NTNU – Trondheim
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Hydraulic capacity of culverts under sediment transport

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Hydropower Development
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MASTEROPPGAVE

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Title: Hydraulic capacity of culverts under sediment transport

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 of the sedimentation basin. The present project work will extend the data set by focusing on the effect of the sedimentation basin width on the discharge capacity. 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
2. Development of a test program for culvert-sedimentation experiments with particular focus on the effect of the basin width on hydraulics and sediment transport
3. Carrying out experiments to investigate issues related to culvert-sedimentation and associated reduction of 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 REFERANCE 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 Tuesday, June 10, 2014.

Trondheim, 16. januar 2014

Jochen Aberle
Professor

Abstract

Sedimentation frequently causes an extensive blockage in culvert which may reduce its design capacity. Culvert guidelines which are extensively used reveal little details about sedimentation in culvert. Requirement of the design guidelines for culvert in steep terrain considering sediment transport condition implies the necessity of the culvert guidelines development. Two prior studies of culvert performance on steep terrain have been conducted. The first study evaluated the effects of expansion section length on the performance of the culvert under jet regime, while the other one investigated the effects of additional roughness installed on the model which then changed the flow regime of the model.

Several laboratory experiments have been conducted during this study. The main focus of the study is to investigate the influence of the width of expansion section on the performance of the culvert. Tests were conducted on the scaled model which represents a culvert in a steep terrain. The model is designed for inlet control focusing only on a circular pipe, which consists of an upstream reservoir, an approach channel, and a channel expansion section. Streams on the model are supercritical at the approach channel and subcritical at the expansion section. The experiments simulated performances of the culvert under clear water and sediment transport conditions.

The experimental phase was performed with three different inlet setups in various widths of expansion section. In the sediment transport experiments, various sizes and amount of sediments were used and combined with different methods of feeding the sediments. Flow pattern, sediment efficiency, and sediment deposition pattern were observed on the experimental works. The results of the experiments are shown through the inlet control performance curve which represents the ratio of the water depth to the culvert barrel diameter as a function of dimensionless discharge.

As the main result, the performance of the culvert under clear water and sediment transport conditions is influenced by the width of expansion section and the inlet setup. In general, narrower width develops better culvert performance. The amount of sediment deposited in the expansion section and its deposition pattern are associated with the phenomena that occur on flows as a result of the expansion section widths effects.

FOREWORDS

This Master thesis titled “Hydraulic capacity of culverts under sediment transport” is a partial requirements for the degree of Master of Science in Hydropower Development Program at Norwegian University of Science and Technology.

The thesis work started from January 2013 to June 2014 under the supervision of Professor Jochen Aberle. The study is based on the data obtained from the experimental works that performed at the Hydraulics Laboratory of Department of Hydraulic and Environmental Engineering, NTNU.

I hereby declare the result presented is my own work and I have acknowledged all the sources used in the thesis.

Masdiwati Minati Putri

Trondheim, June 2014

ACKNOWLEDGEMENT

Bismillahirrohmannirrohim,

First of all, I am very grateful to Allah SWT for every chances and possibilities in my life.

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Alhamdulillah, thank you all very much, Indeed!

List of Abbreviations

FHWA	Federal Highway Administration
HPDE	High-density polyethylene
h0/D	Water depth to the culvert diameter
Kg	Kilogram(s)
l/s	Liter(s) per second(s)
Mm	Millimeter(s)
NPRA	Norwegian Public Road Administration
NTNU	Norwegian University of Science and Technology
NVE	Norges Vassgdrags –og Energidirektorat
	(Norwegian Water Resources and Energy Directorate)
PVC	Polyvinyl chloride
Q	Discharge
Q*	Discharge (dimensionless)
s	Second(s)
USGS	United States Geological Survey

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1 INTRODUCTION

1.1 Background of the Study

In mountainous region such as Norway, where the water mainly comes from the mountains through rivers or other artificial channels with bed load, sedimentation is one of the most important issues. Culvert is one of the hydraulic structures that are affected by this problem because the bed loads which is carried further downstream will accumulate resulting sedimentation. According to the FHWA, sedimentation can either happen in the culvert inlet or outlet and it accumulates to three fourth or more of the culvert barrel. Due to this problem, hydraulic capacity of culvert and its associated channel can be reduced dramatically, especially during flood events, which then increasing the risk of serious damages and transportation lines failures (Gotvassli et al., 2014).

The hydraulics performance of culverts has been extensively studied and developed as guidelines in some countries. However, few of them focused on the sedimentation problem. In Norway, most of the prominent culvert's problems are related to the sedimentation and environmental issues such as the aquatic organism passage issue. An adequate study of culvert design is necessary to minimize the problems. Thus, the Norwegian Public Road Administration (NPRA), the Norwegian National Rail Administration (NNRA), and the Norwegian Water Resources and Energy Directorate (NVE), initiated a study with the Norwegian University of Science and Technology (NTNU) to develop a culvert design that can be applied in mountainous region considering sedimentation condition and other related issues.

The hydraulic characteristics, geometric design of culverts, and deposition of the sediment at culverts may be validated through the physical model study. Physical model study of the culvert can replicate the flow pattern and sedimentation process occur in the prototype.

1.2 Previous Works

Sedimentation at culvert in steep streams has been studied before by Gotvassli (2013) and Hendler (2014) through the laboratory experiments in the Hydraulics Laboratory of NTNU.

Gotvassli studied the hydraulics performance of single barrel culvert with regards to the length of the expansion section on hydraulics and sediment transport. The experiments were studied under jet-regime flow that occurred at the expansion section of the culvert model. In (Gotvassli et al., 2014) it was mentioned that *jet flow regime found to be unfavorable for natural conditions due to the appearance of high energy jet*. In the study, factors influencing the hydraulics performance of the culvert were investigated. Inlet geometries, expansion section length, slope of the approach channel, ways of feeding the sediments, amount of the sediment, and sediment size respectively, were the factors influencing the culvert performance.

In the continuation of the study, Hendler modified the model by installing an additional roughness element, three energy dissipater blocks, which then changed the flow regime at the expansion section. The study was meant to observe the effects of the blocks installed on the culvert performance. From the study, it was found that blocks established a stable flows in expansion section and resulted in the water depth that was in line to the existing design guideline value.

1.3 Objectives of the Study

This study is the continuation of Gotvassli (2013) and Hendler (2014) previous study. The main objective is to examine the effects of the sediment transport on the culvert performance with regards to the width of the expansion section with different inlet setup.

To pursue the study objectives, following tasks were performed:

1. Determine the hydraulics performance of culvert under clear water and sediment transport condition (analytical and laboratory observation);
2. Investigate the sediment deposition pattern in culvert.

1.4 Flowchart of Laboratory Work and Analysis

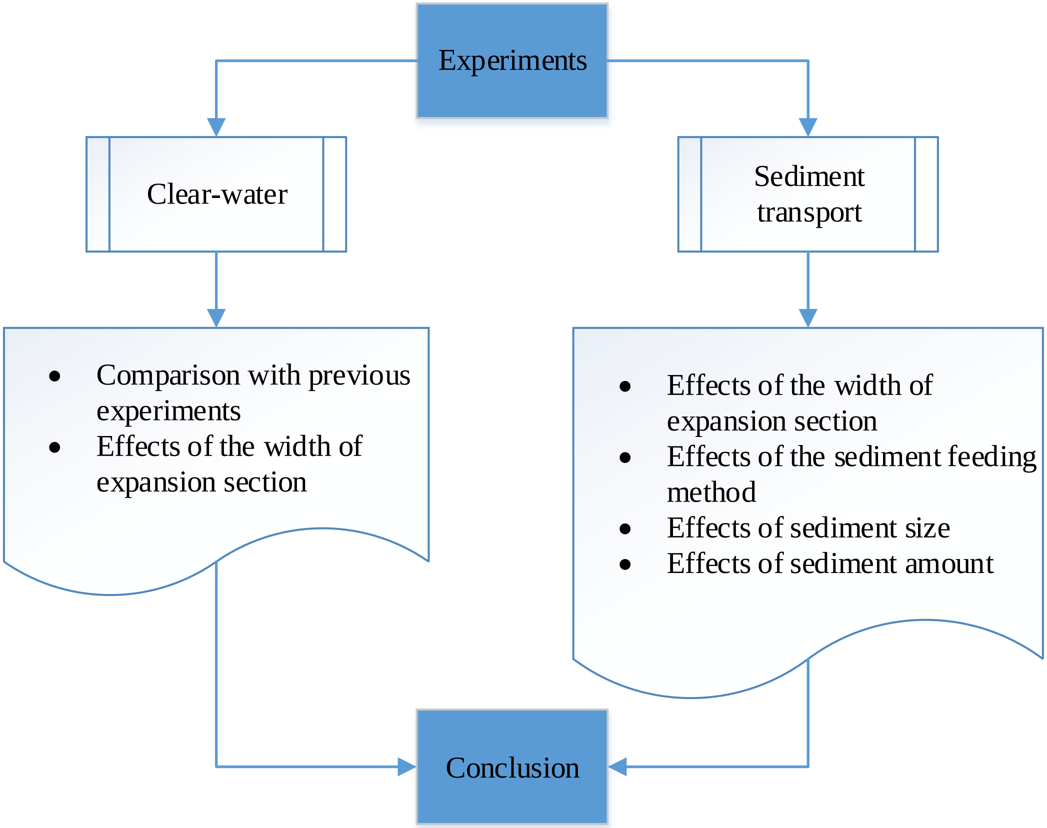

Figure 1-1 Laboratory work and analysis flowchart

2 FUNDAMENTAL OF CULVERT AND CULVERT DESIGN

This chapter describes the fundamental of culvert in general, the theoretical study used for a culvert design that is implemented on the model and the problems related to culverts.

2.1 General

Cross drainage structure in highways usually provided by culverts. Culvert defined as *a relatively short segment of conduit that is typically used to transport water underneath a roadway or other type of earthen embankment* (Creamer, 2007). Culvert usually has a relatively short span, and consists of an inlet, a culvert barrel, and an outlet. Illustration of culvert is shown in Figure 2-1.

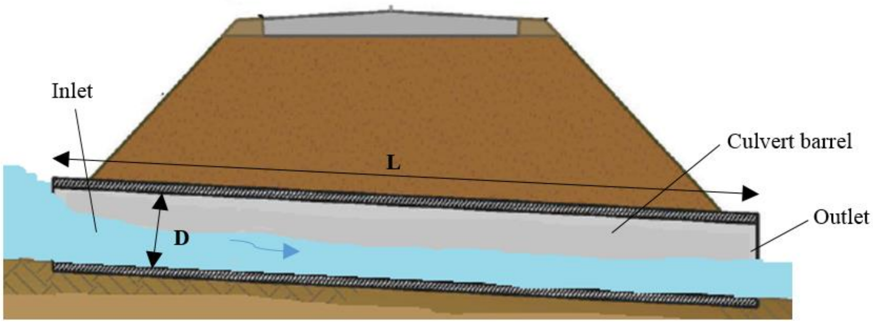

Figure 2-1 Illustration of culvert

It is important to have a proper design of the culvert according to its design discharge for normal or flood period without exceeding the overtopping limit. In Norway, the overtopping limit defined as twice of the culvert diameter from invert and culverts usually have an opening of 1 meter to 2.5 meters, and if the opening is more than 2.5, the structure defined as a bridge (Vegvesen, 2011).

2.1.1 Shapes

There are many kinds of culvert shapes but the widely use are circular pipes, rectangular boxes, ellipses, and arches. The most common culvert shape is circular, which is available in various sizes and strength. Rectangular box shape is favorable for larger flow and low headwater situation. Elliptical shape is usually used as an alternatives of circular shape when limited cover or overfill is needed. Arches culverts is generally used when the natural stream bottom is wished to be maintained as a streambed.

2.1.2 Materials

Most of the culverts are made of concrete (reinforced and non-reinforced) and corrugated metal (aluminum or steel). Occasionally, plastic (PVC or HDPE) is also used and commonly found in culverts which have small diameter. The type of material used for culvert depends on various factors, such as the material strength, durability, abrasion and corrosion resistance, cost, and sometimes the availability of the materials.

2.1.3 Inlet Configuration

Normally, a contraction occurred at the culvert inlet because the channel expansion is wider than the culvert barrel. Inadequacy of the culvert inlet design can reduce its capacity to convey water. Based on the laboratory investigation, (Straub et al., 1953), the culvert inlet configuration has a strong relation with the head, respectively to the discharge of the culvert. The inlet configuration significantly affecting the hydraulic capacity of culverts. Rounded or beveled-edge inlets are found to be more efficient compared to a square-edge inlet. Beveled-edge induces more gradual flow transition which will minimize the energy loss. Tapered inlet is also a solution to improve the hydraulic performance (Schall et al., 2012). Nevertheless, the magnitude of culvert inlet geometry's impact is greatly influenced by the location of the control section. (Further explanations about control section will be described on subchapter 2.2.3). The four standard of inlet-edge types widely used presently are:

1. Projecting;
2. Mitered;
3. Square-edge;
4. 45-degree bevels (Schall et al., 2012).

The manual book of NPRA for roads construction, Haanboka no 18 vegbygging (2011) and NVE's Vassdraghaanboka (2010) implicitly mentioned about the hydraulic capacity of three inlet types, shown in Table 2-1. For culvert with a less than 1 meter diameter, wing walls inlet gives the highest capacity and projecting gives the worst. Yet, for culvert with a larger than 1 meter diameter cut inlet has the highest capacity, followed by wing walls and projecting inlet respectively.

Table 2-1 Hydraulic capacity of culverts with inlet control, h/D = 1.0

Inlet design	Diameter (mm)								
	300	**400**	**500**	**600**	**800**	**1000**	**1200**	**1400**	**1600**
Wing wall	67	135	232	361	726	1247	1940	2818	3895
Cut	65	132	228	357	723	1250	1954	2851	3956
Projecting	57	117	204	320	652	1133	1789	2607	3628

2.1.4 Culvert Design

Many culvert guidelines are available worldwide, such as the design guidelines by the USGS, FHWA, etc. In Norway there are also some hydraulic structures design guidelines in general, such as The Statens Vegvesen (NPRA) Haanboka series and Vassdraghaanboka by NVE. Nevertheless, most of the design guidelines provide design specification only for the clear water condition which assume that sediment might deposit at normal flow condition and flush during storm events prevail. The present design guidelines give little attention to the interaction effects between the stream, the culvert, and the sedimentation problems. (Ho, 2010). However, the results of the present study will be compare accordingly to the research's results of FHWA.

2.2 Culvert Hydraulics

This subchapter will describe the theories related to the culvert hydraulics, specifically about the energy balance, the flow condition which may occur, and the control section of the culvert. The analysis of the data obtained from the laboratory experiments will be presented through the performance curve of the culvert, which will also be explained in this subchapter.

2.2.1 Energy Balance of Culvert

The hydraulics calculation of culverts, from the immediately upstream of the inlet to the outlet, is calculated based on the energy balance using Bernoulli's equation.

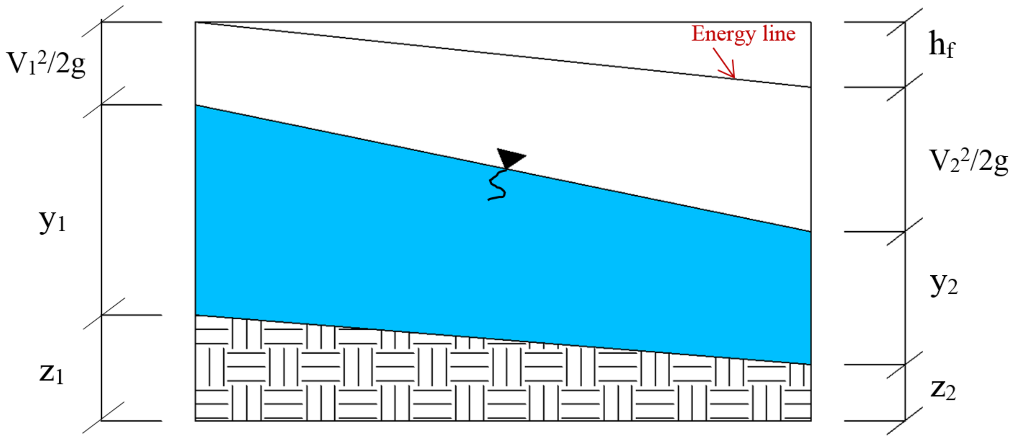

Figure 2-2 Illustration of the energy balance in culvert

$$z_1 + y_1 + \frac{{v_1}^2}{2g} = z_2 + y_2 + \frac{{v_2}^2}{2g} + h_f \tag{2-1}$$

$$h_f = I_e . L \tag{2-2}$$

$$z_1 - z_2 = I_b . L \tag{2-3}$$

So, the energy balance can be written as:

$$y_1 + \frac{{v_1}^2}{2g} = y_2 + \frac{{v_2}^2}{2g} + L(I_e - I_b) \tag{2-4}$$

Where z = elevation above datum, m

y = water depth, m

v = velocity of flow, m/s

g = gravity acceleration, 9.81 m/s^2

h_f = head loss, m

L = culvert length, m

I_e = energy line slope

I_b = culvert barrel slope

With notation 1 and 2 on the equation represents the inlet and outlet respectively.

2.2.2 Flow Conditions through Culverts

There are two types of flow that may occur in culvert barrel, a full flow or partly full flow, depending upon upstream and downstream condition, barrel characteristic, and inlet geometry (Schall et al., 2012).

a. Full Flow

Full flow also known as pressure flow, occurs when the flow throughout culvert is flowing full, which is means that the full capacity of the culvert is being used. Full flow can be caused by a high water surface elevation in upstream or downstream, which induced a back pressure on culverts, and the hydraulic characteristic of the culvert. (*ibid*)

b. Partly Full Flow

When the flow is not fully flow, normally it is also called as free surface flow or open channel flow. Based on the Froude number criterion, open channel flow is categorized into three regimes; a subcritical, a critical, and a supercritical flow. The Froude number, equation 2-5, defined as the ratio of inertial forces to gravity forces which representing the effect of gravity upon the state of flow (Chow, 1959).

$$F=\sqrt{\frac{\text{Inertial Forces}}{\text{Gravity forces}}}=\sqrt{\frac{\rho L^2 u^2}{\rho L^2 g}}=\frac{V}{\sqrt{gL}} \tag{2-5}$$

Where ρ = density, kg/m^3

L = characteristic length, m

g = gravity acceleration, 9.81 m/s^2

V = mean velocity of flow, m/s

When the F is equal to unity, F=1, the flow is said to be in critical state. If F is less than unity, F<1, the flow is in subcritical and characterized as a tranquil and streaming. Subcritical flow is ruled by the gravity forces, so the flow occur when the water is deep and has low velocity. Whereas, when F is greater than unity, F>1, the flow is in supercritical and characterized as a rapid, shooting, and torrential. The inertial forces is dominant in this state of low so it is occur when the water is shallow and has high velocity (*ibid*).

2.2.3 Culvert Control section

When the control of flow is achieved at a certain section, this section is a control section (Chow, 1959). According to FHWA Hydraulic Design Series No. 5 (HDS-5) culvert is governed by one of two control section types; an inlet control or outlet control (Schall et al., 2012).

a. Inlet Control

Inlet control occurs when the culvert barrel is capable of conveying water flow than the inlet will accept. For culverts operating under inlet control, the control section is located just inside the culvert entrance where the critical depth also occurs at or near this location. (*ibid*). Free flow will exist along the culvert barrel since the culvert does not flowing full over its length (Creamer, 2007). Under inlet control culvert performs as a weir when the inlet is unsubmerged and as an orifice when it is submerged. Figure 2-3 illustrates the inlet control flow according to HDS Number 5, FHWA. Explanation about flow type on the culvert is tabulated in Table 2-2.

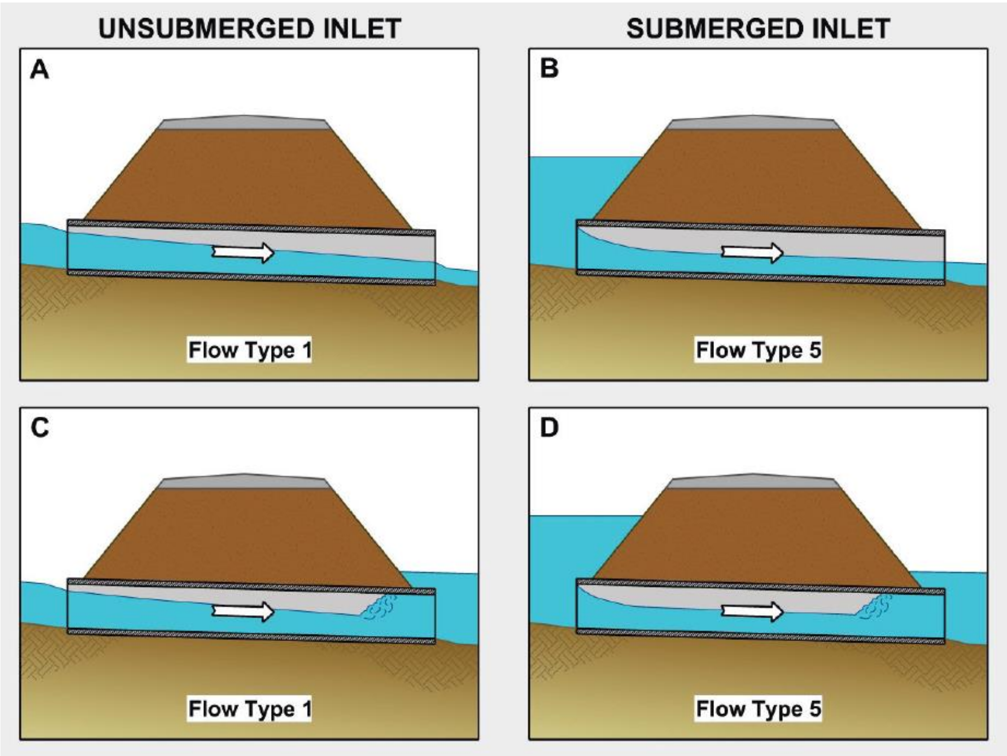

Figure 2-3 Illustration of Inlet control condition (Schall et al., 2012)

b. Outlet Control

Outlet control occurs *when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept.* The control section located at the barrel exit or further downstream. Thus, either subcritical or pressure flow exist on the barrel for culverts operating under outlet control (Schall et al., 2012). Illustration shown in Figure 2-4.

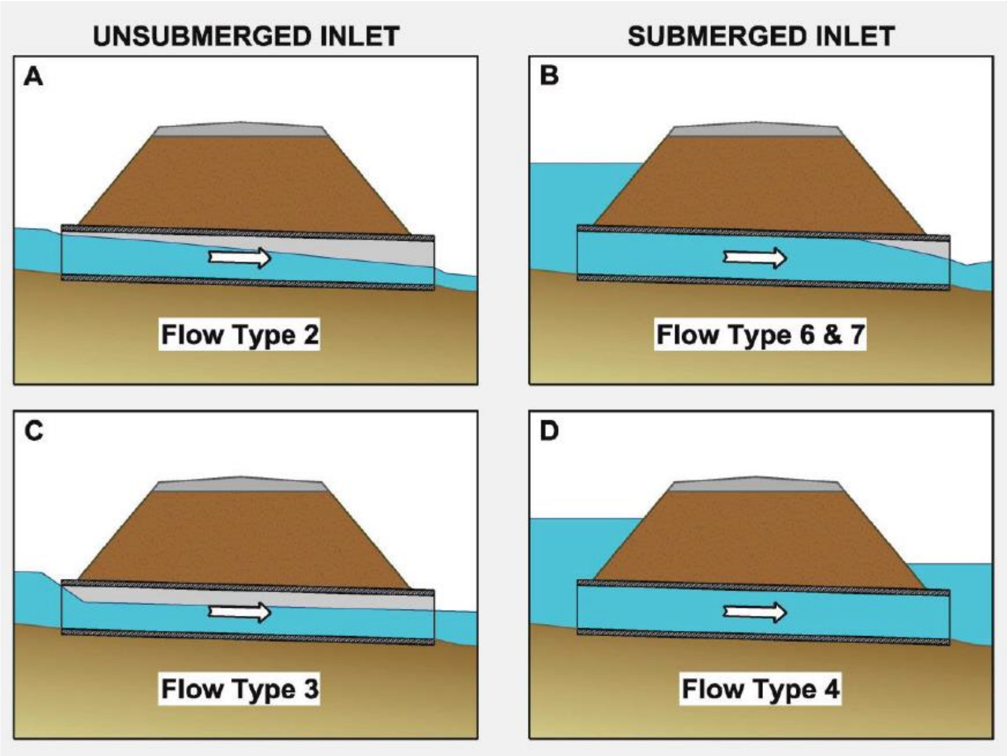

Figure 2-4 Illustration of outlet control condition (Schall et al., 2012)

Table 2-2 Flow types in culvert (Schall et al., 2012)

Flow Type	Flow Control	Submerged Inlet HW>D	Submerged Outlet TW>D	Length Full
1	Inlet	No	No	None
5	Inlet	Yes	No	None
2	Outlet	No	No	None
3	Outlet	No	No	None
4	Outlet	Yes	Yes	All
6	Outlet	Yes	No	Most
7	Outlet	Yes	No	Part

The geometry of the inlet becomes very important when the control section of the culvert occurs at the inlet because the only factor affecting the hydraulic capacity of the culvert is the inlet geometry. In contrast, the geometry of the inlet becomes less important when the control section occurs at the outlet as the outlet controlled depends upon the barrel characteristic and the tailwater. (*ibid*). The factors governing culvert control section are shown in Table 2-3.

Table 2-3 Governing factors of culvert control section

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

2.2.4 Performance Curve

Performance curve is described as the relationship between the headwater and the culvert barrel discharge (Charbeneau et al., 2006). Performance curve shows the consequences of high water flow rates and it is used to evaluate the hydraulic capacity of a culvert for various headwater.

It is necessary to plot both inlet and outlet control when developing performance curve because the dominant control flow at a given headwater is hard to predict. The control section of culverts might be shift between inlet and outlet control (Schall et al., 2012).

Common design criterion of culvert is under inlet control condition, therefore the inlet plays an important role in the culvert performance. The model used in the present experiments is designed under inlet control condition. Thus, outlet control condition can occur on the experiments.

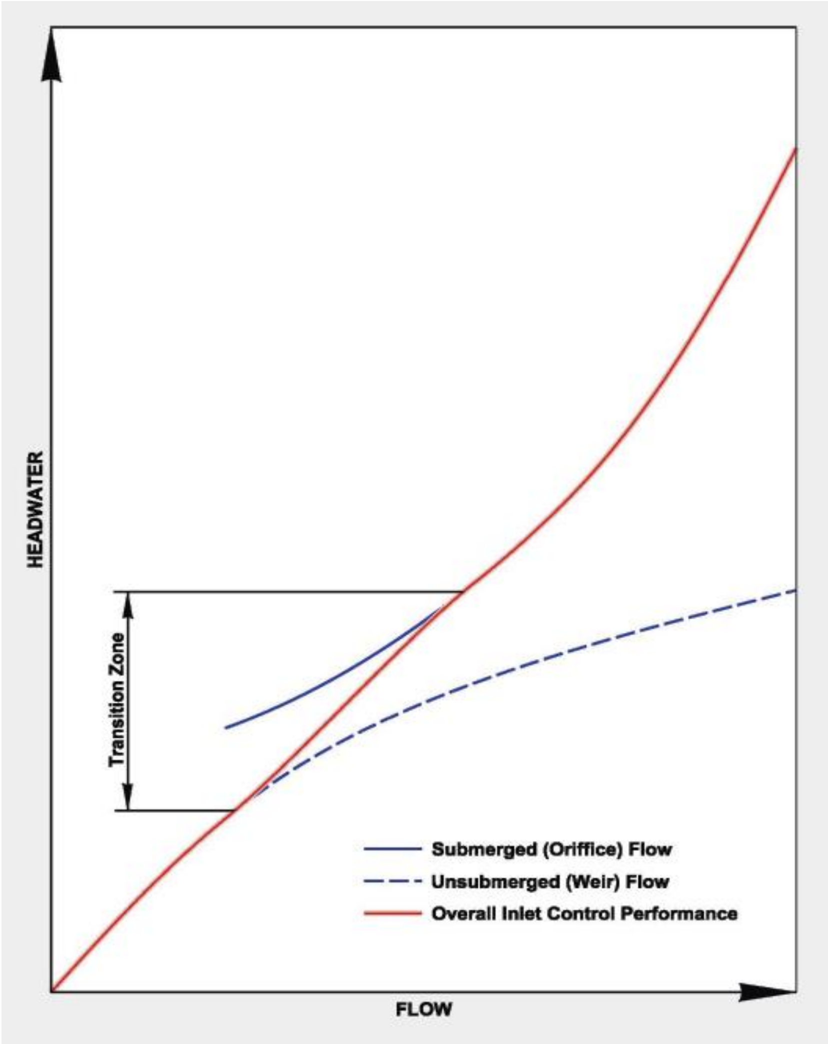

Figure 2-5 Illustration of performance curve under inlet control (Schall et al., 2012)

<u>Dimensionless Performance Curve</u>

The experiment results in the present study will be presented through the dimensionless performance curve so that it will be possible to scale up the results of the model to the prototype. The functional relationship for dimensionless performance curve is:

$$\frac{Q}{\sqrt{g.D^5}} = f\left(\frac{Hw}{D}\right) \quad (2\text{-}6)$$

Where Q = discharge, m^3/s

Hw = water depth above inlet control section invert, m

D = diameter of the conduit, m

g = gravity acceleration, 9.81 m/s^2

The variable $Q/(gd5)^{1/2}$ is a form of the Froude number (McEnroe and Bartley, 1993). Figure 2-6 and Figure 2-7 show the illustration of performance curve and dimensionless performance curve.

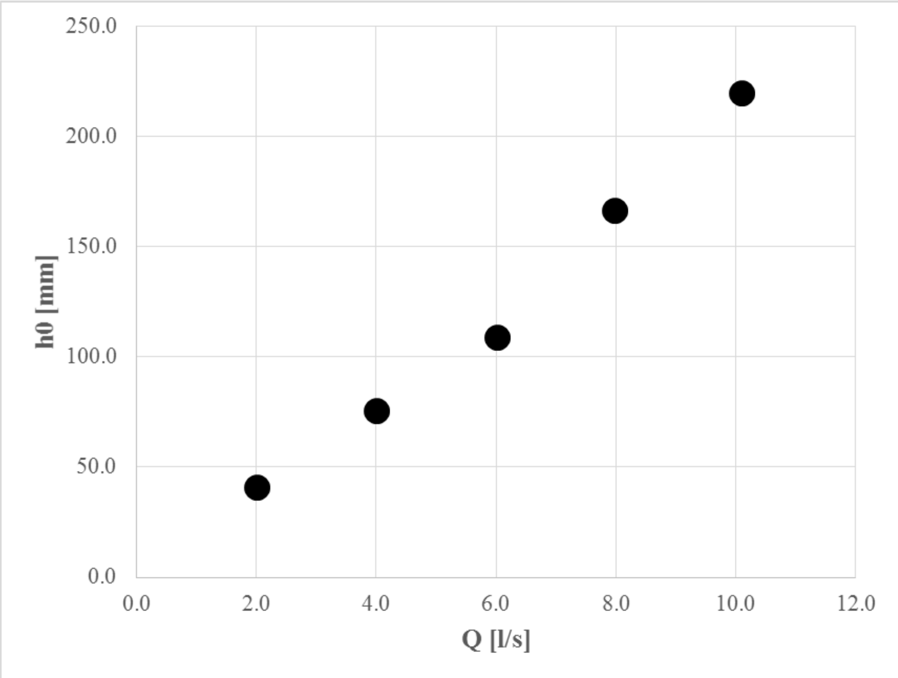

Figure 2-6 Illustration of the performance curve

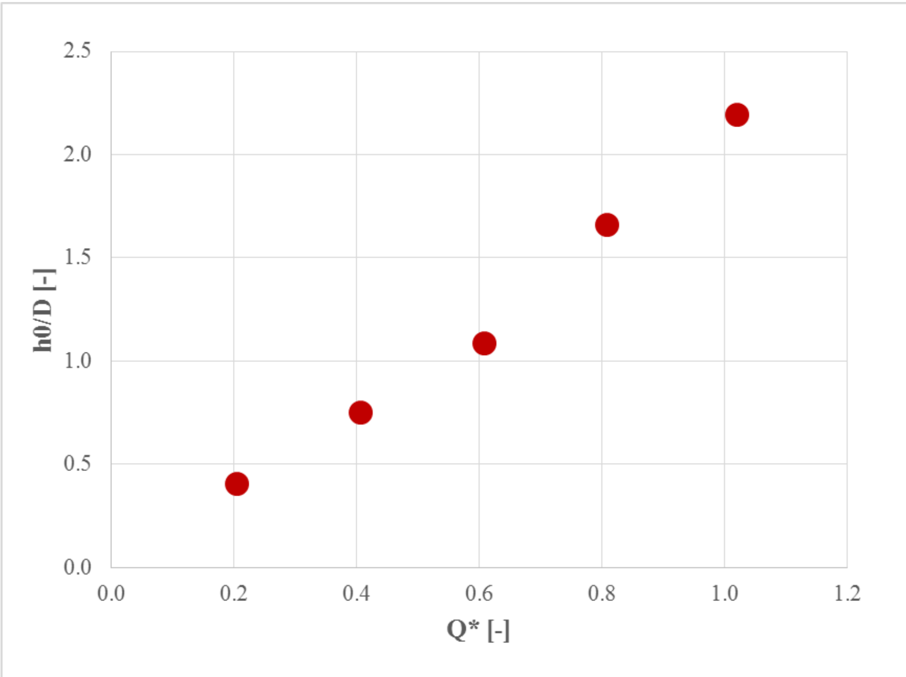

Figure 2-7 Illustration of the dimensionless performance curve

2.3 Sedimentation Problems on Culvert

To avoid supercritical flow upstream the entrance, culverts are usually constructed on a relative mild channel slope. This condition increases the probability of the sediments deposited near culverts. The deposition of sediment at culverts influenced by the size and characteristic of the channel's material, the hydraulic characteristic under different hydrologic events, the culvert geometry design, channel transition design, and the presence of vegetation around the channel (Ho, 2010).

However, one of the prior study (Rigby et al., 2002) show that culverts can experienced full blockage to completely unblocked. By default culverts convey flow that is of lower velocity and lesser depth than the design flow (Ho, 2010). *Blockage by sediment typically occurs both in the culvert entrance and along the barrel of the culvert* (Rigby et al., 2002).

Culvert blockage by the sediment may leads to scouring and embankment failure by the overtopping flow. Blockage resulted the flood levels of road and rail crossing increased and floodwater might diverted out of the normal stream channel which increasing the extend of the damage. (*ibid*).

3 EXPERIMENTAL SETUP

The experiment of this master thesis was conducted at the Hydraulic laboratory of the Norwegian University of Science and Technology. To perform the measurement, testing procedures were applied to standardize the experiments with different setup. In this study, the experiments were performed to investigate the effects of various expansion section widths on the culvert performance with different inlet types on hydraulics and sediment transport. However, the experiments were only focusing on a circular pipe.

3.1 Laboratory Setup

The model in this study was used previously by Gotvassli (2013) and Hendler (2014). In Gotvassli's study, the model was modified regarding to various expansion section lengths. Then, on the next study by Hendler, blocks were installed on the model. In this study, the model is modified with regards to various expansion section widths with blocks installed on the model. The model scale was 1:10 and made from plywood, except for the culvert barrel that made from plastic and the blocks from glasses.

The scaled model was to represent a culvert in steep terrain, which is typical for Norwegian culvert. The model consisted of three main sections, an upstream reservoir; an approach channel; and a channel expansion. The channel expansion consisted of a culvert inlet, and a single culvert barrel (Gotvassli et al., 2014). Illustration of the model is shown in Figure 3-1.

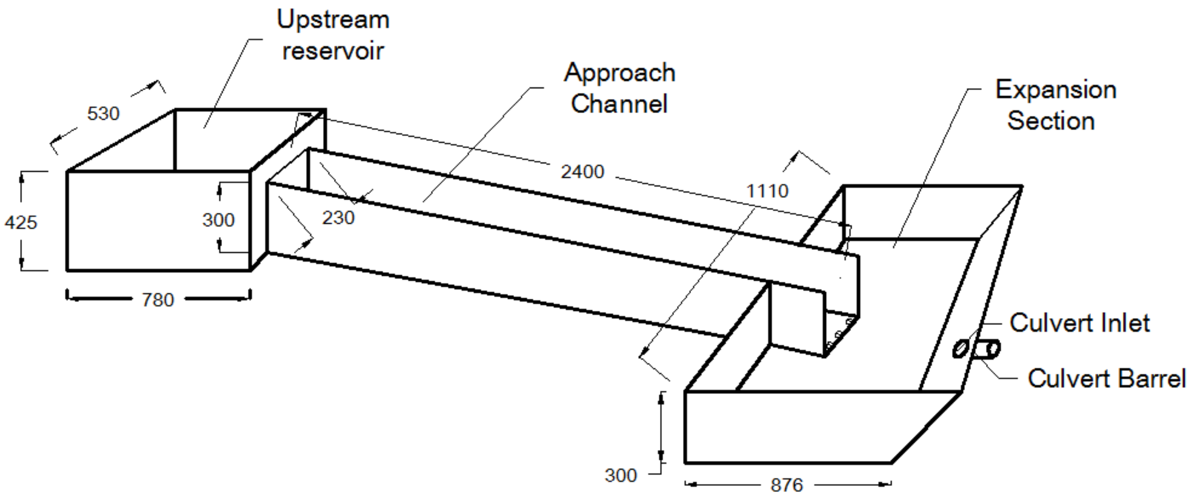

Figure 3-1 Sketch of the Model

Upstream reservoir is utilized to collect water from the main reservoir, before it is transferred through the approach channel and into the channel expansion. The height of the upstream reservoir is adjustable, so that the slope of the approach channel can be easily modified. Based on the results by Hendler, slope of 11% showed better performance as compared to slope of 2% or 20%. Therefore, in the present experiments, only the slope of 11% or 1:9 is studied.

A vibrating machine, Figure 3-5 c, is placed at the beginning section of the approach channel. It is used to perform continuous sediment feeding of the sediment experiment. The approach channel which represents a steep terrain has a dimension of 2400 mm long, 230 mm wide, and 300 high. The Gotvassli experiment found that the streams on the approach channel was always in a supercritical regime.

The last section of the model is the channel expansion with 1110 mm in width and 876 mm in length. At the edge of the channel expansion, the wall with 1:2 slope and 300 mm high represents the culvert embankment, where a culvert barrel with 100 mm in diameter is installed. The culvert inlet is placed on the central axis of the model. However, the position was adjustable, either to the left or right side of the central axis, depending on which experimental setup that is needed. However, all experiment in the present study were executed with the inlet installed on the central axis, except for one test that placed the inlet to the right side of the central axis. The size of the culvert barrel is the same as the culvert inlet. The model is only designed only for inlet control, therefore, the outlet structure design is neglected. Specification of the model is shown in Table 3-1.

Table 3-1 Technical specifications of the model

Sections	Unit	Length	Width	Height	Diameter
Upstream reservoir	mm	780	530	425	-
Approach Channel	mm	2400	230	300	-
- Blocks	mm	20	20	20	-
Channel Expansion	mm	876	1110	300	-
- Culvert Inlet	mm	-	-	-	100
- Culvert Barrel	mm	-	-	-	100

Three different inlet types (shown in Figure 3-2) studied in the experiment are:

1. Wing wall with a 45 degrees flare;
2. Cut inlet;
3. Projecting inlet.

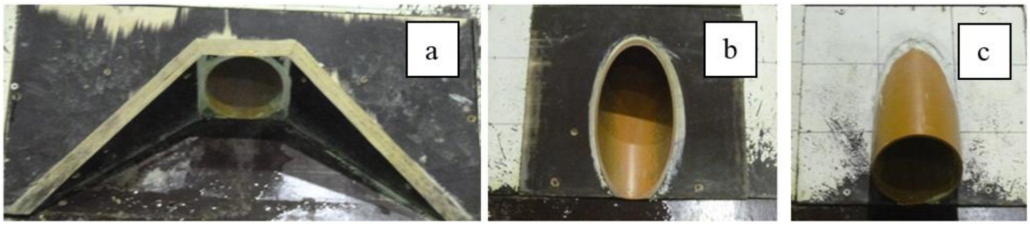

Figure 3-2 Inlet shapes: a) wing wall inlet with a 45 degrees flare, b) cut inlet, and c) projecting inlet

Since the present study was meant to analyze the effects of various expansion section widths, two extra temporary walls are installed on the expansion channel, so the expected width can be adjusted easily. Hendler, in the previous experiment, was only studied the expansion channel width of 1110 mm, therefore in the present experiment, expansion section width of 876 mm, 657 mm, 555 mm, 438 mm, and 292 mm are studied. Sketch and illustration of the extra walls are shown in Figure 3-3.

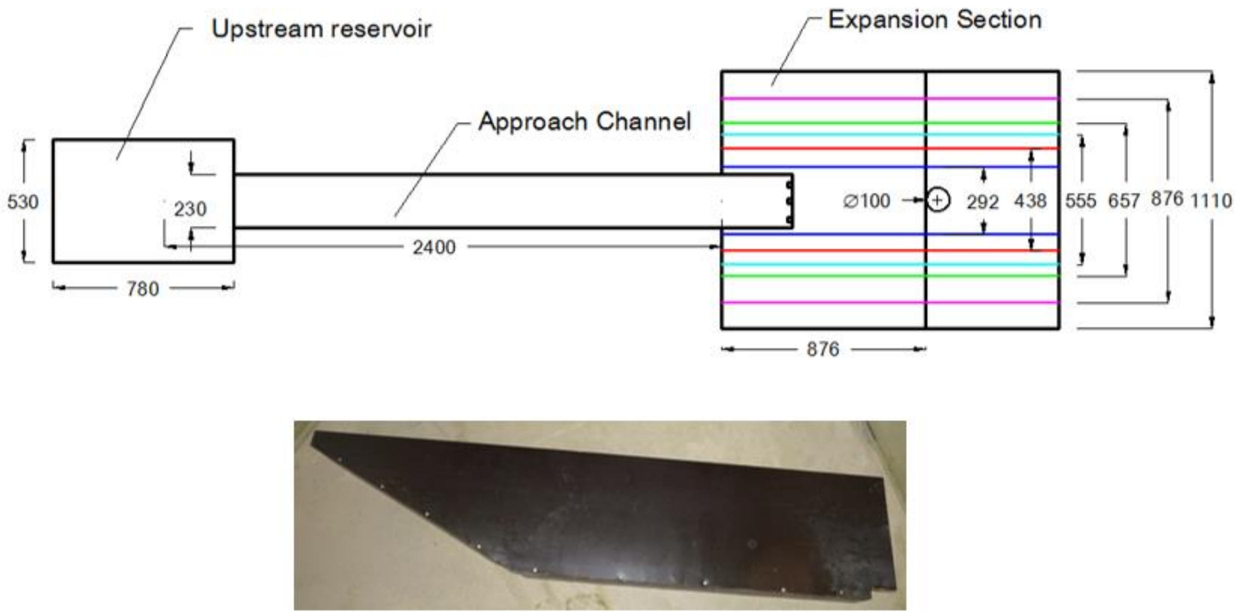

Figure 3-3 Top view of the model and illustration of the extra wall

Jet flow regime was occurred along the experiment that was conducted by Gotvassli. The jet regime led into a sidewise oscillation pattern on the expansion section which made the water unstable. So, to reduce the effects of the jet regime and stabilize the water flow on the expansion section, Hendler installed three energy dissipater blocks at the end of the approach channel. The dimension for each block is 20 x 20x 20 mm, shown in Figure 3-4. Those blocks induced a hydraulic jump on the transition between the approach channel and the channel expansion. Hydraulic jump is useful to dissipate excess energy in supercritical flow by raising the water level on the downstream side of the measuring flume thus maintaining high water level in the channel (Chow, 1959). The blocks is kept for recent study.

Figure 3-4 Energy dissipater blocks

Overall, the stream in the system is supercritical on the approach channel, followed by the hydraulic jump at the section end, then it is maintained to be a subcritical on the expansion section.

3.2 Measurements Setup

The water flow in the model system is measured by a discharge meter called Siemens Sitrans FM Magflo MA5000 (Figure 3-5 a). In this study, only two mic+ 35 Ultrasonic sensors, Figure 3-5 b, with one analogue output are used to measure the water depth at the expansion channel. Those sensors are placed at the right side of the extra temporary walls, but after few experiments done, the sensors are moved to the left side to avoid problems caused by the cable sensors. The average value of the water depth measured form both sensors is used as the input for data analysis. Details about discharge meter and sensor can be found in (Gotvassli, 2013). A measurement with 0 discharge must be completed before starting and after finishing a series of measurement, so the inaccuracy or deviation of the sensors can be detected. It should be noted that a steady flow condition must be obtained before starting a measurement.

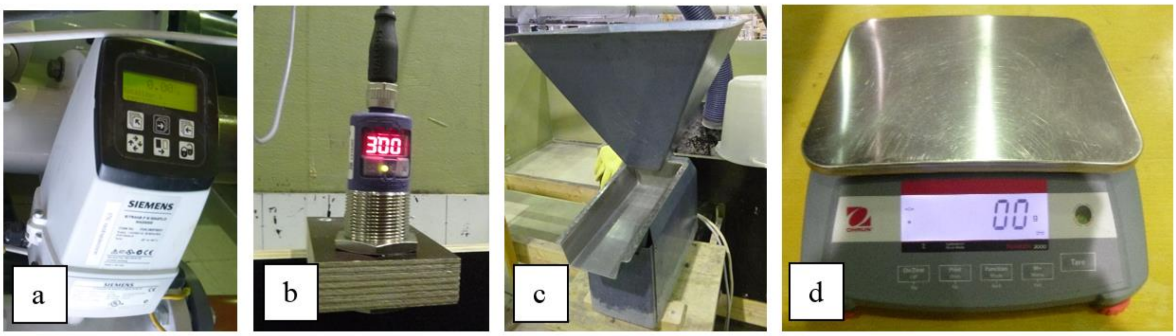

Figure 3-5 Measurement tools: a) discharge meter, b) sensor, c) vibrating machine, d) weighing scale

3.2.1 Clear Water Experiments

The aim of the clear water experiments is to compare the experiment results to the existing design guideline that used in Norway and to study the effects of the width of the expansion section.

<u>Procedure</u>

The water depth under clear water condition is measured for 60 seconds for each discharge starting from 2 l/s with an increment of 2 l/s. The experiment should be stopped when the culvert reaches outlet control condition or when the water depth in the expansion section exceeds the overtopping limit of the culvert which is twice of the culvert diameter (200 mm). Since there is no sensor installed on the culvert barrel, the outlet control is judged based on the visual observation when the outlet is flowing full. Flowchart of clear water experiment procedure is shown in Figure 3-6.

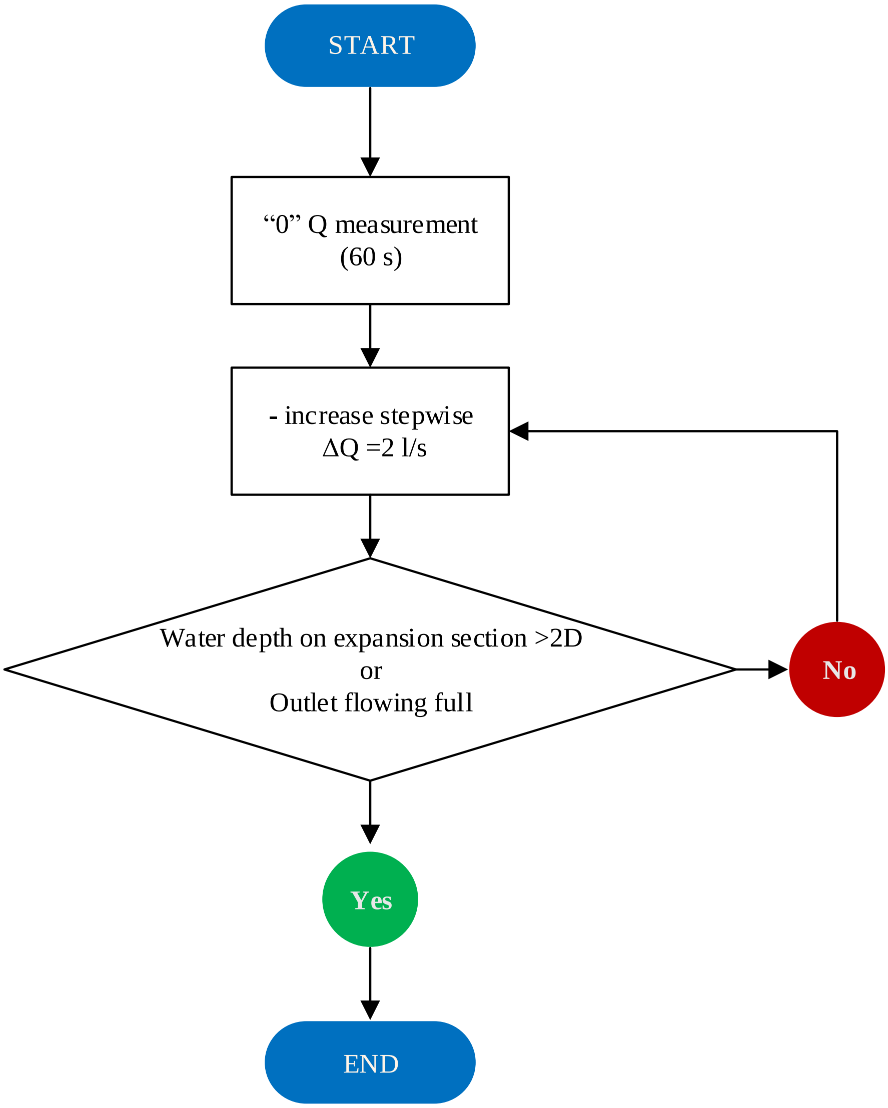

Figure 3-6 Flowchart of the clear-water experiment

3.2.2 Sediment Experiments

In this experiment, two different methods of sediment feeding, a continuous and all at once feeding, are tested in combination with different sediment sizes and amounts for each inlet type and width. A continuous feeding is meant to simulate sediment that transported in normal condition whereas the all at once feeding simulates the landslide. Flowchart of sediment experiment shown in Figure 3-7.

Sediment size and amount

Two different sediment grain sizes, 8-16 mm and 16-32 mm, in 5 or 7 kg are used in present experiment. The grain size and amount that is used in this study is also used by Gotvassli and Hendler in their study. However, only the sediment of 8-16 mm that is mostly used in this study.

Procedure

Before starting a measurement with continuous or all at once feeding, the water depth on the expansion channel must be stabilized and should be in a reasonable range compared to the clear water experiment result by running a clear water measurement for 60 seconds. The, the experiment may continue to the next step.

a. Continuous feeding

A continuous feeding measurement needs 1200 seconds, in which the details are describe below.

1. Add a selected amount of sediment to the vibrating machine
2. Set the vibrating machine to the pace that sediment feeding will be finished within 900 seconds, turn on the machine, then start the measurement.
3. When the sediment feeding is completed, wait for another 300 seconds ensure that the water and the sediment that are deposited at the culvert model has stabilized.
4. Weighed separately the sediment that is transported through the culvert and deposited on the expansion section or and the approach channel.

It should be noted that the sediments which sometimes stuck on the vibrating machine or the vibrating machine's inaccuracy will cause the process of sediment feeding run less than or even longer than 900 seconds.

b. All at once

All at once measurement needs 900 seconds in total. Details are shown below.

1. Drop selected amount of sediment into the approach channel in ± 5 seconds
2. Wait until the water and the sediment deposited at the culvert model has been stabilized. (± 895seconds)
3. After 900 seconds or about 15 minutes, the sediment that transported through the culvert and deposited at the culvert model is weighed separately.

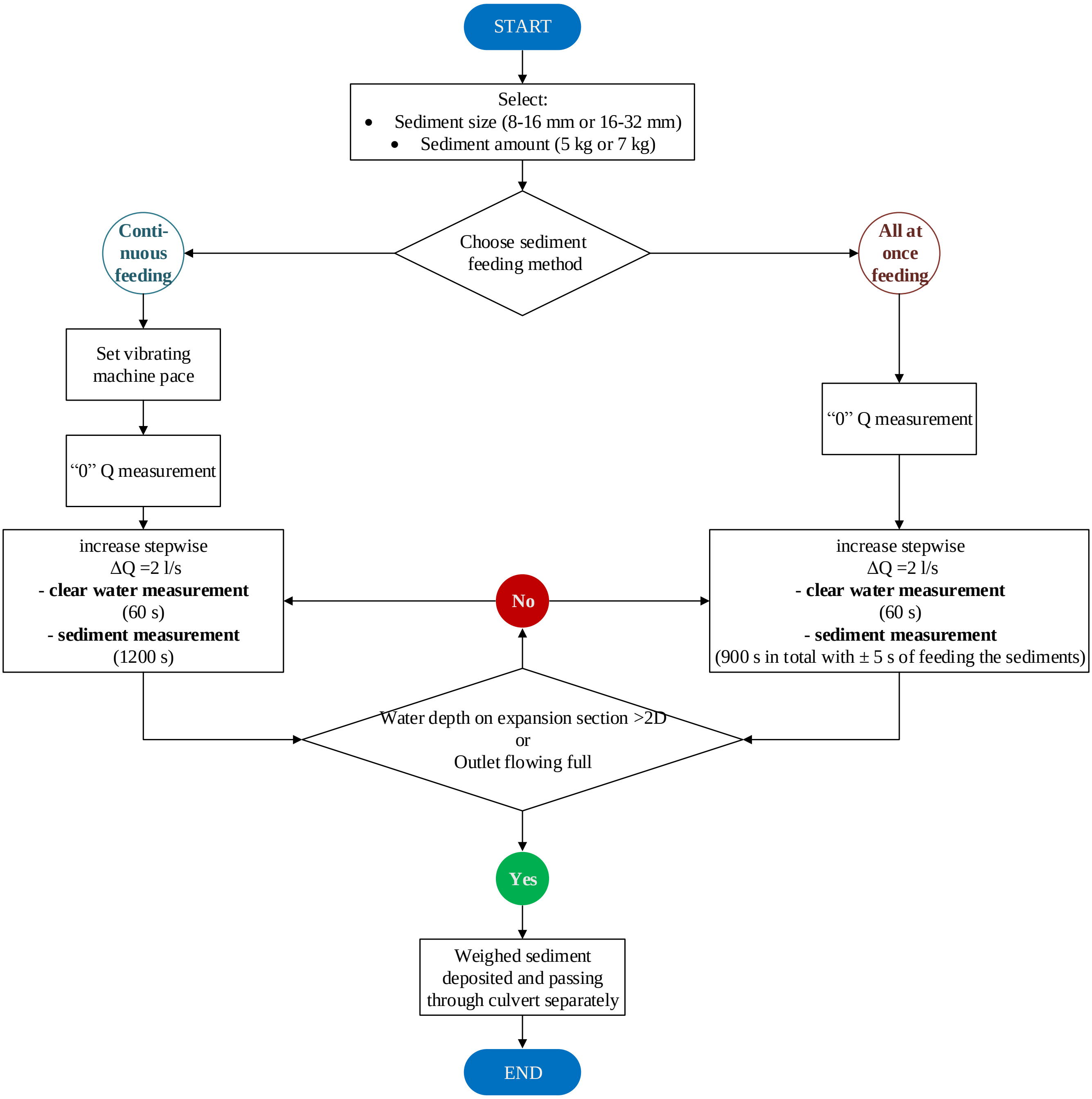

Figure 3-7 Flowchart of the sediment experiment

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Flow pattern, sediment transport efficiency, sediment deposition pattern and other things observed during the experimental works at the laboratory are presented in this chapter. The experimental results of the culvert performance on hydraulics and sediment transport are presented through the graphs which represent the ratio of the water depth measured in the expansion section to the culvert barrel diameter as a function of dimensionless discharge.

4.1 Summary of the Experiments

In total, 45 of clear-water and sediment experiments were performed. Lists of the experiments conducted in this study are tabulated below.

4.1.1 Summary of clear water experiments

Under clear-water condition, 16 experiments were conducted based on the inlet geometries and expansion section widths. Details of the experiments are shown in Table 4-1.

Table 4-1 Summary of the clear water experiments

Inlet type	Cut	Projecting	Wingwall
Expansion channel width			
1110	-	X *)	-
876	X	X	X
657	X	X	X
555	X	X	-
438	X	X	X
292	X	X	X

*) 2 inlet positions were tested for this expansion section width, one located on the central axis and the other one located to the right of the central axis of the model.

Results of the repeated experiments in comparison with results of the previous study (Subchapter 4.2) and effects of the width of the expansion section on the culvert performance under clear-water condition (Subchapter 4.3) will be compared with the existing design guideline which was taken from Chart 2A on Appendix C of the Hydraulic Design Series Number 5, FHWA.

4.1.2 Summary of sediment experiments

In total, 29 experiments were performed under sediment transport condition using the combination of:

1. Different inlet geometries;
2. Various widths of expansion section;
3. Various sediment sizes;
4. Various sediment amounts; and
5. Different methods of feeding the sediment.

Details of the experiments are shown in Table 4-2.

Table 4-2 Summary of the sediment experiments

Inlet type	Projecting						Cut						Wing wall					
Width	876		438		292		876		438		292		876		438		292	
Sediment size (mm)	G*)	A**)	G	A	G	A	G	A	G	A	G	A	G	A	G	A	G	A
8-16	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
16-32	x	x	-	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-
Sediment amount (kg)																		
5	x	x	-	-	-	-	x	x	-	-	-	-	x	x	-	-	-	-
7	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

*) G: Continuous feeding, **) A: All at once feeding

Culvert performance of different inlet geometries under sediment transport condition were analyzed based on:

- Effects of the width of expansion section under sediment transport (Subchapter 4.4);
- Effects of the sediment feeding method (Subchapter 4.5);
- Effects of the sediment size (Subchapter 4.6);
- Effects of the amount of sediment (Subchapter 4.7).

4.2 Comparison with previous experiments

Two experiments were conducted to check if the new experiment results were still in the reasonable range as compared to the previous experiment results by Hendler. Experiment results presented below are the experiment with projecting inlet in 1110 mm width of expansion section. Two inlet positions were tested, one located on the central axis and another located to the right of it.

Figure 4-1 shows the result of the present experiment with inlet positioned on the central axis. Present results are slightly higher than Hendler's, however both results are still in line and comparable to the existing design guideline.

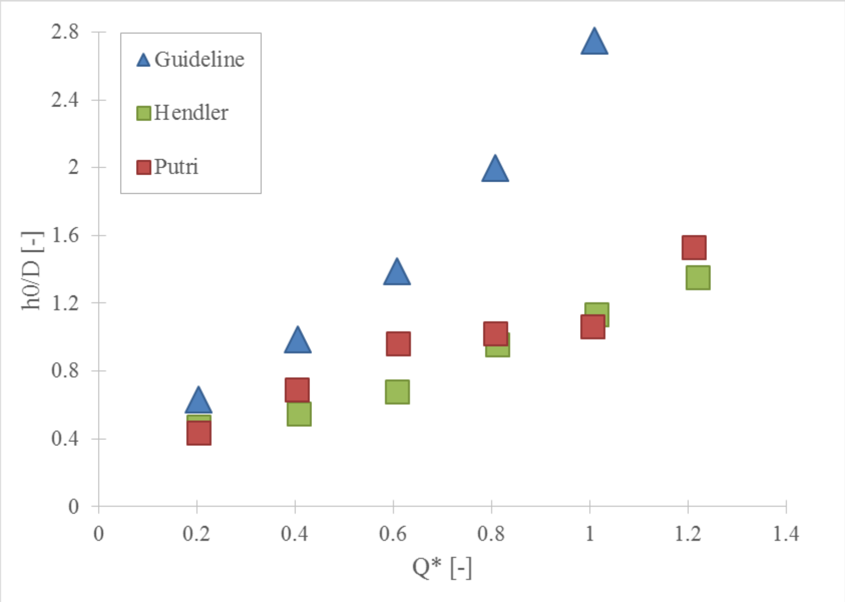

Figure 4-1 Performance curve of projecting inlet located in the central axis of the model, expansion section width of 1110 mm

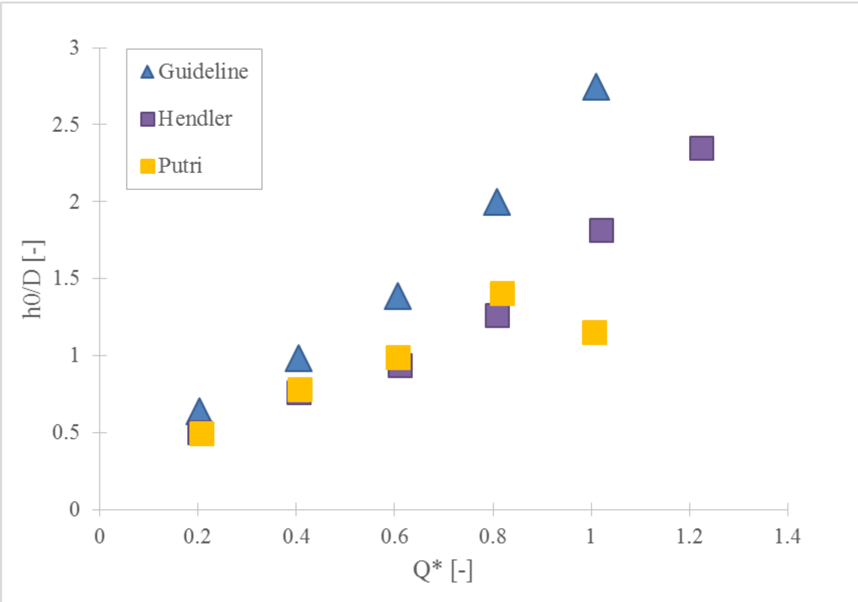

Figure 4-2 Performance curve of projecting inlet located to the right side of the central axis of the model, expansion section width of 1110 mm

Figure 4-2 shows the results of the experiment with inlet positioned to the right side of the central line. Most of the time, ratio of the water depth to the culvert diameter (h0/D) in the present experiment fits the previous experiment results, with an exception for Q* = 1.0, where the ratio of present experiment is lower than previous experiment. From the laboratory test it was observed at Q = 10 l/s culvert was operated under outlet control. Thus, after the flow had stabilized, water depth in expansion section was lowered suddenly.

In general, data obtained from the present work fit the trend of results in the previous experiment. It sets a good basis for next experiments.

4.3 Effects of the width of the expansion section on the culvert performance under clear-water condition

Five different expansion section widths, 876 mm; 657 mm; 555 mm; 438 mm; and 292 mm, were tested with different inlet setup to study the hydraulics and its effects on the culvert performance. Results of these experiments are presented below.

4.3.1 Results of the experiments and data analysis

a. Projecting Inlet

From the laboratory observation it was found that sidewise oscillation and circular pattern of the flow occurred at Q = 2 l/s with all widths of expansion section and became stronger at Q = 4l/s. The sidewise oscillation continued even at Q = 6 l/s with expansion section width of 876 and 675 mm, but with the remaining widths, 555 mm; 438 mm; and 292 mm, the oscillation diminished as the inlet was about to submerge. Sidewise oscillation occurred when the inlet was unsubmerged. As the inlet got submerged, the sidewise oscillation gradually changed into wave movements or normal oscillation. In this study, sidewise oscillation is defined as the movement of the flow unequally and alternately oscillated to the right and left side of the inlet. Example of the sidewise oscillation is shown in Figure 4-3.

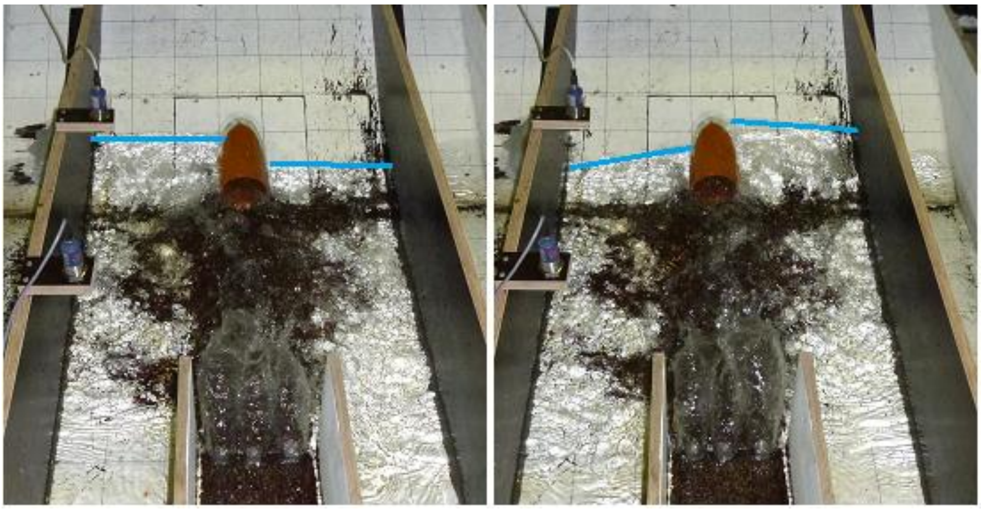

Figure 4-3 Sidewise oscillation with expansion section width of 657 mm at Q = 4 l/s

During the experiment, it was observed that expansion section width of 876 mm operated under outlet control at Q between 10 l/s and 12 l/s, while expansion section width of 657 mm reached outlet control at Q = 8 l/s. At Q = 8 l/s, for the 555 mm width, culvert barrel was flowing full and for the 438 mm width, water depth measured was more than the overtopping limit, so for both width outlet control may be obtained at Q between 6 l/s and 8 l/s. For expansion section width of 292 mm, at Q = 8 l/s outlet was flowing full periodically, while at Q = 10 l/s the culvert barrel was flowing full constantly. However, outlet control may be obtained at Q between 6 and 8 l/s.

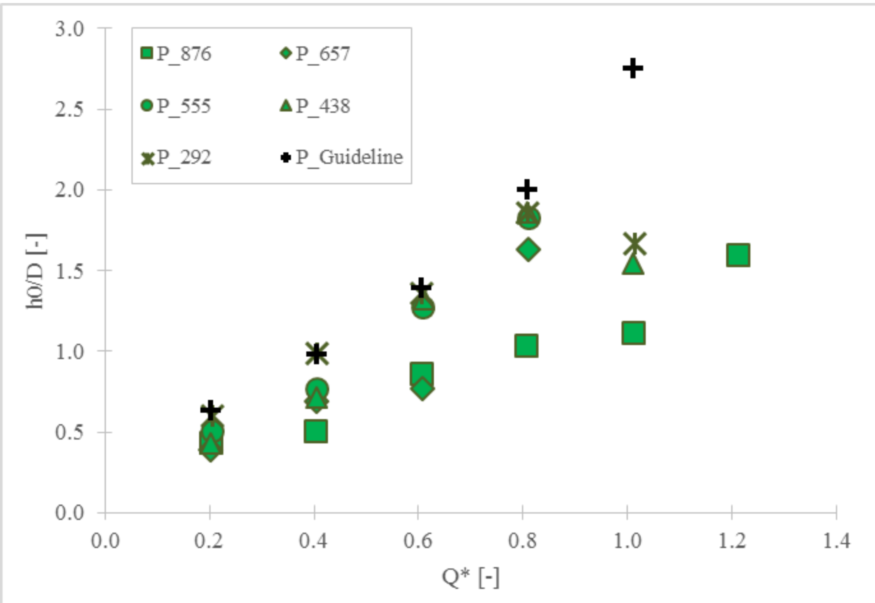

Figure 4-4 Performance curve of projecting inlet in various widths of expansion section under clear-water condition

Figure 4-4 shows the influence of expansion section width on the culvert performance with projecting inlet setup. At $Q^* = 0.2$, the experimental results fit the guideline value, especially for expansion section width of 292 mm. For expansion section widths of 555 mm, 438, and 292 mm, the ratio of h0/D remains comparable to the guideline value until $Q^* = 0.6$. As the discharge increased, h0/D value are lower than the guideline value and become much less at $Q^* = 1.0$ for all widths. At this point all widths were already operated under outlet control. Width of 876 mm resulted in the lowest water depth as compared to other widths and the guideline, with width of 657 mm follows after. The difference of the h0/D ratio for the 555 and 438 mm widths are insignificant. In general, width of 292 mm gave result that is similar with guideline value.

b. Cut Inlet

In general, the oscillation effect for cut inlet was slight calmer than the projecting inlet. With cut inlet sidewise oscillation also occur in all widths of expansion section at $Q < 6$ l/s as shown in Figure 4-5. As the inlet was about to submerged at $Q = 6$ l/s, the sidewise oscillation pattern reduces gradually.

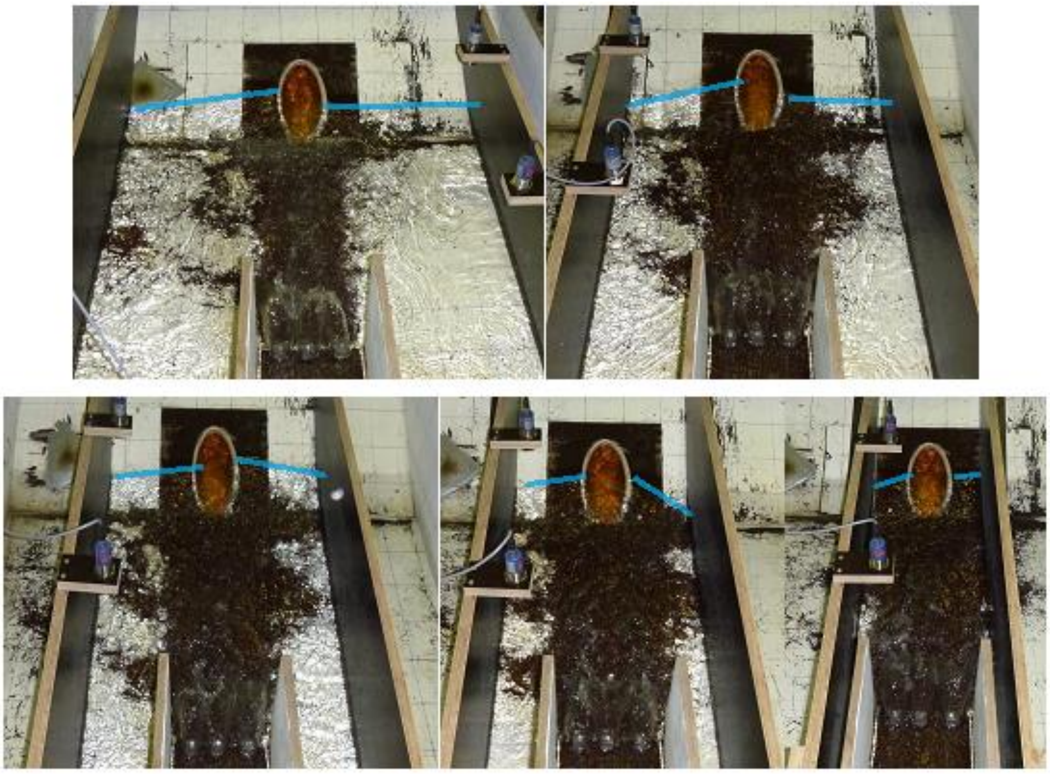

Figure 4-5 Sidewise oscillation occurred with cut inlet at Q = 2 l/s with expansion section width of 876 mm, 657 mm, 555mm, 438 mm, and 292 mm respectively

At Q = 8 l/s, oscillation caused the water periodically touched the overtopping limit with expansion section width of 876 mm, meanwhile at Q = 10 l/s it was found to be outlet controlled. Outlet control may be obtained at Q between 8 l/s and 10 l/s for 876 mm width. With expansion section width of 657 mm at Q = 6 l/s, it was observed that the hydraulic jump occurred on the approach channel, more or less 60 cm further from the section's end. Hence, water on the expansion section was poorly oscillated even though the oscillation would sometimes cause the water touched the overtopping limit. Depth of the water with expansion section with width of 555 mm, 438 mm and 292 mm was higher than the overtopping limit at Q = 8 l/s, therefore, outlet control may be obtained at Q between 6 l/s and 8 l/s for these width.

Figure 4-6 visualizes the performance curve of cut inlet in various widths of expansion section. In general, width of 876 mm shows the lowest ratio of h0/D, while the result for width of 292 mm is most comparable to the guideline, followed by 438 mm, 657 mm, and 555 mm respectively. At Q* = 0.8, expansion section width of 876 and 438 mm have lower value than the guideline. At Q* = 1.0 all widths of the expansion section observed has a lower value compare to the guideline, shows that all widths already operated under outlet control.

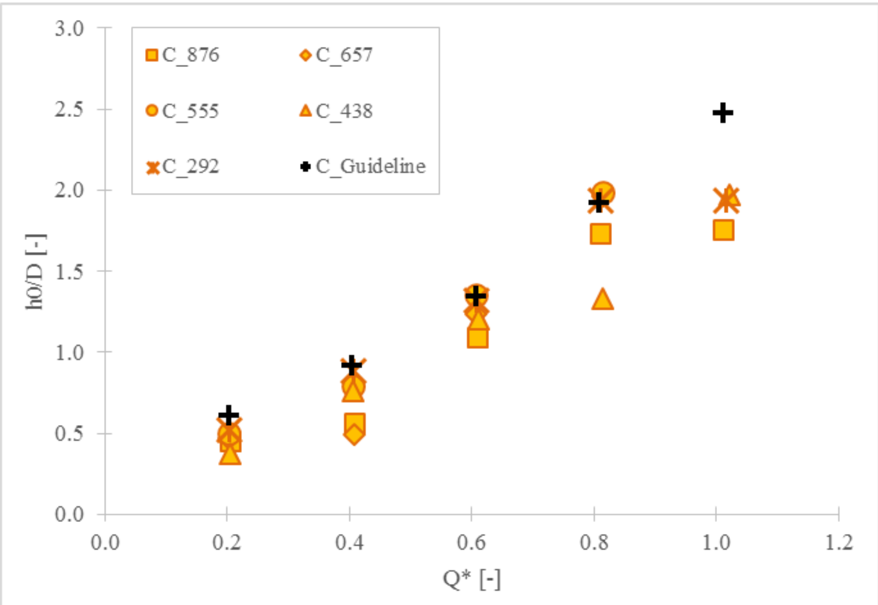

Figure 4-6 Performance curve of cut inlet in various widths of expansion section under clear-water condition

Overall, the ratio of the water depth to the culvert barrel diameter for all widths are quite close to the guideline value, especially at low discharges.

c. Wing wall Inlet

Figure 4-7 shows no significant difference on the ratio of h0/D for different expansion section widths. Result of h0/D ratio for width of 292 mm and 876 mm are quite close to each other. From the laboratory observation it was found that the insignificant differences was caused by the leakage occurred when the temporary walls were adjusted to the width that is narrower than the inlet configuration width. The wing walls inlet has a total width of 500 mm, with 200 mm of width on each flare and a 100 mm of culvert diameter. When the width of the expansion section was adjusted to 438 or 292 mm, a huge leakage occurred due to the geometry of the temporary walls which was not perfectly fit to the expansion section configuration. If the leakage was covered or sealed, water depth on the expansion section might be increased. Illustration of this situation is shown in Figure 4-8.

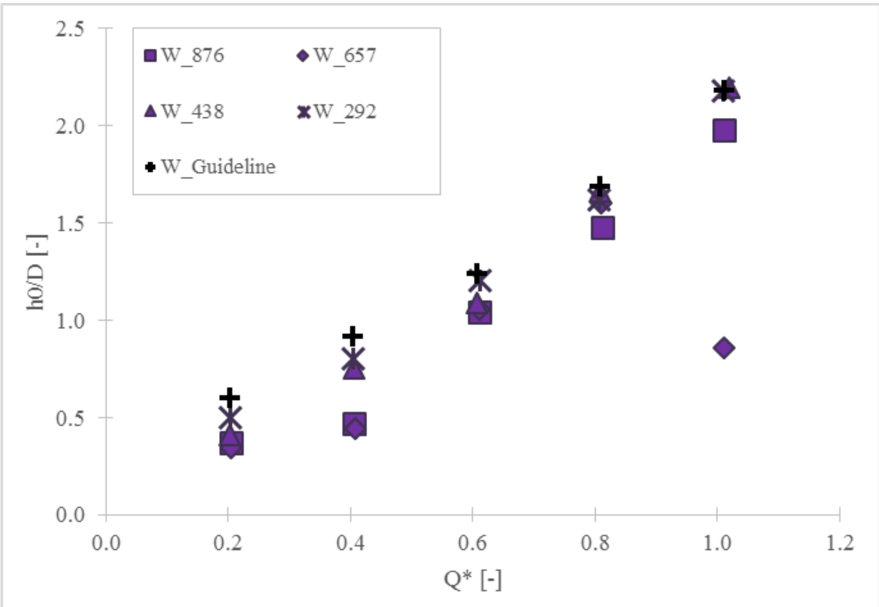

Figure 4-7 Performance curve of wing walls inlet in various widths of expansion section under clear-water condition

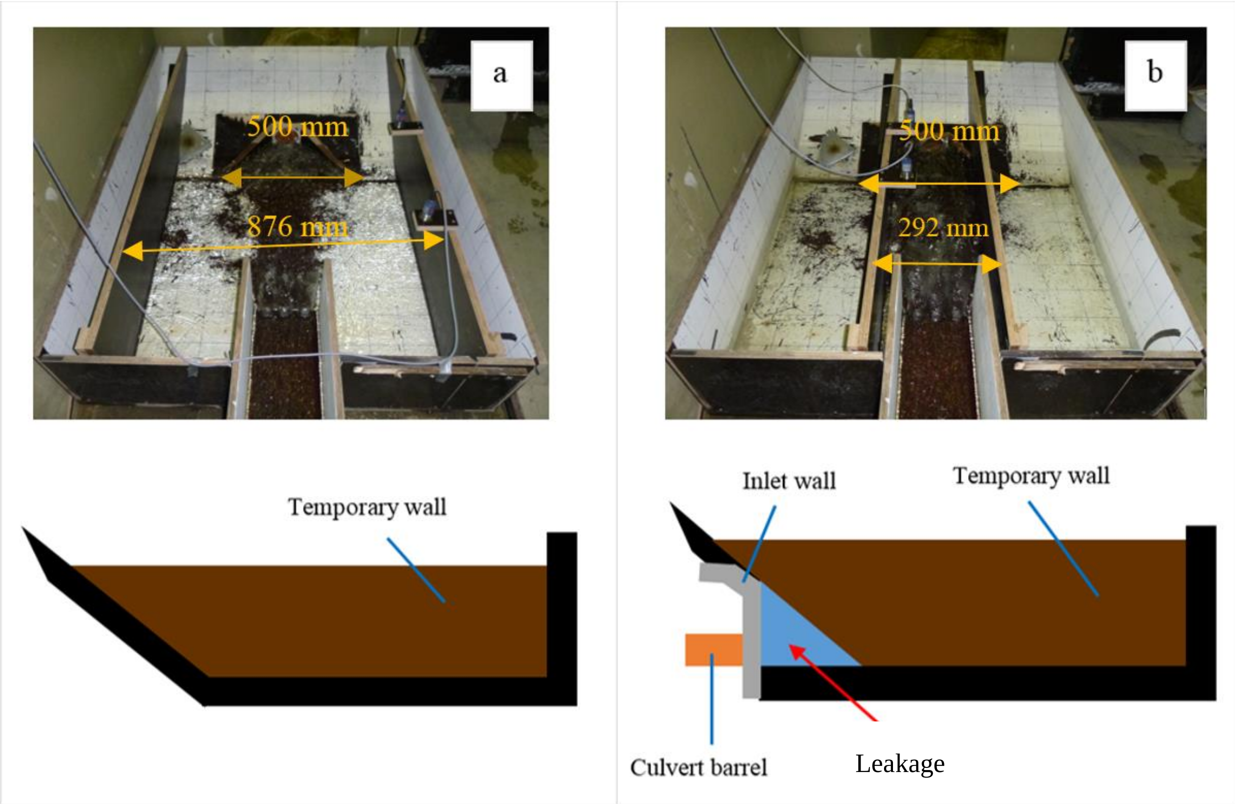

Figure 4-8 Illustration of the model's front view and temporary wall's side view with wing wall inlet with expansion section width of: a) 876 mm, b) 292 mm

From the visual observation, with wing wall inlet, the water did not experienced sidewise oscillation. Expansion section width of 876 mm was operated under outlet control at Q between 8 l/s and 10 l/s. The observation showed that water depth in expansion section depends on how fast the discharge change. Water depth in expansion section increased significantly when the discharge changed gradually by opening the pipe valve slowly, shown in Figure 4-9 a. Yet, when the discharge changed suddenly by opening the pipe valve fast, pressure on the inlet increased so that more water flowing through the culvert. Therefore, water depth in expansion section suddenly decreased and outlet was flowing full, as shown in Figure 4-9 b.

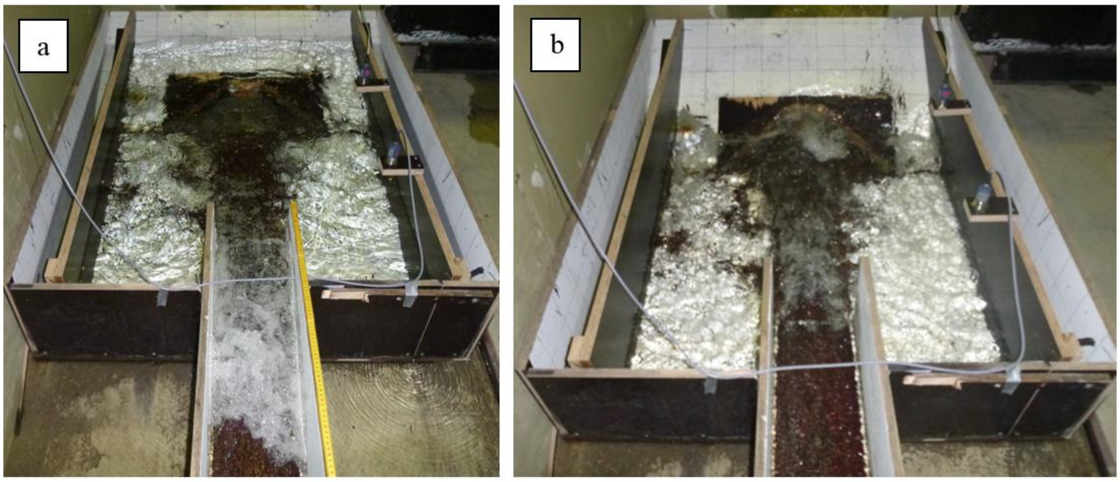

Figure 4-9 Flow on the expansion section width of 876 mm with wing wall inlet at Q = 10 l/s when the discharge changed: a) gradually; b) suddenly

Culvert barrel did not flowing full at Q = 10 l/s with expansion section width of 438 and 292 mm. Yet, the water depth on the expansion section was higher than the overtopping limit. While expansion section width of 657 mm operated under outlet control at Q between 8 l/s and 10 l/s, with width of 438 and 292 mm outlet control condition must be obtained at Q < 8 l/s.

Figure 4-7 shows that at Q* = 1.0, h0/D ratio of 657 mm is extremely low as compared to other widths. It was observed at Q = 8 l/s, water depth on the expansion section was less than the overtopping limit and outlet was flowing three fourth of the diameter. At Q = 10 l/s, water depth on the expansion section decreased gradually and outlet was flowing full after the water had stabilized. Thus, the outlet control condition may be obtained at Q between 8 and 10 l/s.

In general, the result of wing wall inlet is comparable with the guideline as the ratio of h0/D is quite close to guideline value, especially for expansion section width of 292 mm. At Q* = 1.0, h0/D ratio of expansion section width of 292 and 439 mm coincide with the guideline value. Higher ratio may be obtained if the leakage problem discussed above can be solved.

d. All together

Figure 4-10 shows performance curve with three different inlet setup in various expansion section widths. With expansion section width of 876 mm, the projecting inlet performs best, which is then followed by the wing wall inlet, while the cut inlet performs worst out of three. Projecting inlet resulted in the least water depth on the expansion section, especially at high discharge.

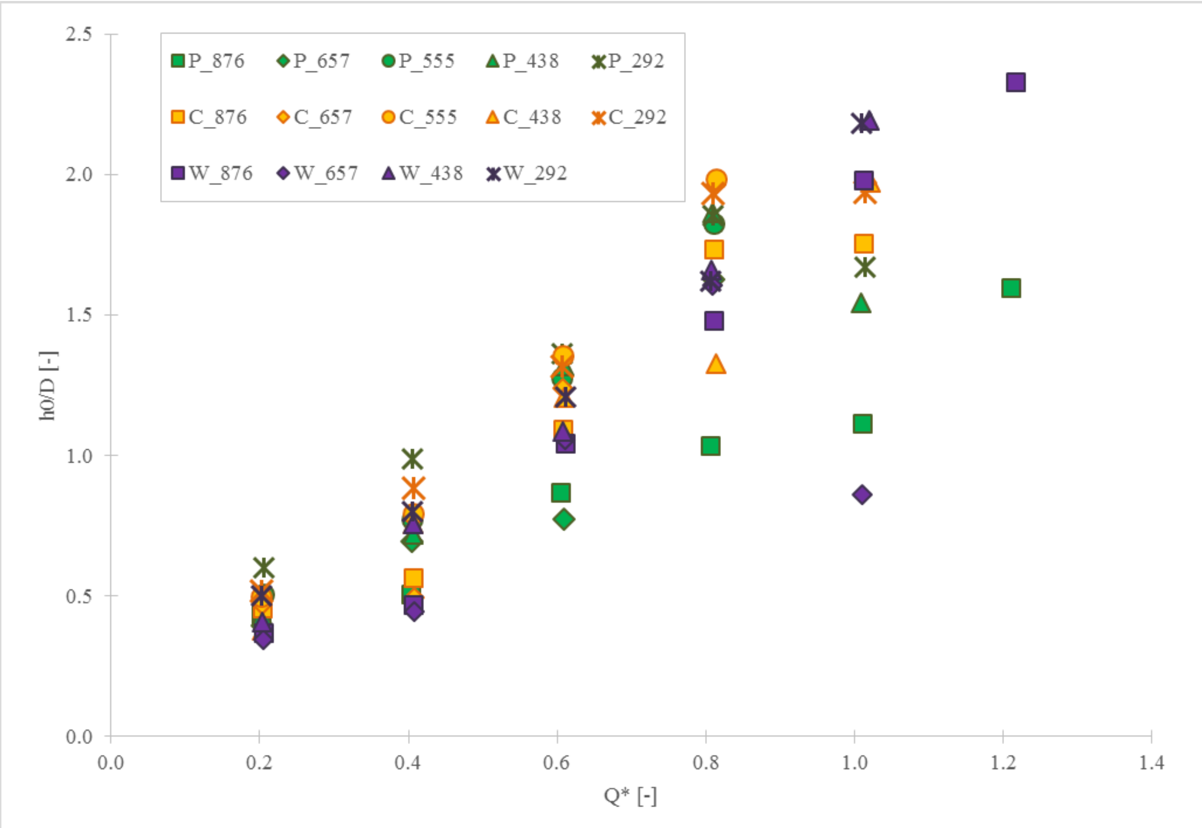

Figure 4-10 Performance curves under clear-water condition with different inlet types in various expansion section width

With expansion section width of 657 mm, among the three inlet types the cut inlet performs the worst, while the wing wall inlet shows the best results for this width. This is then followed by the projecting inlet.

Only two inlet were studied for expansion section width of 555 mm and among these, the projecting inlet performs better than cut inlet. At $Q^* = 0.2$ and 0.4, ratio of h0/D for both inlet coincide, but as the discharge increases, the ratio of the cut inlet is observed to be higher than the projecting inlet.

To determine which inlet perform best with expansion section width of 438 mm is difficult. At Q* = 0.2 and 0.4, the ratio of h0/D of all inlet types almost coincide to each other. As the discharge increases, projecting inlet performs the worst. At the higher discharge, Q* = 0.8 and 1.0, wing wall has higher ratio than cut inlet. Overall, for this width, the performance of cut inlet shows the best, which is followed by the wing wall and lastly by the projecting inlet, which has the worst performance.

With expansion section width of 292 mm, the wing wall inlet ends up with the lowest ratio of the water depth to culver diameter, which is then followed by the cut and projecting inlet respectively. Although at Q* = 1.0, the wing wall inlet suddenly have the highest ratio of h0/D, however in general, it still shows the lowest ratio for all discharges.

4.3.2 Discussions

The observation showed that with projecting and cut inlet setup, sidewise oscillation will occur at low discharges. As mentioned in Gotvassli et al. (2014), the oscillation might occur because of the surface waves in the expansion section and the larger width of the jet as compared to the barrel diameter. At higher discharge, sidewise oscillation diminishes as the water depth increases. The increment of the water depth influenced the occurrence location of the hydraulic jump at the approach channel. The higher the water depth the further the emergence of the hydraulic jump from the end of the approach channel. Thus, the jet effect (oscillation) from the hydraulic jump diminished in the expansion section.

Among all widths studied, the result of the narrowest width; 292 mm, is the closest to the guideline. With wing wall inlet setup, the width of expansion section has less influence to the culvert performance. This result is totally different for the other two inlets, which are influenced by the width of the expansion section.

Width of the expansion section influences the overall water depth in expansion section and sometimes on the approach channel due to the back water effect. At the same discharge, water depth in expansion section is lower with wider expansion section, meanwhile it is higher with narrower expansion section. Narrow width cause the increment of water depth on the approach channel due to the back water effect. The ratio of h0/D for narrow expansion section are close to the guideline value.

Overall, from the ratio of the water depth to the culvert barrel and its comparability to the guideline value, projecting inlet has the worst culvert capacity as compared to the other inlet types. Cut inlet performance is the second best, while wing wall inlet performance is shown as the best one. Similar result mentioned in the manual book of NPRA (2011), NVE (2010) and observed by Hendler (2014) on her study.

4.4 Effects of the width of the expansion section under sediment transport condition

In this subchapter, experiments of three inlet types in various expansion section widths under sediment transport condition are discussed. The aim of the experiments is to investigate the effects of expansion section widths and the sediment on the culvert performance. Three widths of expansion section tested are: 876 mm, 438 mm, and 292 mm. In the experiments, 7 kg of 8-16 mm of sediments used with continuous feeding.

4.4.1 Results of the experiments and data analysis

a. Projecting Inlet

Figure 4-11 presents the performance curve of projecting inlet in various widths of expansion section on sediment transport. In the graph values at $Q^* = 0.2$ with various widths of the expansion section coincide to each other. From the experiment work, it was observed that the sediment deposition pattern were similar for all widths at $Q = 2$ l/s, with most of the sediments were deposited in the expansion section. A slight difference noticed was with width of 876 mm, sediments spread reached near the inlet mouth and as the expansion section get narrowed, sediments tends to gathered together. Therefore, with expansion section width of 292 mm range of the spreading narrowed.

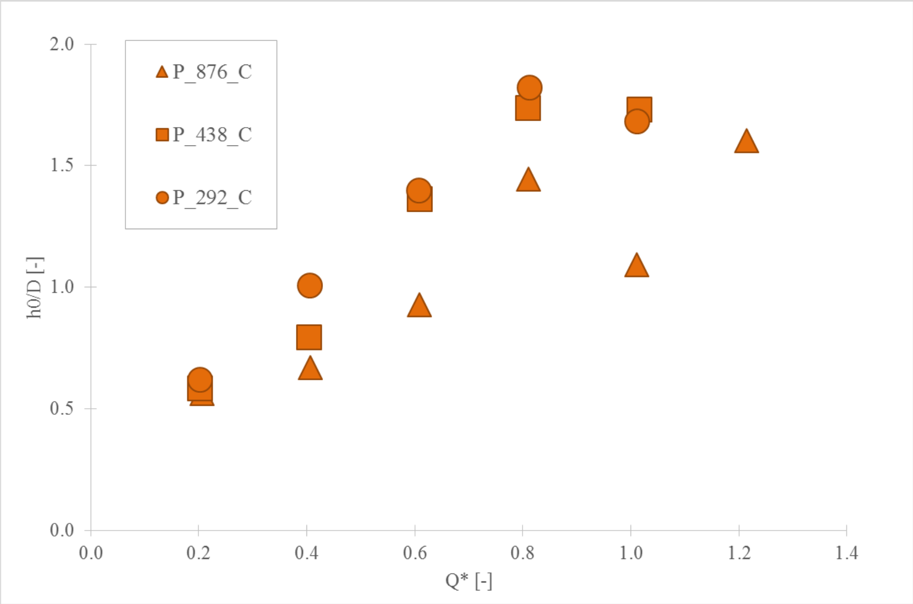

Figure 4-11 Performance curve of projecting inlet in various widths of expansion section under sediment transport condition

At Q = 4 l/s water depth in the expansion section increased significantly with expansion section width of 292 mm. Hydraulic jump occurred exactly before the blocks and the sediments settled after the hydraulic jump, gathered together made the water depth increased. With expansion section width of 438 mm water depth only increased a bit since some sediments passing through the culvert barrel. With expansion section width of 876 mm, the increment of the water depth was insignificant, because the jet caused the sediments moved towards the inlet, therefore, a lot of sediments were transported through the culvert barrel. The deposition pattern in different widths at this discharge is shown in Figure 4-12.

Figure 4-11 shows that at Q* = 0.6, 0.8, and 1.0, there were only marginal differences on water depth ratio and amount of sediment deposited in the expansion section with expansion section width of 438 and 292 mm. It was observed from the experiments that at Q = 6 l/s, 8 l/s, and 10 l/s, both widths ended up with similar amount and deposition pattern of sediment deposited in the expansion section. With expansion section width of 876 mm more sediments were transported through the culvert barrel at higher discharge, therefore the water depth on the expansion section resulted in similar water depth in the clear water experiment.

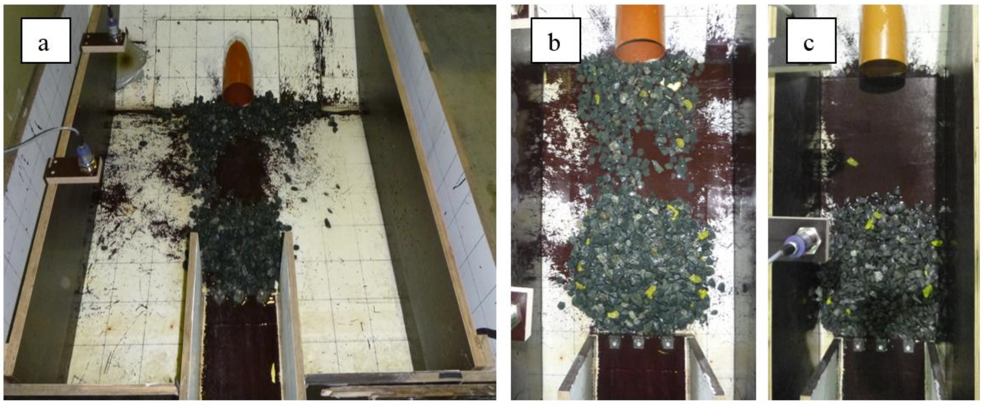

Figure 4-12 Sediment deposition pattern with projecting inlet at Q = 4 l/s with expansion section width of: a) 876 mm; b) 438 mm; c) 292 mm

b. Cut Inlet

Figure 4-13 shows the ratio of the water depth to the culvert barrel diameter of all expansion section widths with cut inlet. It is pointed out that with cut inlet the expansion section width has less influences to the culvert capacity. Most of the time, there are only slight differences of h0/D ratio among all widths as the discharge increases.

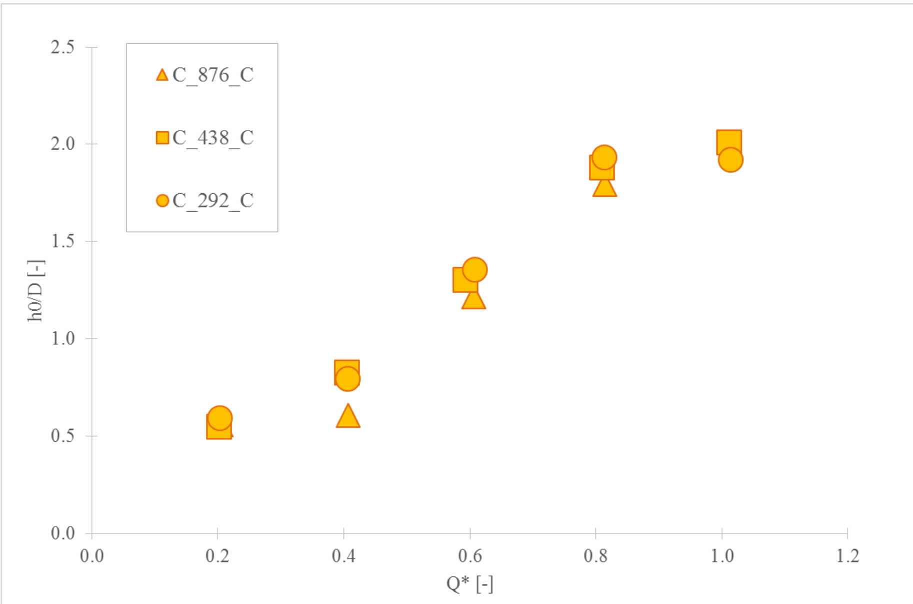

Figure 4-13 Performance curve of cut inlet in various widths of expansion section under sediment transport condition

At Q* = 0.2 ratio of h0/D coincide well for all widths of expansion section. At Q* = 0.4 width of 438 and 292 mm ratio coincide at the same point, but width of 876 mm has less water depth. From the experiment it was found that some sediments were transported through the culvert barrel at Q = 4 l/s with expansion section width of 876 mm, whereas for the other two widths no sediment were passing through the barrel.

At Q* ≥ 6 l/s, the difference of the water depth to the culvert barrel diameter ratio and the sediment amount deposited in the expansion section were insignificant. From the observation it was observed that with cut inlet, at Q = 6 l/s and above, hydraulic jump occurred on the approach channel and sediment deposition pattern observed for all widths were similar. The sediment deposition patterns in various widths tested at different discharge were shown in Figure 4-14.

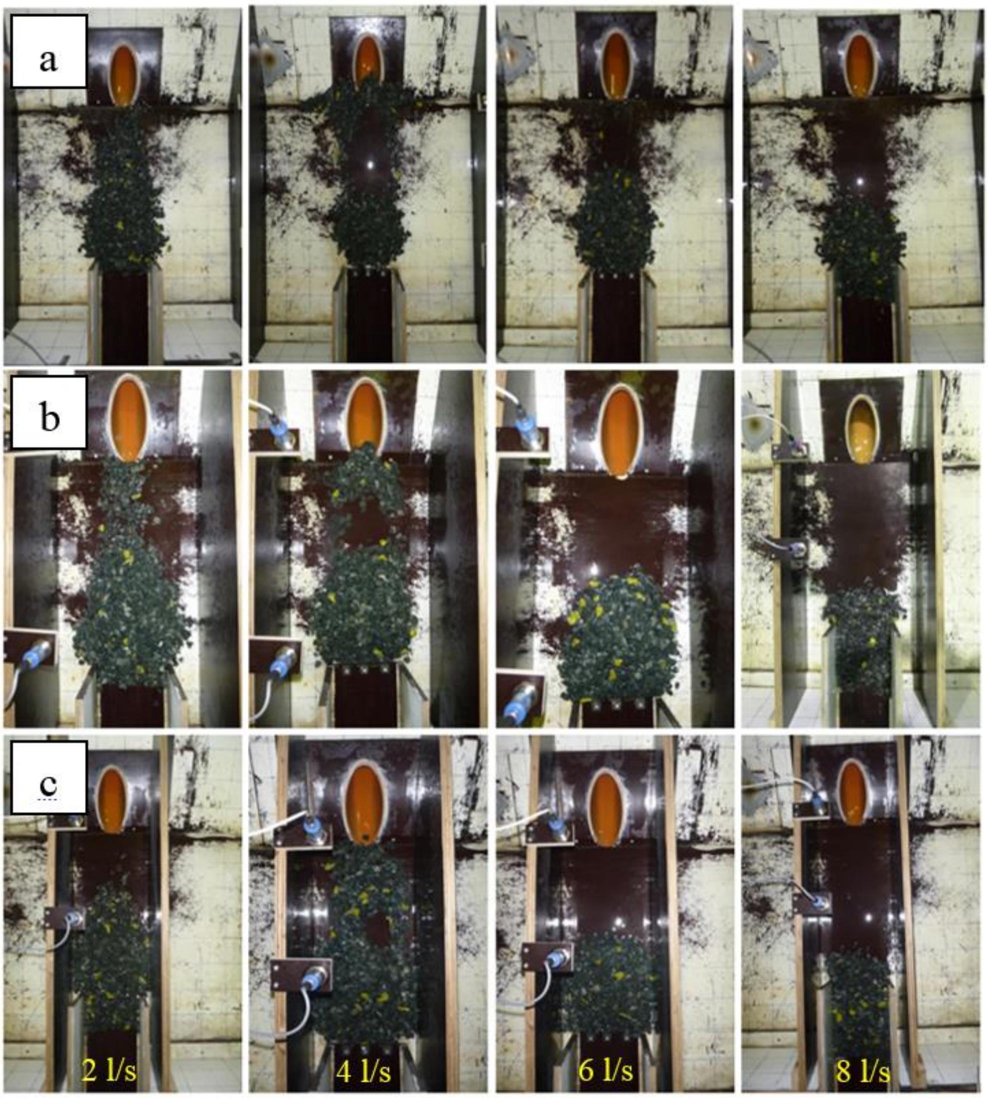

Figure 4-14 Sediment deposition pattern with cut inlet setup with expansion section width of: a) 876 mm, b) 438 mm, and c) 292 mm at Q = 2 l/s, 4 l/s, 6 l/s, 8 l/s respectively

c. Wing wall Inlet

Figure 4-15 shows the ratio of the water depth to the culvert barrel diameter of all expansion section widths with wing wall inlet. Wing wall inlet ended up with similar result to cut inlet. The recurrence behavior was observed with cut inlet, same deposition pattern with cut inlet was also detected. A minor difference noticed implies the sediment amount deposited on the expansion section at Q* = 0.4, with wing wall inlet the sediment transported through culvert barrel was less.

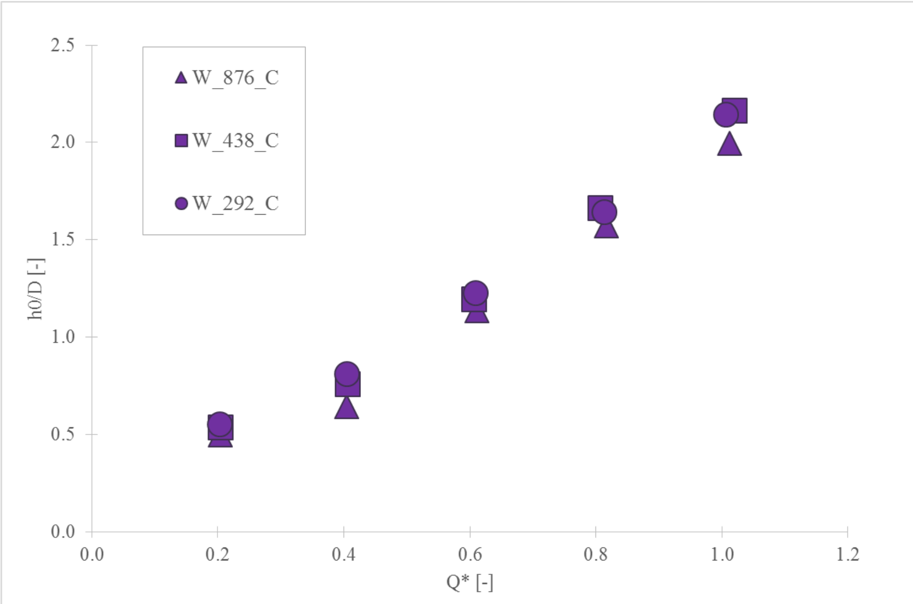

Figure 4-15 Performance curve of wing wall inlet in various widths of expansion section under sediment transport condition

d. All Together

Corresponding to the culvert capacity, Figure 4-16 shows that projecting inlet yielded the highest ratio of h0/D as compared to other inlet types, the second is cut inlet and lastly followed by wing wall inlet which has the least ratio amongst all.

With expansion section width of 876 mm, projecting resulted in the least water depth to culvert barrel diameter ratio, followed by wing wall and cut inlet. At higher discharge, with projecting inlet more sediments were transported through the culvert as shown in Figure 4-17.

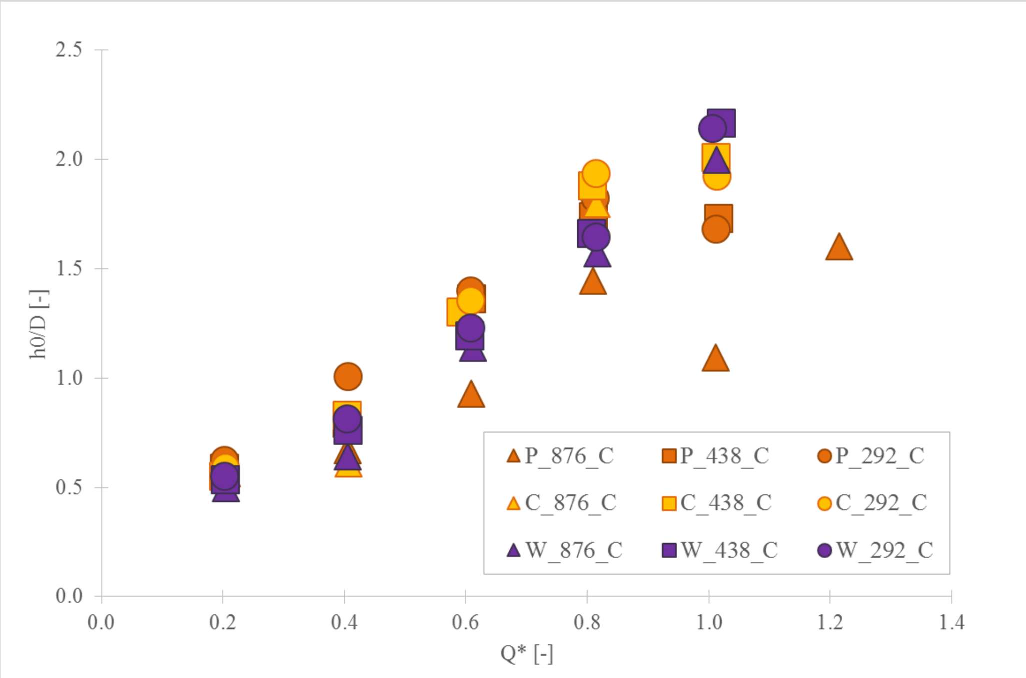

Figure 4-16 Performance curves on hydraulics with different inlet types in various widths of expansion section

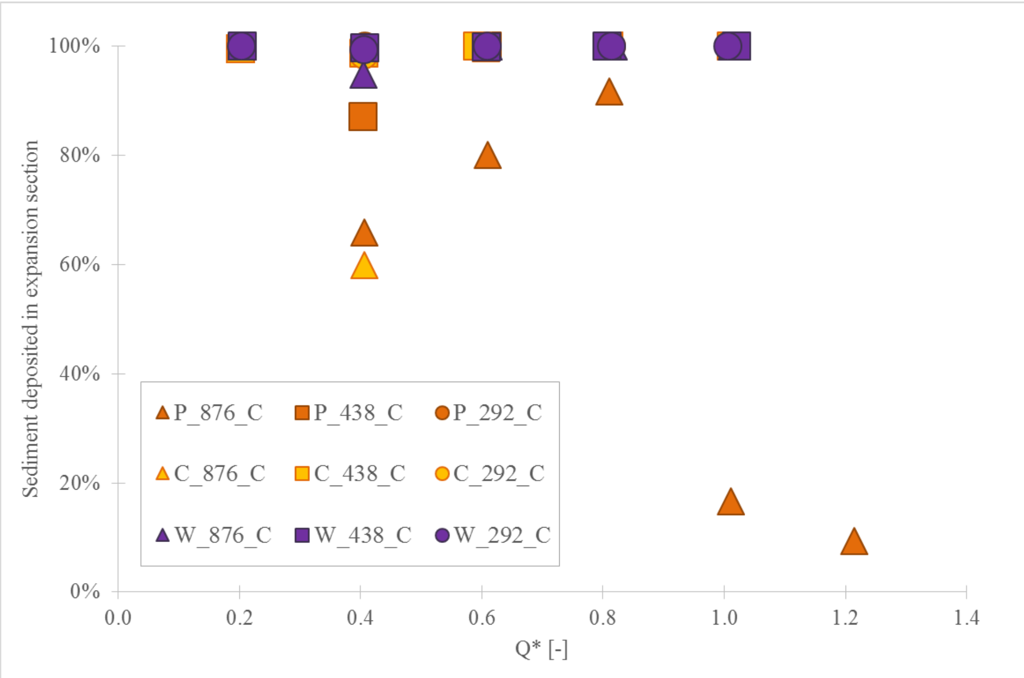

Figure 4-17 Sediment deposited in the expansion section for continuous feeding with different inlet types in various widths of expansion section

As seen in Figure 4-16, with expansion section width of 438 mm, wing wall has the least h0/D ratio, whereas the ratios of cut and projecting inlet are almost overlap each other. At Q* = 0.6, ratio of projecting is higher than cut inlet, but as the discharge increases, cut inlet has a higher ratio than projecting at Q* = 0.8. At Q* = 1.0, ratio of projecting inlet decreases, so cut inlet at this discharge has a higher ratio again. It was observed that at Q = 10 l/s, projecting inlet was operated under outlet control because the culvert barrel flowing full at this discharge, whereas with cut inlet the water depth was higher than the overtopping limit. From the amount of the sediment transported, cut is slightly better than projecting and wing walls, as seen from Figure 4-17. At Q* = 0.4 more sediments were transported with cut inlet. Overall, with expansion section width of 438 mm, wing wall ends up the best, which is then followed by cut and projecting inlet respectively.

With expansion section width of 292 mm, wing wall inlet observed has the minimum ratio, followed by cut inlet and projecting inlet. All sediments were deposited on the expansion section with this width, different inlet types had less influence to the sediment transported.

4.4.2 Discussions

Figure 4-17 shows that wider width has less sediment transport efficiency. The velocity profile of water influenced the movement of the sediment, especially in open channel. With the same discharge, wider expansion section had lower water depth as compared to the narrower one. Water flow in rectangular channel reached its maximum velocity near the surface and minimum when it is closer to the bank. With wide width of expansion section sediments spreading was closer to the surface, therefore, the amount sediment transported was higher.

As seen from Figure 4-16 at Q* = 0.4, sediment transported through the culvert barrel is high, especially with projecting inlet. This phenomenon possibly caused by the inlet configuration combined with hydraulic jump that was higher than the water depth on the expansion section. Projecting inlet configuration caused the inlet entrance experiencing more contraction. Position of the projecting inlet entrance is close to the hydraulic jump, which then caused the sediments transported towards the culvert inlet. With wing wall inlet contraction on the inlet entrance was little and position of the inlet entrance was further back than projecting or cut inlet, therefore sediments transported with this inlet was less as the energy from hydraulic jump was insufficient to push sediments towards the inlet entrance.

Overall from the result presented, projecting has the worst performance on hydraulics although more sediment were transported through the barrel with this inlet. In contrary, wing wall inlet resulted the best performance on hydraulics, yet sediments transported through the culvert barrel were less.

4.5 Effects of the sediment feeding method

Two different methods of sediment feeding, all at once and continuous, were tested to study the effect of different methods of sediment feeding on the culvert capacity with different inlet setup. Results shown below were executed using 7 kg of 8-16 mm sediments with expansion section width of 438mm. The performance curve of other widths are shown in Appendix A.

4.5.1 Results of the experiments and data analysis

a. Projecting Inlet

Figure 4-18 shows how the effect of sediment feeding techniques affected the hydraulics performance of culvert. Overall, feeding the sediment with all at once resulted in a slight higher water depth as compared to continuous.

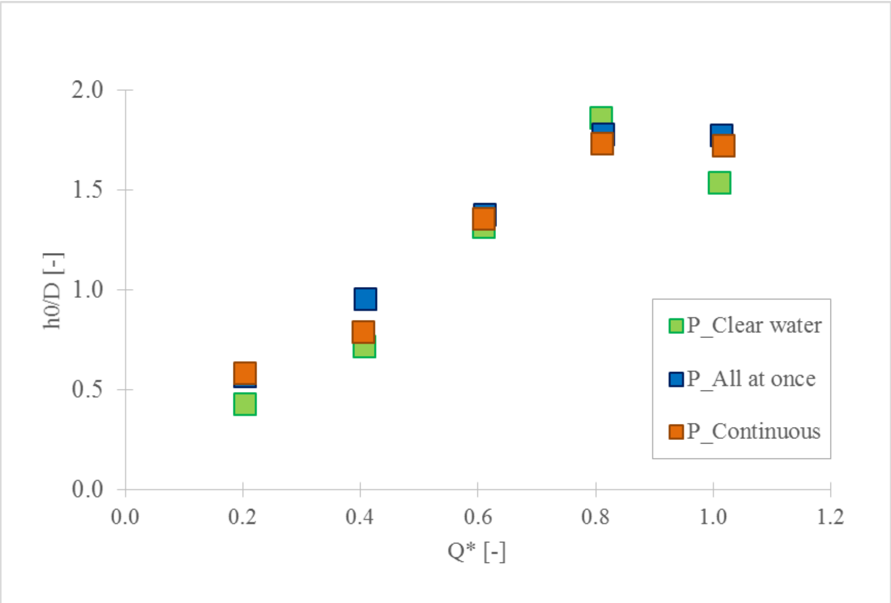

Figure 4-18 Performance curve expansion section width of 438 mm with projecting inlet setup

At Q* = 0.2, continuous feeding yielded almost the same height as the all at once feeding even though the deposition pattern was totally different. With continuous feeding, sediments were deposited scattered on the expansion section, whereas with all at once feeding, sediments were deposited along the approach channel (± 33 cm further from the end of the approach channel).

As mentioned on subchapter 4.3.1 a. that sidewise oscillation occurred with projecting inlet in low discharge. It was observed at Q = 4 l/s with continuous feeding, the oscillation continued even after the sediment feeding finished and the deposited sediments were settled. This was caused by the hydraulic jump on the expansion section that reached almost half of the expansion section length. Vice versa to continuous feeding, with all at once feeding the oscillation disappeared after all sediments had settled. The sediment deposition pattern, shown in Figure 4-19, made the oscillation fall off since the hydraulic jump occurred further back on the approach channel. As the sediments were settled, then it formed as a mass, water depth increases, noticed from Figure 4-18 at Q* = 0.4.

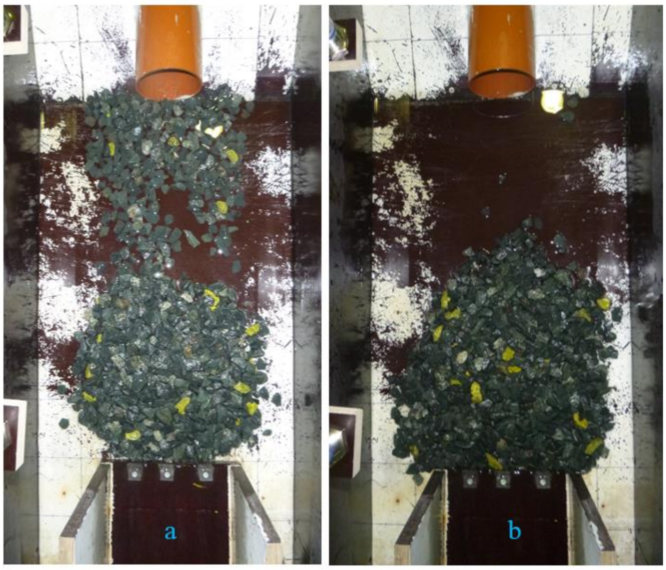

Figure 4-19 Sediment deposition pattern at Q = 4 l/s with: a) continuous feeding, b) all at once feeding

Figure 4-18 shows at Q* = 0.6, ratio of h0/D with both continuous and all at once feeding coincide and this also happen for Q* > 0.6. At Q > 6 l/s, hydraulic jump occurred on the approach channel and sediments deposited right after it. Similar deposition pattern of both feeding methods at Q > 6 l/s yielded a similar depth in the expansion section. Sediment deposition pattern for Q > 6 l/s is shown in Figure 4-20. At Q = 10 l/s culvert was outlet controlled, water depth in the expansion section was lowered after water had stabilized. Therefore, as seen from Figure 4-18, values at Q* = 1.0 shows insignificant difference as compared to Q* = 0.8.

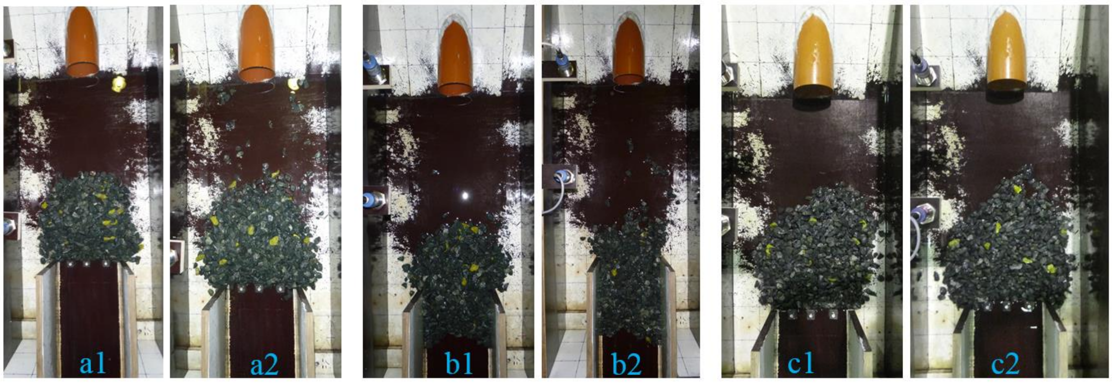

Figure 4-20 Sediment deposition pattern at discharge of a) 6 l/s, b) 8l/s, and c) 10 l/s for 1) continuous feeding and 2) all at once feeding

b. Cut Inlet

Figure 4-21 shows the values coincide for continuous and all at once feeding, therefore, there are marginal height differences developed.

At Q* = 0.2, ratio of h0/D coincide for both methods of feeding. Similar deposition pattern was observed with both ways of feeding. Continuous feeding resulted in the sediment scattered from the end section of the approach channel to the front of the inlet, whereas all at once feeding resulted in the sediment deposited along the approach channel (± 60 cm from the section's end).

At Q* = 0.4, the value of clear water, continuous, and all at once feeding coincide. Result of the water depth development of continuous and all at once feeding at Q = 4 l/s was clearly visualized in Figure 4-22. The graph shows that with continuous feeding water depth changes over time and becomes stable after 540 s. At second of 120, some sediments were settled right after the blocks and moved a little to the front of the inlet, the hydraulic jump induced on the expansion section was drop off. Hence, water depth on the expansion section also decreased. It was observed that sediment feeding finished in 780 seconds, it possibly happened due to the inaccuracy of the vibrating machine. After sore sediments settled near the blocks and some more moved to the inlet entrance, water depth start to increase. Sediment deposition pattern for continuous feeding is shown in Figure 4-23. With all at once feeding, sensors recorded that water depth on the expansion section increases over the time and stabilized after 540 seconds. All sediments clogged in the approach channel exactly after the sediment feeding was finished, thus hydraulic jump occurred on the approach channel. After sometimes, sediments started to move towards the expansion section. The emergence of hydraulic jump made water depth increases significantly and pushed the sediments towards the inlet. Water depth kept developing until the sediment settled and stabilized. Sidewise oscillation also occurred along the experiment with continuous and all at once feeding, but the magnitude decreases over time as more sediments were fed.

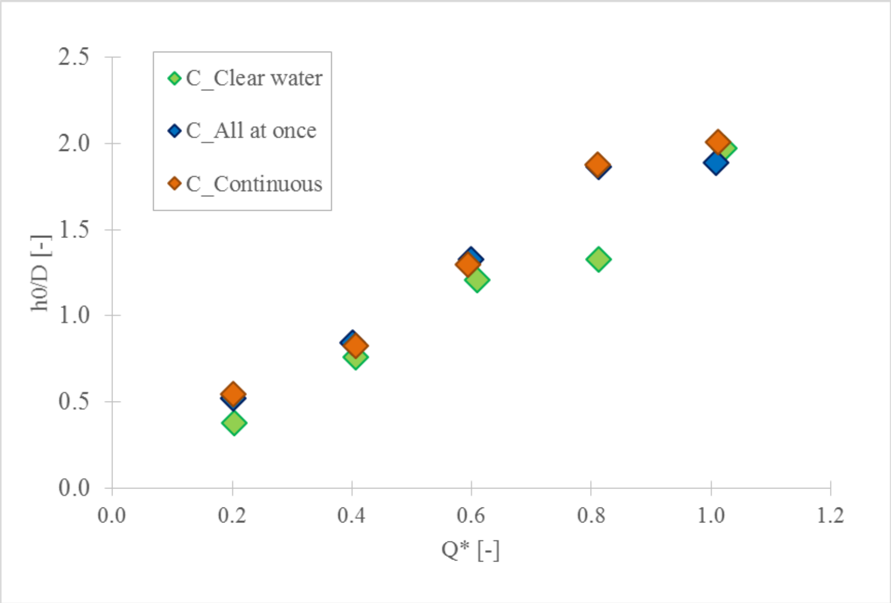

Figure 4-21 Performance curve of 438 mm width of expansion section with cut inlet setup

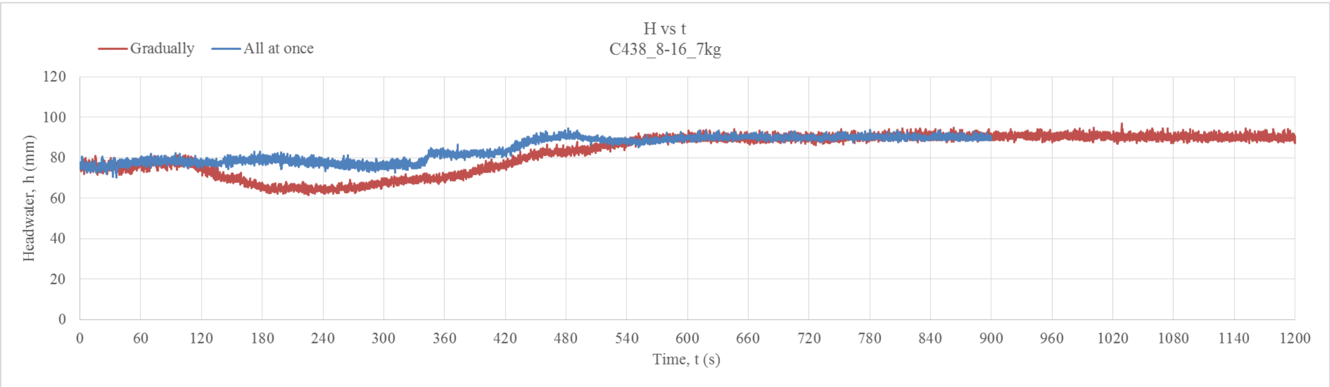

Figure 4-22 Water depth development with continuous and all at once feeding

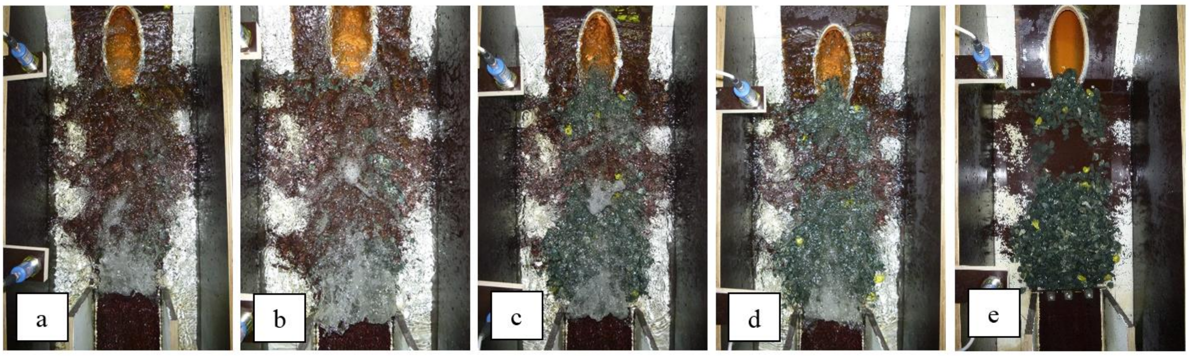

Figure 4-23 Development of the sediment deposition of cut inlet with expansion section width of 438 mm with continuous feeding at Q = 4 l/s after: a) 60 s; b) 120 s; c) 540 s; d) 1080 s; e) >1200 s

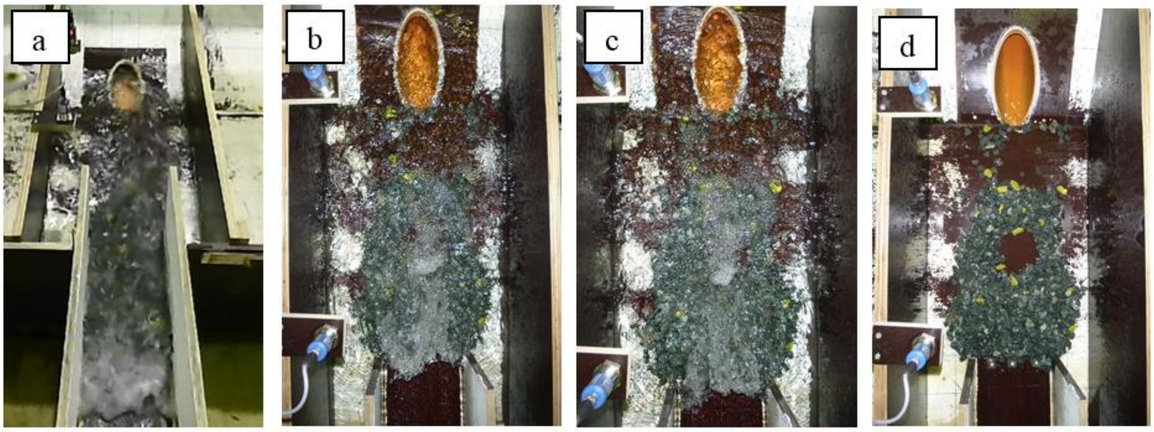

Figure 4-24 Development of the sediment deposition of cut inlet with expansion section width of 438 mm with all at once feeding at Q = 4 l/s after: a) 60 s; b) 480 s; c) 780 s; d) >900 s

With continuous and all at once feeding, it was observed that at Q $\geq$ 6 l/s, water became very turbulent. Figure 4-21 shows that at Q* = 0.8, the value of continuous and all at once feeding were much higher than clear water situation. From the laboratory observation at Q = 8l/s, water depth in the approach channel increased because all of the sediments deposited on the approach channel. At Q = 8 l/s, oscillation resulted in the water would sometimes touched the overtopping limit, but at Q = 10 l/s water depth was obviously greater than the overtopping limit. Sediment deposition pattern of cut inlet at Q $\geq$ 6 l/s were similar to the sediment deposition pattern of projecting inlet.

c. Wing wall Inlet

Figure 4-25 shows in general, with wing wall inlet setup, ratio of the water depth to culvert diameter coincide very well for both methods of feeding.

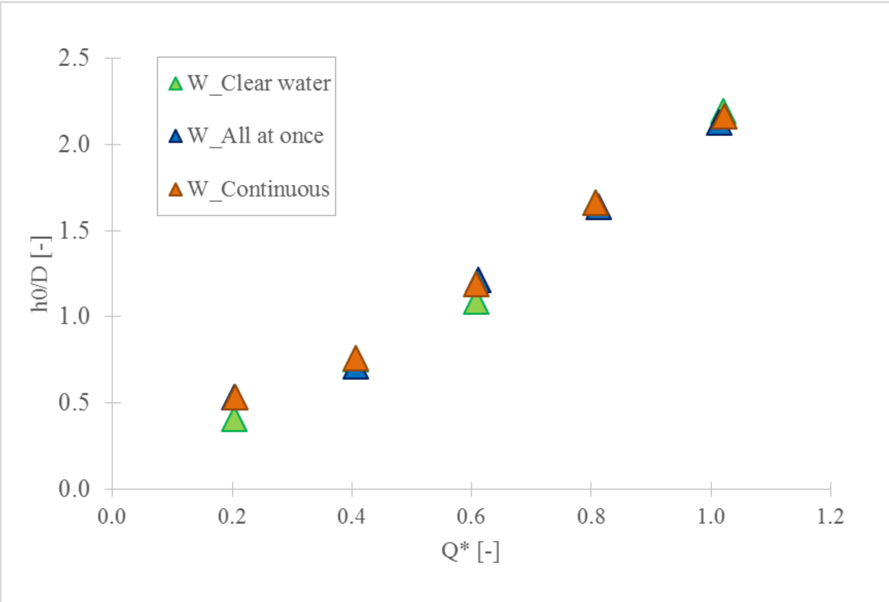

Figure 4-25 Performance curve of 438 mm wide expansion section with wing wall inlet setup

At Q* = 0.2, the value of both methods of feeding yielded at the same point. From the laboratory observation at Q = 2 l/s, no sediments were transported through the culvert with both methods, however, the deposition pattern were different. With continuous feeding, at Q = 2 l/s, all sediments were deposited in the expansion section, whereas for all at once, half of the sediments deposited at the approach channel and the other half deposited after the blocks. Sediment deposition pattern for both methods of feeding is shown in Figure 4-26.

At Q = 4 l/s, with both ways of feeding, some sediments were deposited in expansion section and some transported through the culvert barrel. The deposition pattern was quite different for both methods of feeding. With continuous feeding, sediments experiencing higher pressure, therefore, some sediments deposited near the inlet mouth with a hole developed in the middle of the settlement (similar deposition pattern found with cut inlet at Q = 4 l/s). With all at once feeding sediment deposited after the blocks with less sediment moved towards the inlet.

Hydraulic jump occurred in the approach channel at Q = 6 l/s, 8 l/s, and 10 l/s, therefore, with both methods of feeding, all sediments deposited exactly after the hydraulic jump and resulted in similar deposition pattern. At Q = 6 l/s and 8 l/s almost of the sediments deposited after the blocks because at these discharges, hydraulic jump emerged close to the end of the approach channel. At Q = 6 l/s hydraulic jump occurred exactly before the blocks, while at Q = 8 l/s hydraulic jump occurred more or less 30 cm further from the end of approach channel.

With wing wall inlet setup, only little differences observed in the sediment deposition pattern and the water depth for with ways of feeding. Example of the sediment deposition pattern shown in Figure 4-26.

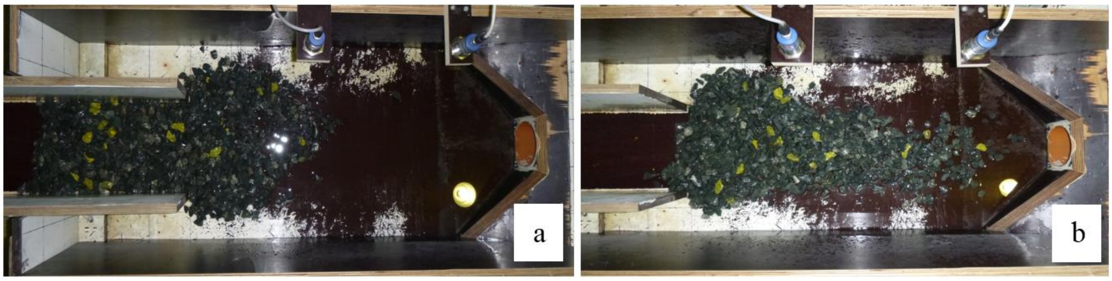

Figure 4-26 Sediment deposition pattern of wing wall inlet with expansion section of 438 mm at Q = 2 l/s with: a) all at once feeding; b) continuous feeding

d. Sediment Amount

Table 4-1 shows sediment transport efficiency with expansion section width of 438 mm with both methods of sediment feeding. Most of the sediments were not transported through the culvert barrel with all inlet types. The table reveals that projecting performed better than other inlet types, although only 14% of the sediment materials were transported. Results for other inlet types and width are tabulated in Appendix B.

Table 4-3 Amount of sediment deposited in the expansion section width of 438 mm with 7 kg of sediments

Width of 438 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	99.5 %	99.5 %	100.0 %	100.0 %	100.0 %	100.0 %
4	86.9 %	98.7 %	99.6 %	99.5 %	99.5 %	99.5 %
6	100.0 %	100.0 %	99.8 %	99.7 %	100.0 %	99.8 %
8	100.0 %	100.0 %	100.0 %	98.9 %	100.0 %	100.0 %
10	100.0 %	100.0 %	100.0 %	99.6 %	100.0 %	100.0 %

4.5.2 Discussions

From the test results above and the data on Appendix A, it is observed that methods of sediment feeding have less influence to the culvert capacity, as seen from the ratio of h0/D with both ways of feeding and clear water condition sometimes overlap. However, feeding the sediment continuously will give a better culvert capacity.

Sediment deposition pattern and hydraulic jump emergence affects water depth in expansion section. Sediment tend to deposited exactly after the emergence of hydraulic jump. From the experiments it was observed that if the hydraulic jump occurred at the approach channel, the sediment will obviously deposited there. This happened caused by the velocity profile on a rectangular channel, also describe in section 4.1.2, which then resulted in most of the sediments did not transported further and triggered them to deposit as a mass. Nevertheless, it affects significantly on the proportion of the sediment transported through the culvert and deposited before the inlet.

Results in Table 4-3 and Appendix B shows amount of the sediment deposited in expansion section for every inlet types. From the table it reveals that the methods of sediment feeding has little influence on the sediment transport efficiency. However, continuous feeding method observed to be the best with regards to the amount of the sediment transported.

In general, continuous feeding in combination with projecting inlet give the best performance, which is then followed by cut and wing wall inlet.

4.6 Effects of the sediment size

Two different sediment grain size of 8-16 mm and 16-32 mm were tested to investigate how the sediment size effect the culvert performance. Results shown below are the result of the experiments with projecting inlet setup and expansion section width of 876 mm. Total of the sediment used in this experiment was 7 kg with continuous and all at once feeding.

4.6.1 Results of the experiments and data analysis

Figure 4-27 and Figure 4-28 show the ratio of h0/D and amount of sediment deposited in the expansion section for both sediment sizes in line most of the time. Sediment size has less influence on the development of water depth and the amount of sediment deposited in expansion section. From the observation it was found that the deposition pattern of the sediment was similar for both sediment size. Sediment deposition pattern for sediment fed continuously is shown in Figure 4-29, similar pattern observed for with all at once feeding.

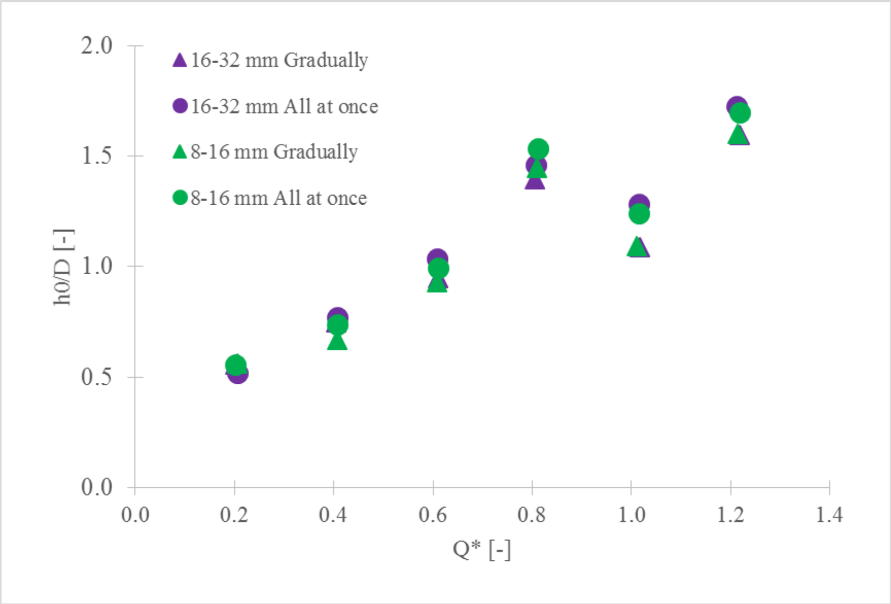

Figure 4-27 Sediment size effects on expansion section of 876 mm with projecting inlet

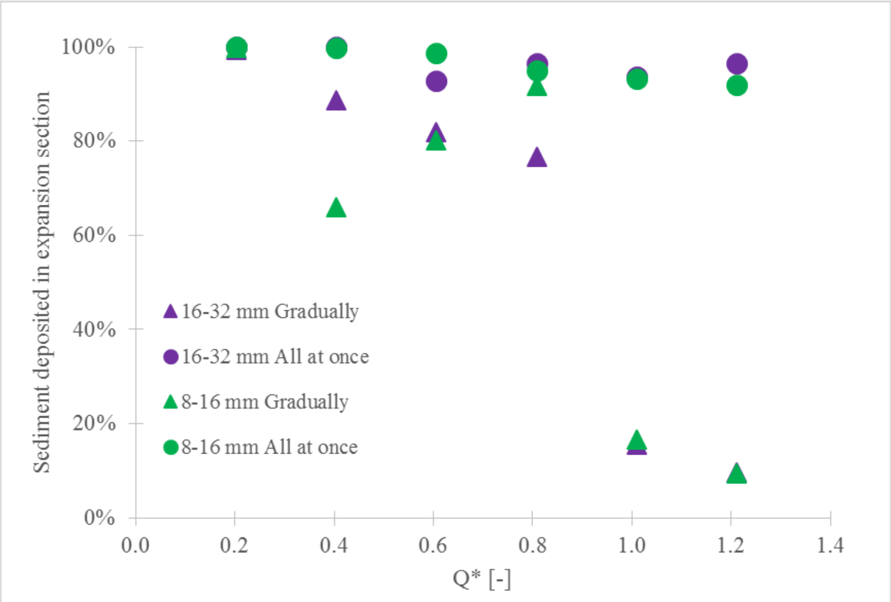

Figure 4-28 Sediment amount deposited in expansion section for the 876 mm wide with projecting inlet

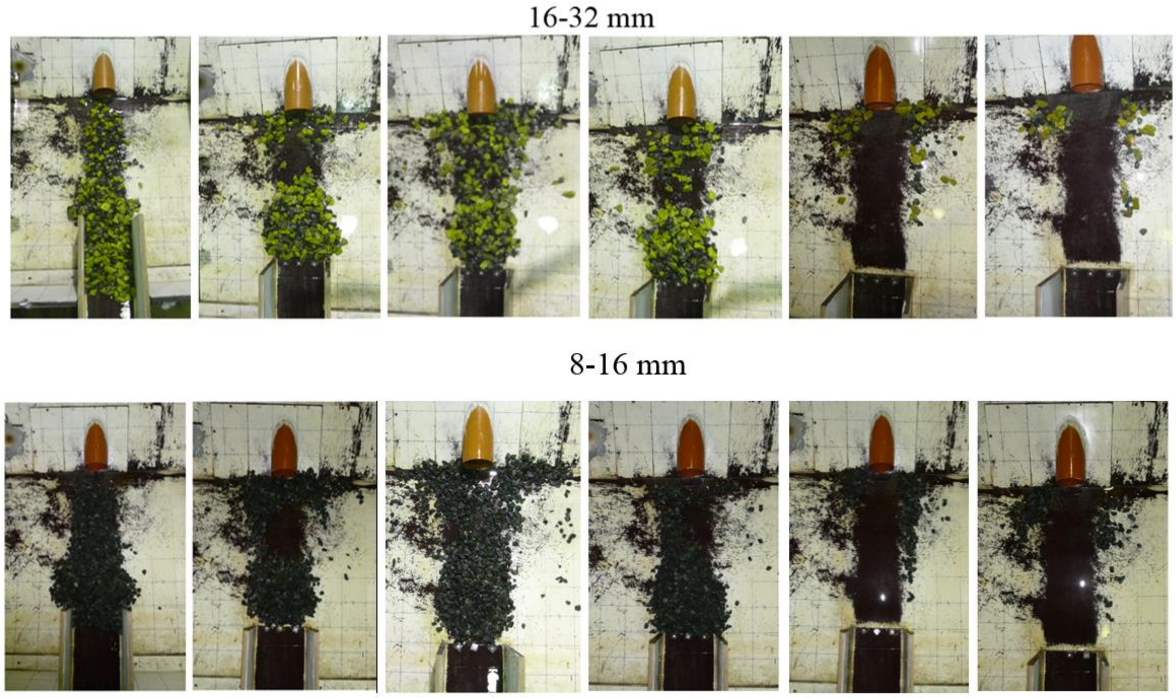

Figure 4-29 Sediment deposition pattern with continuous feeding for different sediment grain sizes

4.6.2 Discussions

Sediment size effects on the culvert performance was previously studied by Gotvassli and Hendler. From the study conducted by Gotvassli, without energy dissipaters installed in 1:5 slope of the approach channel with continuous sediment feeding, it was found that sediment size had less influence on the culvert performance. In the next study using a wing wall inlet with energy dissipater blocks installed on the approach channel of 1:5 slope with all at once sediment feeding, Hendler found that sediment deposition pattern is the same for both sediment sizes. In the present study, using projecting inlet with 1:9 slope of approach channel and blocks installed, it was observed from the water depth, the composition of the sediment deposited in the expansion section, and its deposition pattern which describe above, sediment size was obviously had less influence on the culvert performance.

4.7 Effects of the sediment amount

To investigate if the amount of sediment influence on the culvert performance, two different amount of sediment, 5 kg and 7 kg, were tested with expansion section width of 876 mm using 8-16 mm grain size.

4.7.1 Results of the experiments and data analysis

a. With continuous feeding

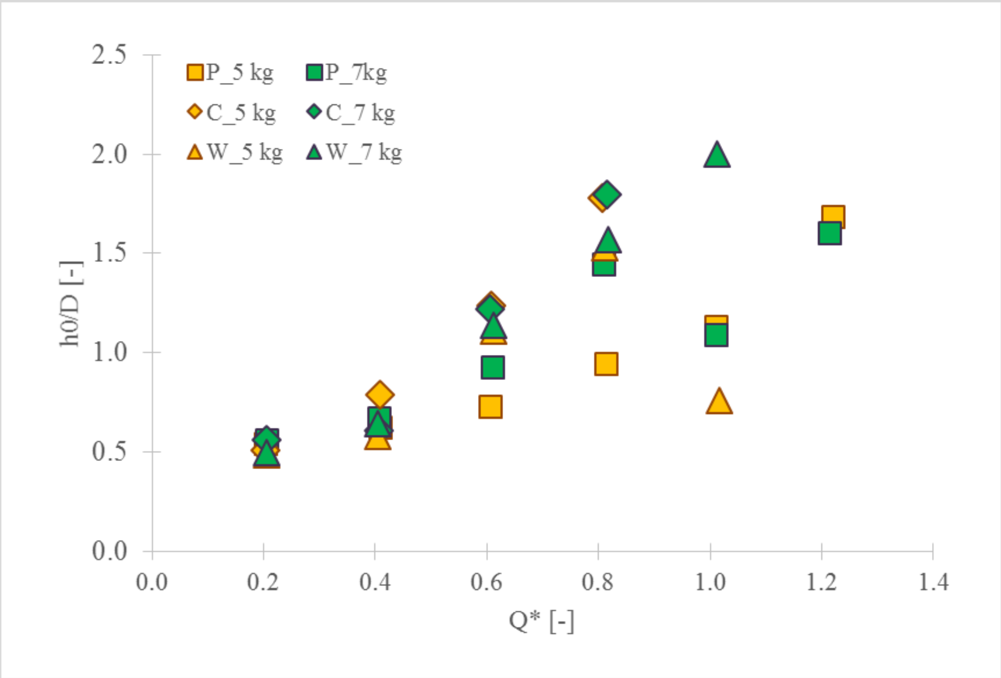

Figure 4-30 Performance curve of various inlet types (P: Projecting, C: Cut, W: Wing wall), in expansion section of 876 mm with continuous feeding

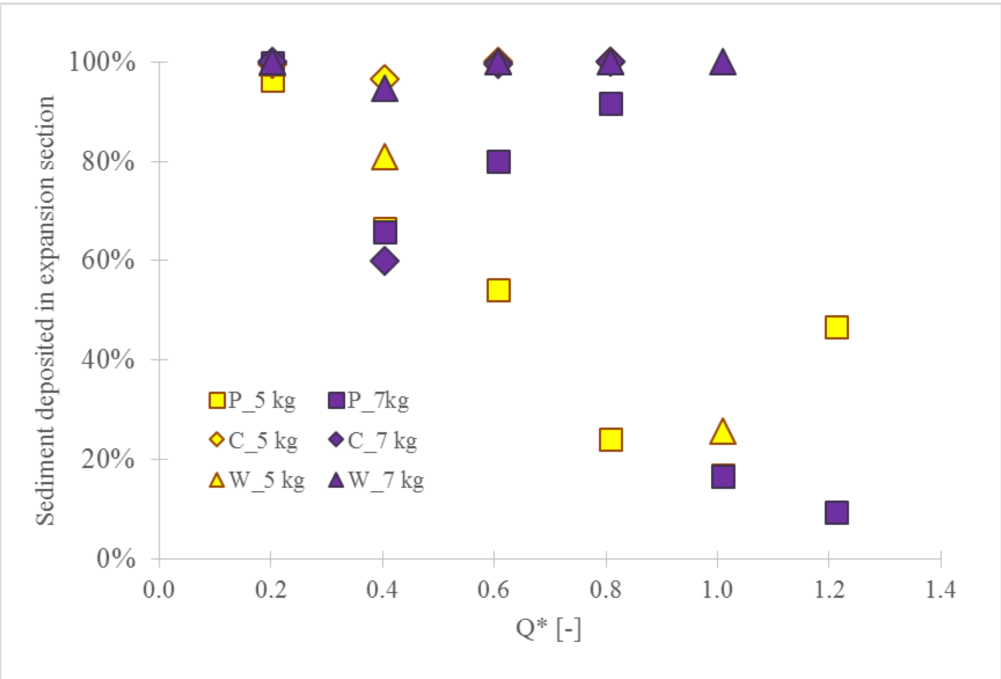

Figure 4-31 Amount of sediment deposited in expansion section of 876 mm with various inlet types (P: Projecting, C: Cut, W: Wing wall) and continuous feeding

With projecting inlet, Figure 4-30 and Figure 4-31 show that ratio of h0/D at Q* = 0.2 and 0.4 and sediment transported through the barrel coincide with both amounts. The deposition pattern of the sediment was similar with both amounts. Difference noticed at Q* = 0.6, 5 kg of sediment gives lower ratio of h0/D and more sediments are transported as compared to 7 kg. The sediment deposition pattern were totally different for both amounts, shown in Figure 4-32. Sidewise oscillation still occurred after all the sediment has been added, but with 7 kg of sediment water depth increased a lot. At Q* = 0.8 more sediments are transported through the barrel with 5 kg of sediment. With 7 kg of sediment water depth in expansion section increased a lot after half of the sediments amount were fed, thus hydraulic jump occurred further from the approach channel's end, as shown in Figure 4-33. At Q* = 1.0 and above, more sediments were transported through the culvert barrel as the outlet was flowing full at these discharges. When outlet was flowing full, pressure on the inlet entrance was high enough to push the sediments moved towards inlet.

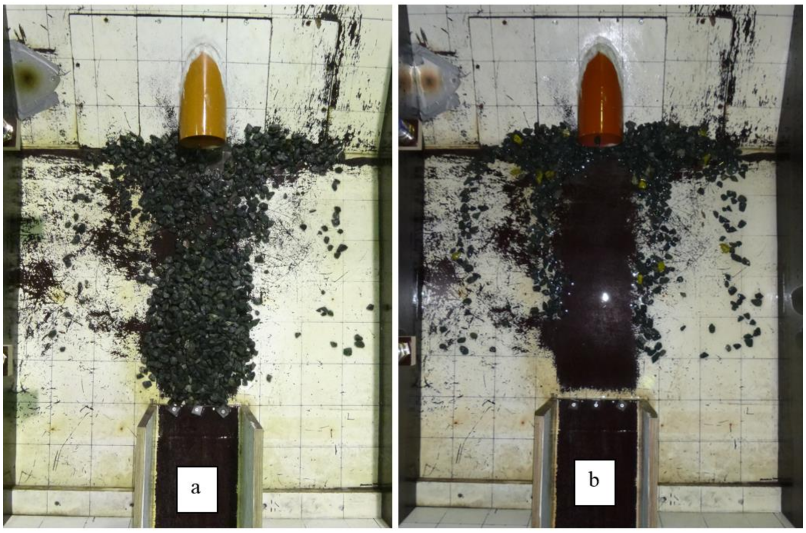

Figure 4-32 Sediment deposition pattern with projecting inlet with expansion section of 876 mm at Q = 6 l/s using sediment amount of: a) 7 kg; b) 5 kg

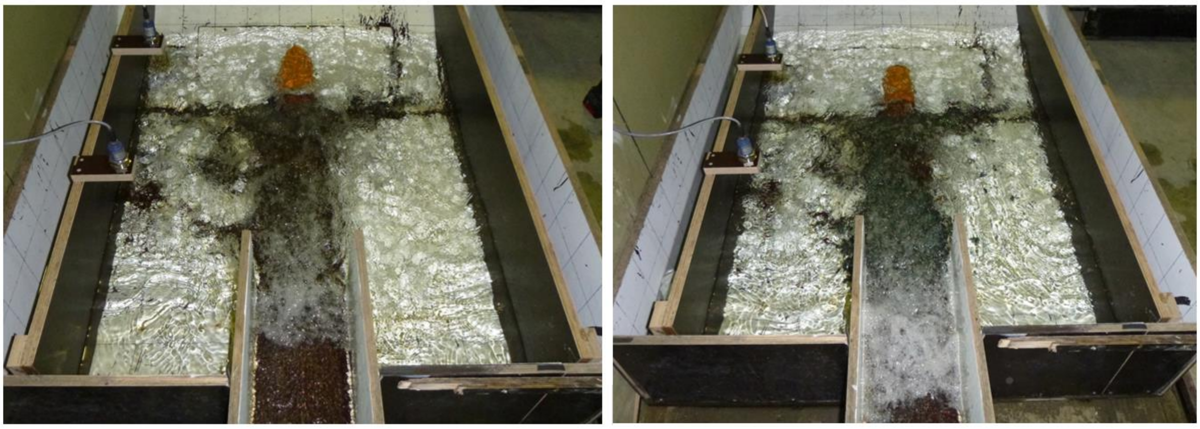

Figure 4-33 Changes on the water depth at 8 l/s with 7 kg amount of sediment

With cut inlet, h0/D ratio and amount of sediment deposited in expansion section coincide well for 5 kg and 7 kg, with an exception for the value at Q* = 0.4, more sediments passed through the culvert when 5 kg was added. However, deposition pattern of sediment was similar for both amounts, as shown in Figure 4-34. In experiment with a 5 kg of sediment the blocks installed at the approach channel were loose, therefore, before starting a 7 kg experiment blocks were tightened. Consequently, energy produced from the hydraulic jump was higher after the blocks were tightened. This may be a reason of more sediments transported with 7 kg. At $Q^* \geq 0.6$, h0/D ratio and amount of sediment deposited in expansion section are typical for 5 kg and 7 kg. This happened because from the laboratory observations it was found that at $Q \geq 6$ l/s, hydraulic jump occurred at the approach channel and all sediments deposited exactly after it.

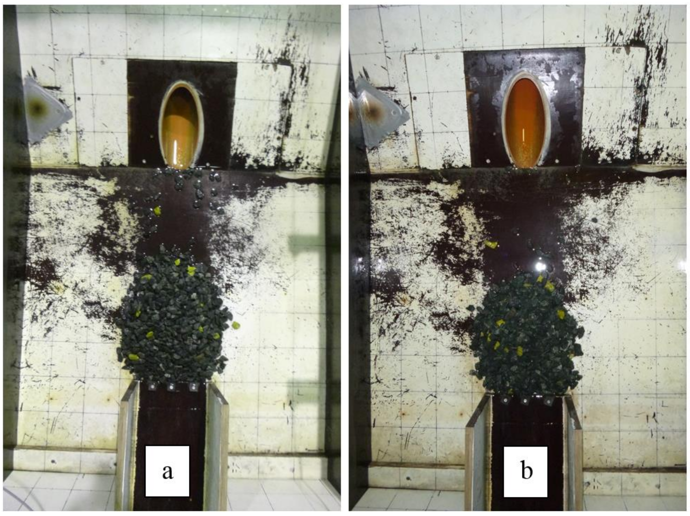

Figure 4-34 Sediment deposition pattern with cut inlet with expansion section of 876 mm at Q = 4 l/s using sediment amount of: a) 7 kg; b) 5 kg

In the experiment with wing wall inlet, most of the time, h0/D ratio and amount of sediment deposited in expansion section coincide well for both 5 kg and 7 kg. The differences noticed is at Q* = 0.4 and 1.0, more sediments are transported with 5 kg. At Q* = 1.0, huge amount of sediments were transported with 5 kg caused by differences on the hydraulics (mentioned in section 4.3.1 c). In the experiment with 5 kg, outlet was flowing full, thus, the pressure towards inlet was higher, thus more sediments transported. With 7 kg, water depth in expansion section and approach channel was much higher, while the outlet was not flowing full (shown in Figure 4-35), therefore, no sediments were transported.

Figure 4-35 Hydraulics and deposition pattern with wing wall inlet at 10 l/s using sediment amount of: a) 7 kg, b) 5 kg

b. With all at once feeding

Using 5 and 7 kg of sediments, tests with all at once feeding gave similar pattern result to the continuous feeding. Ratio of h0/D and sediment transported through the barrel were quite similar with continuous feeding, even more sediments were transported with continuous feeding.

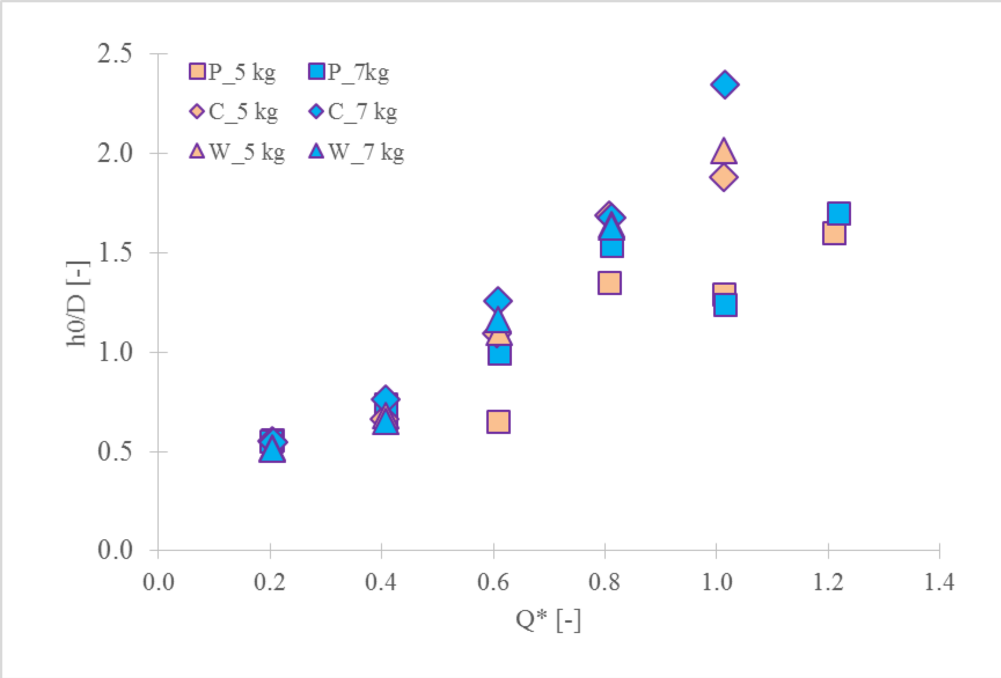

Figure 4-36 Performance curve of various inlet types (P: Projecting, C: Cut, W: Wing wall) in expansion section of 876 mm with all at once feeding

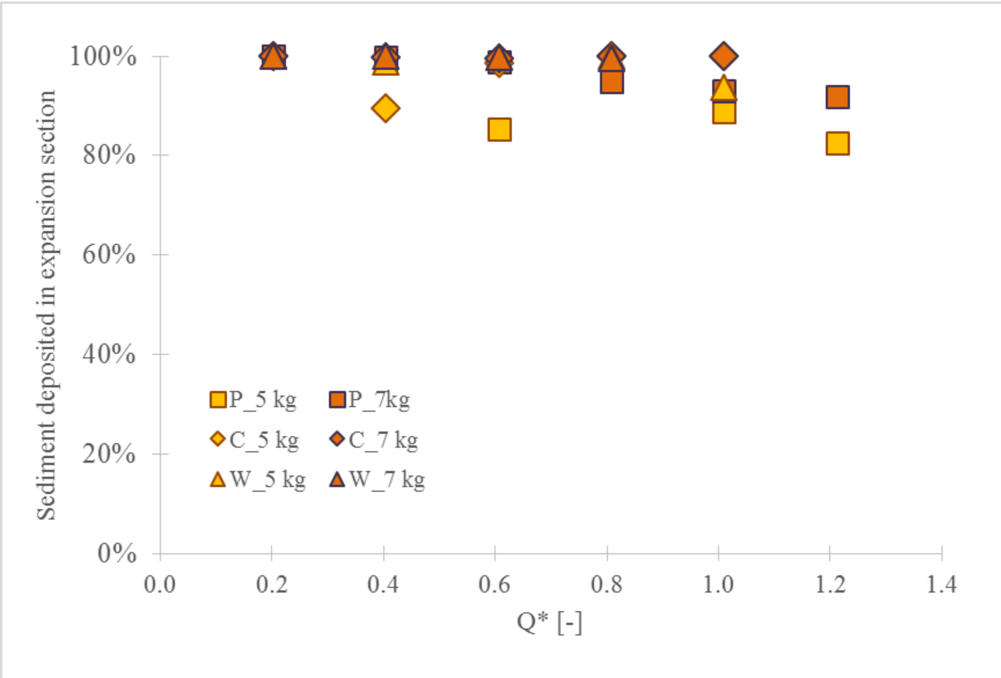

Figure 4-37 Amount of sediment deposited expansion section width of 876 mm with various inlet types (P: Projecting, C: Cut, W: Wing wall) and all at once feeding

4.7.2 Discussions

Amount of sediment have less effect on the culvert capacity. As seen in Figure 4-30 and Figure 4-36, using 5 or 7 kg of sediment did not affect a lot on the water depth. For both amounts with the same inlet, the value coincide many times. With regards to the culvert performance, inlet configuration has more effects than the amount of the sediment. In general, projecting inlet gives the best culvert capacity and more sediment were transported. The second is wing wall inlet and followed by cut inlet. The result presented was different from the result obtained by Gotvassli on her previous experiment. Without blocks installed at the approach channel, amount of the sediment influences the performance of the culvert, especially for projecting and cut inlet.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the experimental observations and data analysis, following conclusions are made:

- Expansion channel width influences the culvert performance. Narrow width gives best culvert performance and comparable to the guideline.
- Under sediment transport conditions, width of the expansion section influences the amount of the sediment deposited.
    - Water depth and the emergence of hydraulic jump on the channel are influenced by the width of the expansion channel.
    - Wide widths are exposed to higher energy caused by the hydraulic jump. Therefore, more sediments transport towards the inlet.
    - Narrow widths result in less sediment being transported through the culvert.
- Deposition pattern of the sediment is associated with the hydraulic jump location. Sediments tend to deposit right after the hydraulic jump emergence.
- The best order of inlet setup related to the hydraulic capacity:
    - Wing wall, cut, and projecting inlet
- The best order of inlet setup related to the amount of sediments transported:
    - Projecting, cut, and wing wall
- In general, sediments reduce the hydraulic capacity of the culvert. Nevertheless, ways of feeding, size, and the amount of the sediments has insignificant influence to the culvert's performances.

5.2 Recommendations

The laboratory work has shown promising results for further study, however some uncertainties on the results may exist. Due to the number of tests done within this project, only limited aspects have been analyzed. Following are the other investigation aspects and improvements that could be made in future experiments:

- Extension to other inlet geometries and various culvert entrance
- Consideration of environmental issues in the study
- Installation of a sensor on the culvert barrel to give a better measurement result
- Improvement on the model to avoid leakage problems

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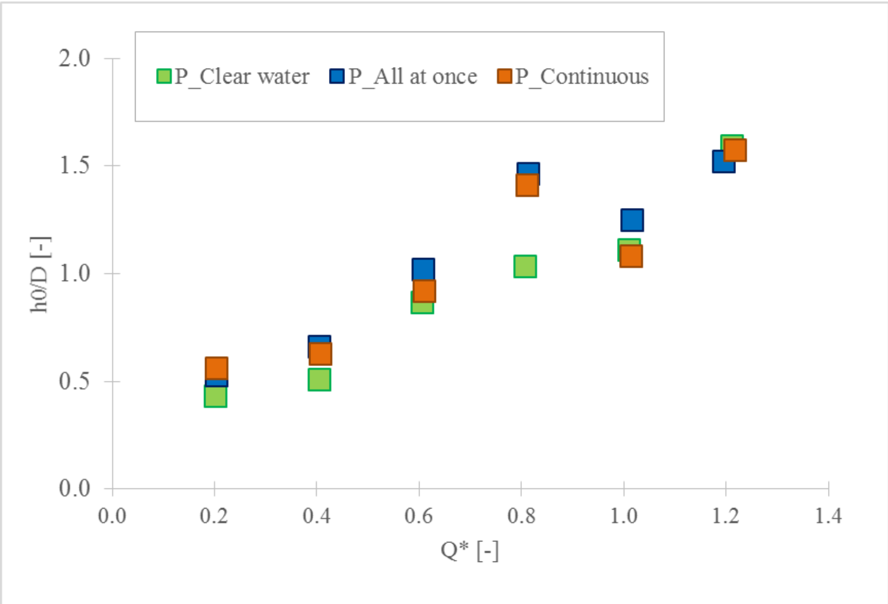
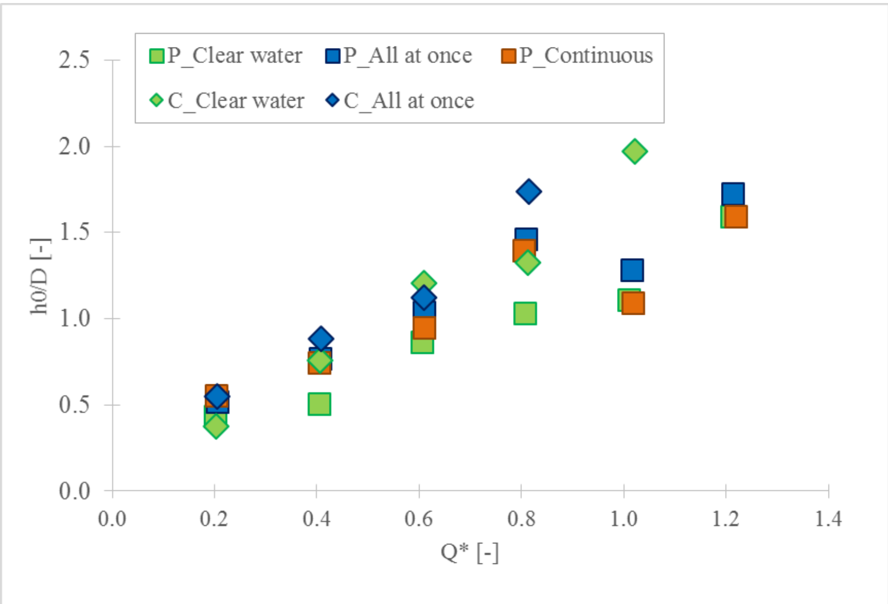
Appendix A

Performance Curve of varying expansion section widths

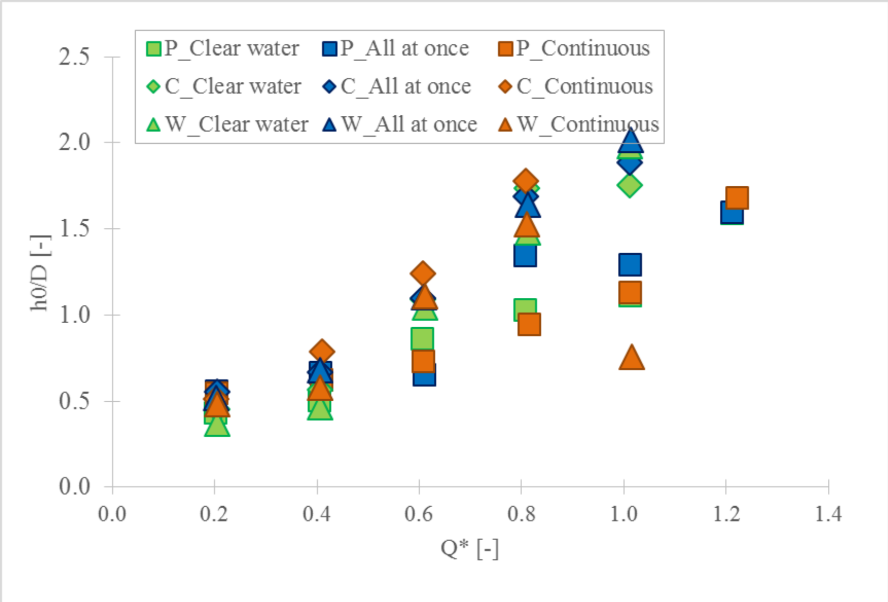
A.1 Performance curve of expansion channel width of 876 mm with sediment size of 16-32 mm and weight of 5 kg



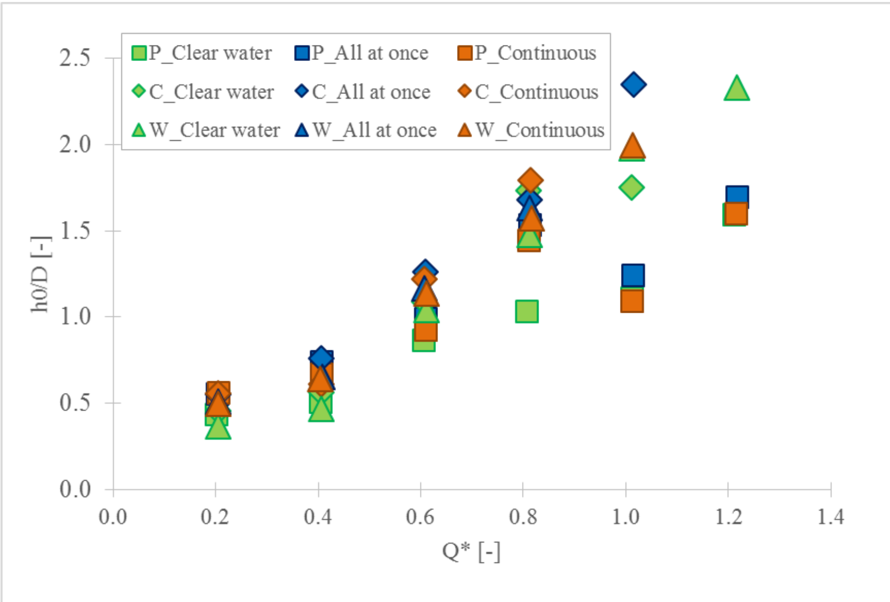
A.2 Performance curve of expansion channel width of 876 mm with sediment size of 16-32 mm and weight of 7 kg



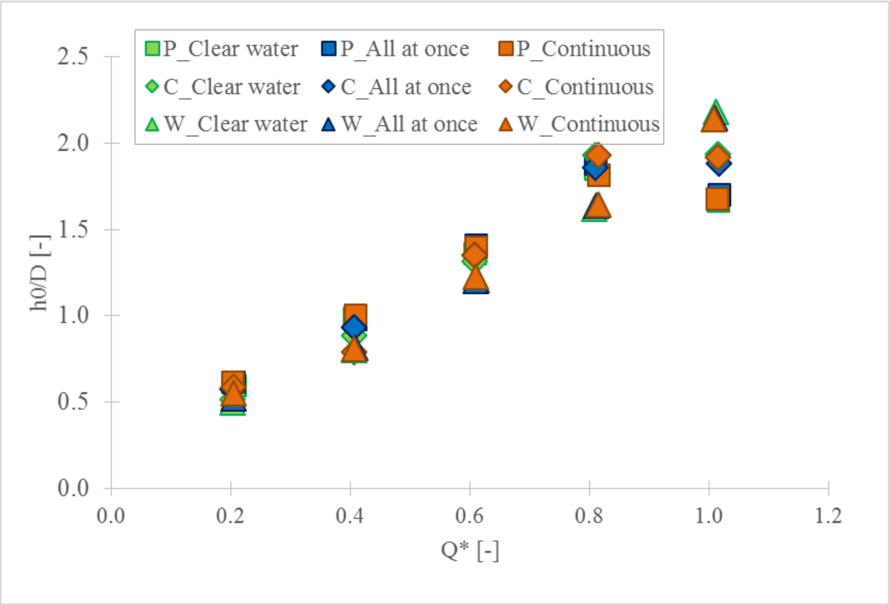
A.3 Performance curve of expansion channel width of 876 mm with sediment size of 8-16 mm and weight of 5 kg



A.4 Performance curve of expansion channel width of 876 mm with sediment size of 8-16 mm and weight of 7 kg



A.5 Performance curve of expansion channel width of 292 mm with sediment size of 8-16 mm and weight of 7 kg



Appendix B

Amount of deposited sediment in expansion section

B.1 Amount of sediment deposited with expansion section of 876 mm and total weight of 5 kg and sediment size of 16-32 mm

Width of 876 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	99.4 %	-	-	100.0 %	-	-
4	78.4 %	-	-	100.0 %	-	-
6	77.7 %	-	-	98.1 %	-	-
8	98.8 %	-	-	85.8 %	-	-
10	24.7 %	-	-	89.4 %	-	-
12	17.0 %	-	-	92.72 %	-	-

B.2 Amount of sediment deposited with expansion section of 876 mm and total weight of 7 kg and sediment size of 16-32 mm

Width of 876 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	99.4 %	-	-	100.0 %	100.0 %	-
4	88.7 %	-	-	100.0 %	100.0 %	-
6	81.9 %	-	-	92.8 %	94.3 %	-
8	76.6 %	-	-	96.6 %	100.0 %	-
10	15.6 %	-	-	93.7 %	-	-
12	9.7 %	-	-	96.49 %	-	-

B.3 Amount of sediment deposited with expansion section of 876 mm and total weight of 5 kg and sediment size of 8-16 mm

Width of 876 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	96.3 %	99.7 %	99.9 %	100.0 %	100.0 %	100.0 %
4	66.4 %	96.6 %	80.9 %	99.0 %	89.6 %	98.8 %
6	54.3 %	100.0 %	100.0 %	85.3 %	98.7 %	99.9 %
8	24.1 %	100.0 %	100.0 %	95.4 %	100.0 %	100.0 %
10	16.9 %	-	25.8 %	88.8 %	100.0 %	93.7 %
12	46.8 %	-	-	82.67 %	-	-

B.4 Amount of sediment deposited with expansion section of 876 mm and total weight of 7 kg and sediment size of 8-16 mm

Width of 876 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	99.9 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %
4	65.9 %	59.9 %	94.8 %	99.8 %	99.9 %	100.0 %
6	80.1 %	99.7 %	100.0 %	98.8 %	99.6 %	99.8 %
8	91.6 %	100.0 %	100.0 %	95.0 %	100.0 %	99.6 %
10	16.7 %	-	100.0 %	93.2 %	100.0 %	-
12	9.3 %	-	-	91.9 %	-	-

B.5 Amount of sediment deposited with expansion section of 292 mm and total weight of 7 kg and sediment size of 8-16 mm

Width of 292 mm	Sediment deposited in expansion section					
Ways of adding	Gradually			All at once		
Discharge (l/s)	Projecting	Cut	Wingwalls	Projecting	Cut	Wingwalls
2	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %
4	100.0 %	98.3 %	99.2 %	99.8 %	99.9 %	99.9 %
6	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	99.4 %
8	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %
10	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %