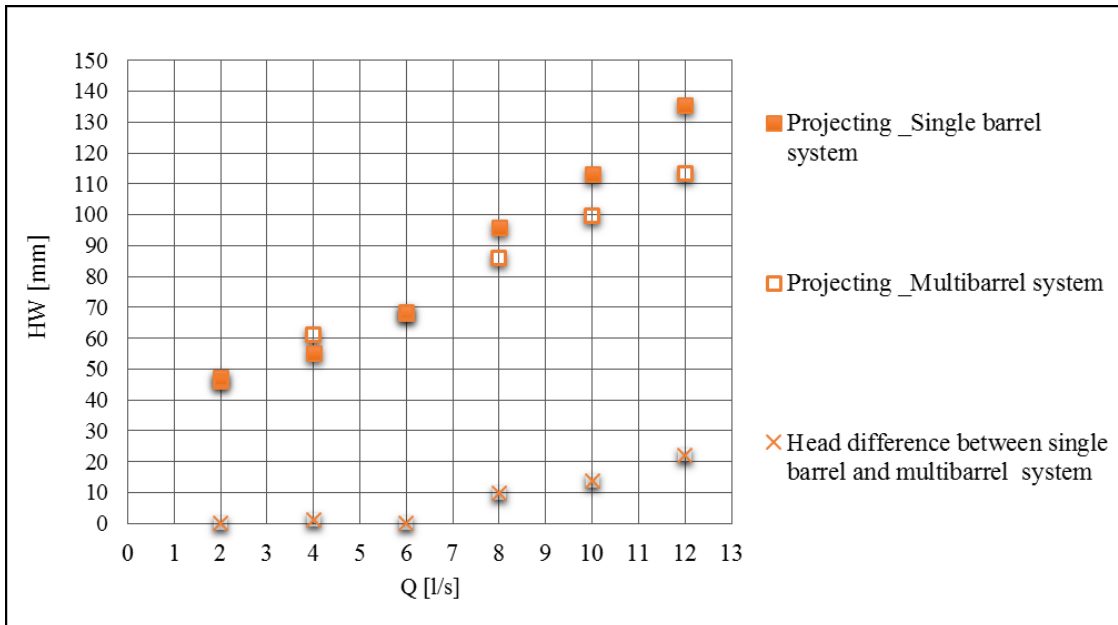


Figure A.2 Headwater results of multibarrel system in comparison with single barrel system for experiments conducted with clear water and projecting inlet.