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Physical Model Tests of Intake Design

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MASTER THESIS SPRING 2013

Student: ***Ida Elisabeth Sørbø Gotvassli***

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Title: **PHYSICAL MODEL TESTS OF INTAKE DESIGN**
Tittel: FYSISKE MODELLFORSØK AV INNTAKSUTFORMING

1 INTRODUCTION

The flow capacity of intakes in watercourses is highly dependent on locale hydraulic conditions and the amount of debris, sediments and ice at the intake area. Both culvert inlets and intakes for hydro power plants in shallow rivers are subjected to risk of reduced capacity or complete blockages due to deposition and accumulation of sediments and debris. There is restricted amount of literature on the effect of the reduction of culvert inlet cross sectional area caused by accumulation of debris and sediments on the intake capacity. And there are no detailed guidelines for the design of culverts including sediments and debris. Likewise, guidelines for good intake design principles for shallow intakes for hydropower plants including sediment handling, debris, leaves, ice (frazil ice and ice drift), entrainment of air, and general hydraulic conditions are restricted. It is a major challenge to meet all the sometimes incompatible requirements in the design of an intake in a shallow river with rapid flow.

2 BACKGROUND

Statens Vegvesen has initiated a project for developing new guidelines for culverts including the effect of debris and sediments. NTNU Vassdragslaboratoriet is contributing to development, verification and innovation within the area of intake hydraulics. In order to study intake hydraulics and intake design for culverts, a physical hydraulic model was constructed in a scale 1:10 in the Vassdragslaboratoriet. The main objective for Statens Vegvesen with this project is to find applicable design criteria for culverts. In the last couple of years it has been studied the possibility of cleaning intake screens with back flushing instead of the conventional method of manual or mechanical cleaning. Back flushing implicate for a short period to let water flow over the rack with the opposite direction to normal operation, and divert loosened debris/trash out of the intake pond. The candidate has in the project work during autumn 2012 studied characteristics of debris adhesion to trash rack both in literature and in the field. Based on gained experiences for debris performance on trash racks and on inlet performance for the culvert inlet tests, a design of an intake optimized for efficient debris and sediment handling, with so called back flushing will be tested in the same test rig as the culvert tests.

3 PROBLEM DESCRIPTION

The physical model tests of intake design will be done in two separate parts. Both test series in the physical model at Vassdragslaboratoriet, NTNU, will be conducted during the spring 2013. The first part will be to conduct test for establishing discharge curves for culverts with and without effect from accumulated sediments and debris. A test program with variations of inlet design, flow conditions and different types of debris and sediments should be designed in cooperation with Statens Vegvesen. The results from the tests should be systematized and thoroughly reported. The second part will be to assess the performance of an intake structures with flushing facilities. The hydraulic conditions through the horizontal racks both during normal operation and during flushing must be studied. The efficiency of the cleaning process of both debris and sediments should be quantified and the operation and maintenance of the intake structure must be assessed. Design recommendation based on the physical model should be given.

4 GOAL

The overall goal of the master thesis is to gain experiences with intake hydraulics from physical models. A specific goal is to establish discharge curves for culverts with and without the effect of debris and sediment accumulation in front of the intake. A recommendation for the design of an intake structure providing for efficient debris and sediment handling based on the physical model study should be provided. Uncertainties and errors should be evaluated. It should be concluded on whether the work has been successful and if there should be conducted further studies.

5 CONTACT PERSONS

NTNU	Leif Lia, Professor (supervisor)
	Hanne Nøvik, PhD-student (co-supervisor)
	Jochen Aberle (Project manager)
Statens vegvesen	Harald Norem

Discussions with colleagues and employees at NTNU, SINTEF and eventually other hydro power plants are recommended. All contributions should be correctly referred.

6 REPORT FORMAT, REFERNECES AND CONTRACT

The report should be written with a text editing software, and figures, tables, photos etc should be of good quality. The report should contain an executive summary, a table of content, a list of figures and tables, a list of references and information about other relevant sources. The report should be submitted electronically in B5-format .pdf-file in DAIM, and three paper copies should be handed in to the institute.

The executive summary should not exceed 450 words, and should be suitable for electronic reporting.
The Master's thesis should be submitted within Monday 10th of June 2013.

Trondheim, 14th of January 2013

Leif Lia	Hanne Nøvik
Professor	PhD-student

Abstract

As there are no detailed guidelines on how to design culverts including sediments and debris, a laboratory model was made to find solutions to how sediments deposit in front of the culvert and how this affects the capacity. The model consisted of a collecting reservoir, receiving the water from the pumps. From the reservoir an approach channel led the water down to a basin, and further through the culvert. The main focus was to create a test program with variation of different effects, including the inlet shape, basin length, slope of the approach channel, how the sediments were added and the size and amount of the sediments. From these effects, performance curves were established to find the influence on the capacity, and when the water level overtopped the filling.

The results from the experiments did not give an absolute solution to how the sedimentation problems should be solved, but good upstream geometries to reduce the risk of overtopping was found. At different discharges, the inlet shape was found to be the most influencing effect on the capacity. The inlet with wingwalls turned out to be the most reliable shape, with stable flow conditions and high amounts of water transport through the barrel. When the inlet was cut, the water flow was often unstable and oscillated, which resulted in the lowest culvert capacity. The basin length effect also showed a significant influence on the capacity, where the shortest length was better than the longer lengths. Additionally, the slope was found to give higher capacities when it was 1:5 compared to 1:9.

When sediments were added to the basin, both gradually and all at once (as a landslide), the curves showed a tendency of an increased capacity. This result does not coincide with previous knowledge on the subject, and it was assumed that the influence of debris in combination with sediments is an important factor in culvert blockage. However, the sediment deposition was strongly influenced by the culvert capacity, hence the inlet shape and basin geometry. For the inlets and geometries that gave low capacities, the amount deposited in the basin was high and the sediments tended to accumulate in front of the inlet.

For projects with similar water and sediment behavior as given in the performance curves, the curves can be very helpful in reducing the risk of overtopping. However, documentation of the sediment transport is necessary for establishment of the sediment deposition in the basin and in front of the inlet. A clean culvert and sediment-free area around the inlet is as important as a functioning inlet and basin geometry when hindering overtopping of road or railway fillings.

Sammendrag

Per i dag finnes det ingen detaljerte retningslinjer som omhandler design av kulverter og tilhørende løsninger på sediment- og drivgodsproblemer. Det ble derfor konstruert en laboratoriemodell for å finne løsninger på hvordan sedimenter avsettes foran kulvertinnløpet, og hvordan dette påvirker kulvertens kapasitet. Modellen besto av et samlebasseng som mottok vann fra pumpesystemene, og førte vannet videre til en tilløpskanal. Kanalen ledet så vannet til et inntaksbasseng, før det til slutt endte ut gjennom en kulvert. Hovedfokuset med oppgaven har vært å lage et testprogram med varierende effekter. Disse effektene inkluderte innløpets utforming, inntaksbassengets lengde, helningen på tilløpskanalen, hvordan sedimentene ble tilsatt og størrelse på og mengden av de tilsatte sedimentene. Ut fra disse effektene ble det produsert kapasitetskurver for å se på de ulike effektenes påvirkning på kulvertens kapasitet, og for å finne ut når vannstanden ville overtoppe fyllingen.

Resultatene fra de ulike eksperimentene ga ingen absolutte svar på hvordan sedimentasjonsproblemene bør løses, men det ble etablert gode utforminger oppstrøms kulverten for å redusere faren for overtopping. Ved test av forskjellige vannføringer, ble det funnet at kulvertens innløpsutforming er den effekten som påvirker kapasiteten mest. Innløpet med vingemur viste seg å være den mest pålitelige utformingen, med stabile strømningsforhold og høye mengder vann transportert gjennom kulverten. Når innløpet var kuttet i henhold til fyllingshelningen ble vannet ofte ustabilt med oscillerende vannstrøm. Dette reduserte kapasiteten i henhold til kravet om overtopping, og det avkuttete innløpet ble klassifisert som dårligst. Effekten av inntaksbassengets lengde viste også en betydelig påvirkning på kulvertens kapasitet, hvor den korteste lengden ga bedre kapasitet enn de lengre. I tillegg ble en helning på tilløpskanalen lik 1:5 funnet bedre egnet enn helning 1:9 med tanke på kapasitetsutnyttelse.

Det viste seg at tilsetting av sedimenter, både gradvis og alt på en gang (skred), økte kapasiteten til kulverten. Dette samsvarer dårlig med kunnskapen som allerede finnes om det gjeldende temaet. Det ble derfor antatt at drivgods, i kombinasjon med sedimenter, har stor innvirkningsgrad på tilstoppingsproblemer rundt kulverter. Likevel viste kurvene at de avsatte sedimentene påvirkes av kulvertens kapasitet og derfor også innløpets utforming og bassengets geometri. De geometrier og innløpsutforminger som ga lav kapasitet ga også høy avsetting av sedimenter i bassenget og foran innløpet.

Ved prosjekter med lignende vann- og sedimentoppførsel som gitt i kapasitetskurvene, kan kurvene være et godt hjelpemiddel for å redusere faren for overtopping. Det er likevel nødvendig med tilstrekkelig dokumentasjon av sedimenttransporten, for å kunne si noe om hvordan sedimentene vil avsettes i inntaksbassenget. Som hovedregel kan det sies at en ren kulvert, med et sedimentfritt område foran innløpet, er like viktig som en god, fungerende innløpsutforming og geometri for å hindre overtopping av veg- og jernbanefyllinger.

Preface

This Masters Thesis is written by Ida Gotvassli in the spring of 2013, and all work described in this thesis were conducted by me in the Hydro Technical Laboratory at the Institute for Hydraulic and Environmental Engineering at NTNU. I have also been lucky to receive help from a student named Daniel, who has helped me a great deal with finishing the model experiments, and for that I am thankful. To be able to work in the laboratory, and with physical modeling, for such a long time has been a great experience, and I feel lucky that I was given the opportunity to do this.

This thesis would not have been possible to conduct if it had not been for such helpful and caring people around me. For the making of the laboratory model, I wish to thank Geir Tesaker who helped me a great deal with establishment of the model and the starting process of running the experiments. He has also been there all the way, along with Samuel Vingerhagen, to assistance me if needed. From Statens Vegvesen (NRPA), Harald Norem has been a good supervisor in bringing necessary knowledge on culverts from real life experiments.

At last, I wish to thank my supervisors Leif Lia, Hanne Nøvik and Jochen Aberle. This thesis would not have been possible if it had not been for them. With his expertise on physical modeling, Jochen has been a great help in understanding the model and always making time in his schedule to guide me through this thesis. Similarly, Hanne has provided me with continuous follow-up during the whole project period, and for that I am very grateful. I really appreciate her commitment and interest concerning my project, which have helped me in completing this thesis.

Trondheim, June 10, 2013

Ida Elisabeth Sørbø Gotvassli

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1 Introduction

The flow capacity of intakes in watercourses and culverts is highly dependent on local hydraulic conditions and the amount of debris, sediments and ice at the intake area. Both culvert inlets and intakes for hydro power plants in shallow rivers are subjected to risk of reduced capacity or complete blockage due to deposition and accumulation of sediments and debris. Unfortunately, there are no detailed guidelines for the design of culverts including sediments and debris. Therefore, Statens Vegvesen, The Norwegian Public Road Administration (NRPA), has initiated a project for developing new guidelines for culverts including the effect of debris and sediments. A test program with variations of inlet design, flow conditions and different types of sedimentation will be completed for the making of performance curves and to find the optimal capacity for different culvert designs. Additionally, a model intake with a horizontal trash rack was supposed to be tested. Since the model did not finish in time, this Masters Thesis only concentrate on the culvert model and theory on this subject.

Model tests were conducted in the Norwegian Hydro-Technical Laboratory at NTNU for a better understanding of how sediments deposit in front of and inside the culvert. The culvert was inlet controlled such that the designs centered on the upstream conditions of the culvert, and the scale was set to be 1:10. It is known that when sediments start to deposit in the culvert or in front of the inlet, the capacity will be reduced. The result is a change in the flow pattern of the water, and the risk of overtopping increases.

The overall goal of this Masters Thesis is to gain a general understanding of and experiences with culvert hydraulics from physical modeling. The experiences gained during the experiment can also be applied in the handling of sedimentation problems at intake structures. The laboratory testing will be used to investigate how different designs can help to decrease the risk of overtopping of roads and railways, especially caused by sediment blocking. Performance curves will be established for culverts with and without the effect of sediments, to learn more about how the culverts capacity is influenced by sedimentation.

2 Culverts

A culvert is a conduit placed under a fill such as a highway embankment, used to convey stream-flow from the uphill side of the fill to the downhill side (Crowe et al., 2010). Figure 2.1 shows a sketch of a culvert in a filling and a picture of how a culvert looks in nature. It should be designed such that runoff from a design storm is transported through without overtopping and erosion of the fill at either the upstream or downstream end. Culverts are available in numerous cross-sectional shapes and sizes, and can be made from a variety of materials. Normally, a culvert is a pipe with diameter from 1 meter up to 2,5 meters. Openings with diameter less than 1 meter are often called subdrain pipes, and those with diameter more than 2,5 meters are defined as bridges (Statens Vegvesen, 2005).

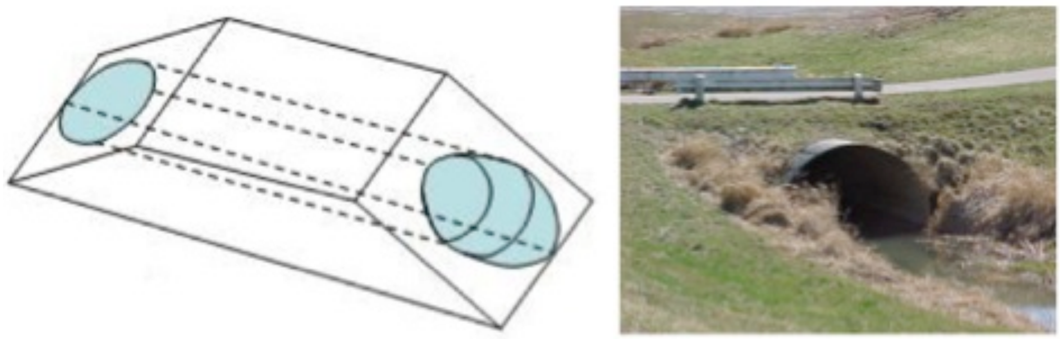


Figure 2.1 Sketch of a culvert through a filling at the left (Amundsen, 2005) and a culvert placed under a road in nature at the right (LMNO Engineering, Research and Software, Ltd., 2010)

The most common materials for the construction of culverts is concrete, corrugated aluminum or corrugated steel, in a circular, rectangular, elliptical or arch shape. A culvert inlet can also vary from prefabricated to constructed-in-place installations. The most commonly used configurations include projecting culvert barrels, cast-in-place concrete headwalls, precast or prefabricated end sections, and culvert ends mitered to conform to the fill slope (Norman et al., 2001). The inlet selection has an impact on the hydraulic efficiency of the culvert. Beveled edges are more efficient than square edges, because they give a more gradual flow transition that will lessen the energy loss and create a more hydraulically efficient inlet condition. Square edges will cause separation to occur at the entrance, which inhibits full flow in the culvert (Straub et al., 1953). Tapered inlets also reduce the flow contraction and further increase the culvert efficiency (Norman et al., 2001).

2.1 Culvert Hydraulics

Flow conditions in a culvert can vary depending on the culvert type, but the flow can also vary in a given type of culvert over time. The upstream and downstream conditions, along with the barrel characteristics and inlet geometry may determine if the culvert barrel flows full over all of its length or party full (Norman et al., 2001). Straub, Anderson and Bowers state in the report "Importance of Inlet Design on Culvert Capacity" that a common problem in culvert design is that culverts are assumed to have a much greater capacity than they actually have. This reduction in capacity is related to inadequate design of the culvert inlet, which often is designed according to the head loss. In reality it is important to consider the overall hydraulics of the culvert when designing the inlet. The best culvert design will be the structure that discharges a given flow with the least head, or if the head and discharge are specified, the structure that provides the most economical culvert. Often the most economical culvert will be the one with the least cross-sectional area (Straub et al., 1953).

2.1.1 General hydraulics

The headwater in culvert hydraulics is *the depth of the upstream water surface measured from the invert at the culvert entrance* (Norman et al., 2001). Such an increased water surface forms from the energy that is needed to force the water through the culvert.

Tailwater is the definition of the water depth downstream the culvert measured from the outlet invert. The cause of tailwater may be an obstruction in the downstream channel or the hydraulic resistance of the channel. To precisely define tailwater it is necessary to make backwater calculations from the downstream control point (Norman et al., 2001).

A culvert is often a constriction of the available channel area, such that the flow velocities in the culvert are higher than in the channel. This velocity increase can cause erosion at the culvert outlet, which is not desirable. Increasing the barrel roughness, or placing energy dissipaters or outlet protection devices at the culvert outlet could avoid such erosion (Norman et al., 2001).

2.1.2 Flow conditions

This section describes the two types of flow that can appear in a culvert, full flow and free surface flow.

Full flow

When a culvert flows full, the hydraulic condition of the situation is called a pressure flow. Backpressure caused by a high downstream water surface elevation or high upstream water surface elevation can cause pressure flow in a culvert (Norman et al., 2001). Either way, the culverts capacity under pressure flow is strongly affected by upstream and downstream conditions and by the hydraulic characteristics of the culvert.

Partly full (free surface) flow

This type of flow is also called "open channel flow", and is categorized as subcritical, critical or supercritical. To determine the flow category, the dimensionless Froude number, F_r, is evaluated, given in equation 2.1.

$$F_r = \sqrt{\frac{inertial\ force}{gravity\ force}} = \sqrt{\frac{\rho L^2 V^2}{\rho L^3 g}} = \frac{V}{\sqrt{gL}} \qquad (2.1)$$

where ρ is the density, L is the length, V represents the volume and g is the acceleration of the gravity.

If $F_r > 1{,}0$, the flow is supercritical and is characterized as rapid and often turbulent. When $F_r < 1{,}0$, the flow is subcritical and characterized as smooth and tranquil, even though turbulent flow can appear for low Froude numbers as well. The flow is critical when $F_r = 1{,}0$, and represents the dividing point between the subcritical and supercritical flow regimes (Norman et al., 2001). Typically, subcritical flow characteristics, such as velocity and depth, can be affected by downstream disturbances. In supercritical flow regimes, such disturbances downstream will not affect the upstream flow characteristics. Subcritical flow is most likely to occur in the upstream channel, critical depth will exist at the culvert inlet and supercritical flow will occur in the culvert barrel (Norman et al., 2001). The transition between supercritical flow to subcritical flow is characterized by a hydraulic jump. This happens when the water surface in the flow direction rises until the slope is too steep to be stable. A local hydraulic jump is induced with strong turbulence and huge energy losses (Fergus et al., 2010).

The energy balance through a culvert can be shown as depicted in Figure 2.2. Throughout the culvert barrel a head loss will occur due to the friction of the barrel, such that the energy level from the culvert inlet to the outlet will decrease in the flow direction (Fergus et al., 2010).

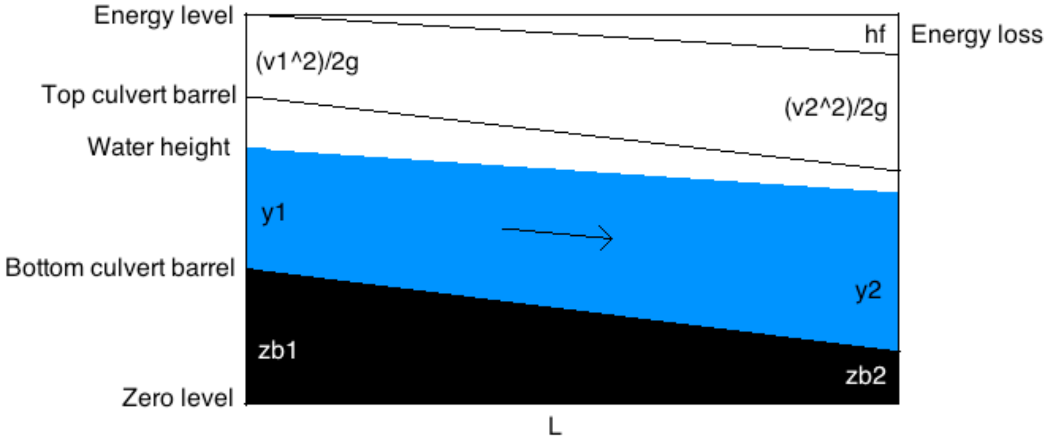


Figure 2.2 Energy balance in a culvert with open-channel flow (Crowe et al., 2010)

Bernoullis equation, shown in equation 2.2, can be used to express the energy balance in open channels, and also for culverts with open channel flow (Crowe et al., 2010).

$$y_1 + \frac{v_1^2}{2g} = y_2 + \frac{v_2^2}{2g} + L(I_e - I_b) \tag{2.2}$$

where y is the water depth, v is the water velocity, L is the length of the culvert, I_e is the slope of the energy line and I_b is the slope of the bottom and the culvert barrel. Notations 1 and 2 represent the inlet and outlet of the culvert.

In channels where the slope is constant $h_f = I_e \cdot L$ and $(z_{b1} - z_{b2}) = I_b \cdot L$, I_e represents the slope of the energy line and $I_b$the slope of the culvert barrel.

2.1.3 Types of flow control

There are two basic types of flow control, and they are called inlet and outlet control. The capacity of the culvert is dependent on the different conditions for each type of control.

Inlet control

When a culvert is inlet controlled, *the culvert barrel is capable of conveying more flow than the inlet will accept* (Norman et al., 2001). This normally means that the culvert barrel will not flow full over its whole length, and thereby result in a free water surface along the structure, as depicted in Figure 2.3. The critical depth occurs near the inlet of the culvert, near or inside the entrance where the control section is located. Supercritical flow also occurs immediately downstream, but the hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity.

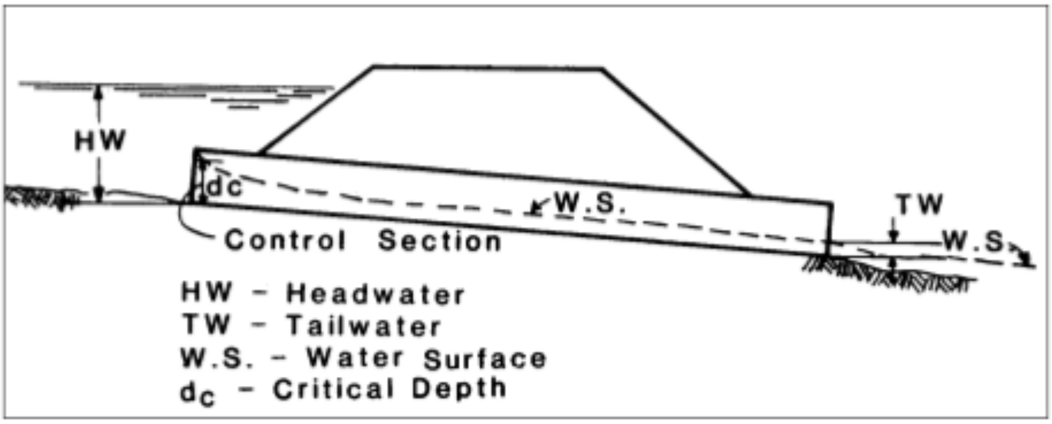


Figure 2.3 Typical inlet control flow conditions (Norman et al., 2001)

For inlet control, the flow pattern at the culvert entrance may be three dimensional with vortices or other unpredictable features (Creamer, 2007). These patterns are influenced by many factors, including the inlet geometry, wingwall configuration, culvert shape and degree of beveling. The inlets geometry and design, and the upstream water depth also determine the capacity of the culvert (Fergus et al., 2010). The inlet geometry includes the pipe diameter, its shape and cross-sectional area and the inlet edge. Inlet control is the most common design criterion for dimensioning culverts. *A culvert with inlet control performs as a weir when the inlet is unsubmerged and as an orifice when it is submerged* (Ho, et al. 2013)

Outlet control

Outlet control in a culvert occurs when *the culvert barrel is not capable of conveying as much flow as the inlet opening will accept* (Norman et al., 2001). This normally means that the culvert barrel flows full or partially full over its length. Here the control section is located at the pipe exit or further downstream, as shown in Figure 2.4.

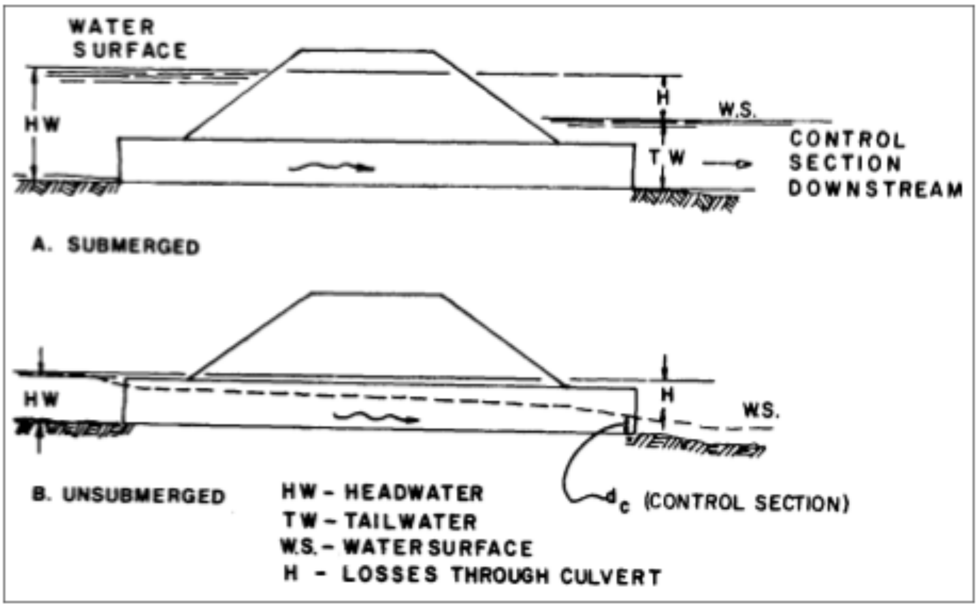


Figure 2.4 Typical outlet control flow conditions (Norman et al., 2001)

This type of control is typically represented by supercritical or pressure flow, and all of the geometric and hydraulic characteristics of the culvert affect the capacity. These characteristics include the inlets geometry and design, the pipe diameter, the length, friction and the slope of the culvert, the water depth at the inlet and the water depth at the outlet (Fergus et al., 2010).

Table 2.1 Factors influencing the culvert performance (Norman et al., 2001)

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X
*Barrel slope affects inlet control performance to a small degree, but may be neglected.		

Table 2.1 gives a summary of the factors that influence culvert performance in the two control types.

2.1.4 Performance curves

Performance curves show a plot of the headwater depth or elevation versus the flow rate, as depicted in Figure 2.5. This type of graphical depiction of culvert operation is a useful tool in evaluating the hydraulic capacity of a culvert for various headwaters. The curve also displays the consequences of higher flow rates at the site and the benefits of inlet improvements (Norman et al., 2001).

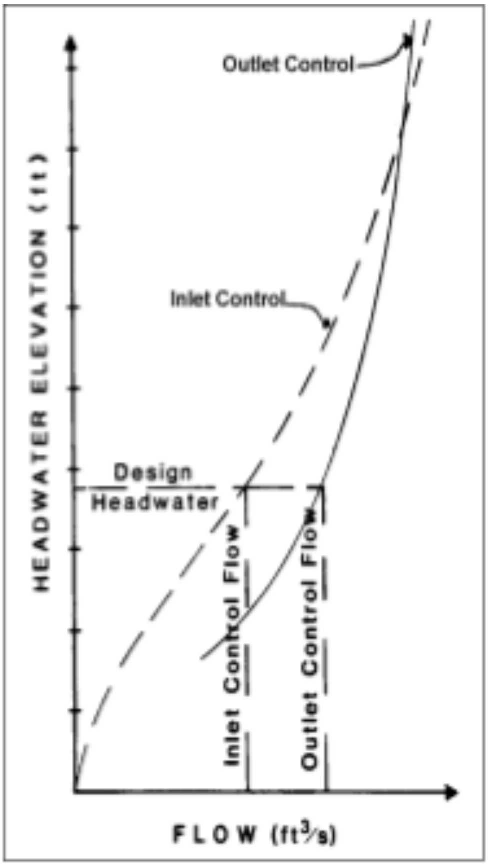


Figure 2.5 Performance curves (Norman et al., 2001)

Figure 2.5 shows a plot of both the inlet and outlet control curves. The graph shows both curves because the dominant control at a given headwater is hard to predict. The control may also shift between the inlet and outlet over a range of flow rates. At design headwater, the culvert always operates under inlet control. In that way inlet improvements can increase the culvert performance to take better advantage of the culvert barrel capacity.

This Masters Thesis will only focus on the culvert being inlet controlled, but it´s known that outlet control can occur. The culvert will experience outlet control when the headwater elevation is higher than the critical depth for the culvert. To find the critical depth, equation 2.3 can be used for a Froude number equal to 1 (Crowe et al., 2010).

$$\frac{Q^2 T_c}{g A_c^3} = 1 \tag{2.3}$$

where T_c is the width of the channel at the water surface, A_c is the area of the water and Q is the discharge. Figure 2.6 shows the critical depth and water surface in a circular culvert.

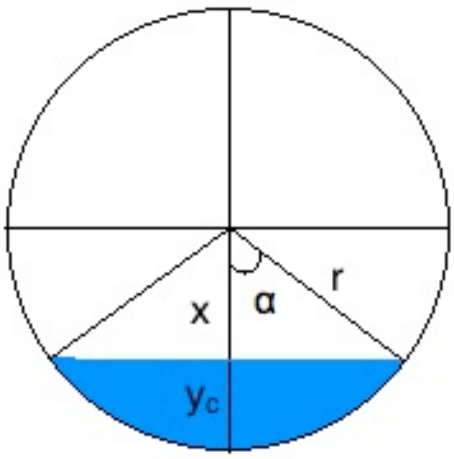


Figure 2.6 Finding the critical depth

A critical discharge can be found by rearranging the formula in equation 2.3, making it as shown in equation 2.4.

$$Q_c = \sqrt{\frac{A_c^3 g}{T_c}} \tag{2.4}$$

Table 2.2 shows a matrix of how A_c and T_c were found. Additionally, different values for y_c were plotted against Q* to find the limit for outlet control. Q* is a dimensionless number for the discharge, explained further in section 4.5, and is here a function of the critical discharge and the diameter of the culvert, as shown in equation 2.5.

$$Q^* = \frac{Q_c}{\sqrt{g} D^{5/2}} \tag{2.5}$$

Table 2.2 Matrix for calculation of critical discharge and depth

Parameter	Value
x	$r - y_c$; if $y_c < r$
	$y_c - r$; if $y_c > r$
α	arccos (x/r)
$\mathbf{A_c}$	$r^2\alpha - x^2\tan\alpha$; if $y_c \leq r$
	$\pi r^2 - r^2\alpha + x^2\tan\alpha$; if $y_c > r$
$\mathbf{T_c}$	$2x\tan\alpha$; if $x > 0$
	$2r$; if $x = 0$

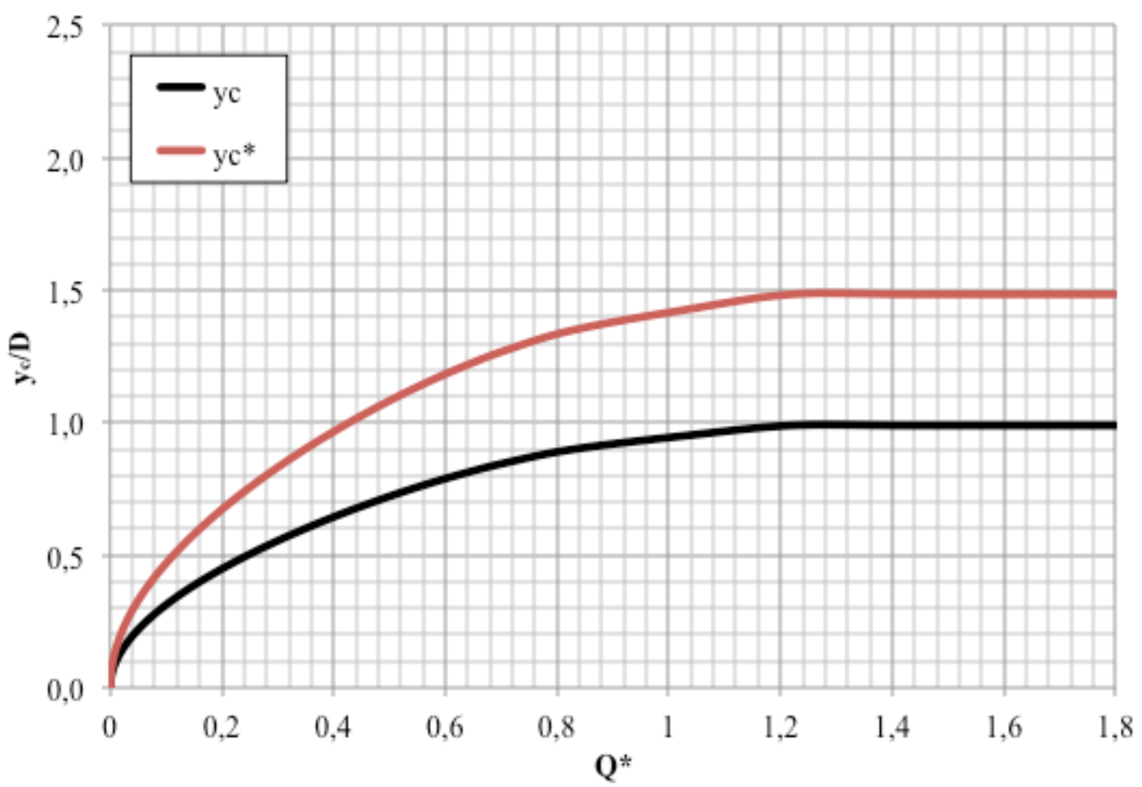


Figure 2.7 Limit for outlet control

Figure 2.7 shows the values of y_c plotted against Q* for a culvert with pipe diameter of 100 mm. Since the headwater values will be somewhat higher than the values for the critical depth, it was chosen to compare the critical depth of y_c*, given in equation 2.6, with Q*.

$$y_c^* = \frac{3}{2} y_c \tag{2.6}$$

The value of y_c* is a theoretical value of the headwater for a culvert with inlet control and flow condition 1 from Vassdragshåndboka (Fergus et al., 2010).

2.2 Culvert design

Statens Vegvesen, The Norwegian Public Road Administration (NPRA), have published a manual named Håndbok 018 Vegbygging for how to build roads. This manual makes the foundation for all the planning, dimensioning and building of roads. Culverts are also included in the manual, and it is described how to build them, and what to consider when the culvert is under construction. Table 2.3 shows how the inlet shape, culvert diameter and the headwater influence the culvert capacity. The Table represents culverts with inlet control and where the ratio between the headwater and the inside culvert diameter, h/D, is equal to 1,0. This is done to give the culvert an extra capacity when the culvert is submerged at the ratio h/D = 1,2 (Statens Vegvesen, 2005).

Table 2.3 Hydraulic capacity (l/s) for culverts with inlet control and h/D = 1,0 (Statens Vegvesen, 2005)

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

From the Table it can be shown that for the subdrain pipes, with diameter less than 1 meter, the wingwalls (shape A) gives the best capacity. The projecting inlet (shape C) is the worst case with the lowest capacity. Figure 2.8 shows a picture of the three different inlet shapes A, B and C.

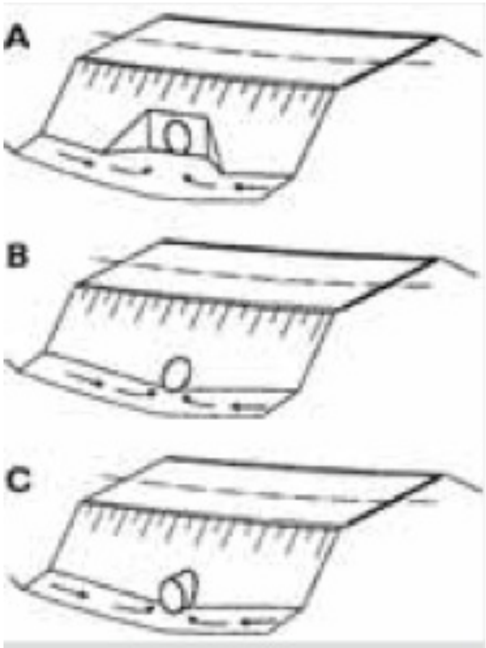


Figure 2.8 Culvert inlet shapes (Statens Vegvesen, 2005)

When it comes to the culverts with diameter larger than 1 meter, it is actually the cut inlet (shape B) that has the best capacity (Statens Vegvesen, 2005). Wingwalls are the second best, and the projecting inlet is still the worst.

2.3 Sedimentation in culverts

Sediment deposition in culverts is a prominent problem, especially for culverts in streams that convey substantial sediment loads. Accumulation of sediments will eventually lead to partial blockage of the culvert and further reduction of the culvert capacity. The consequences of culvert blockage include increased flood levels, flow diversions out of the streams, development of unexpected overland flood flowpaths and scouring of overtopped embankments (Rigby et al., 2002). Changes in the stream cross-section, approach flow conditions, the local topography, soil types and hydrologic events are all factors that can be related to accumulation of sediments. Typically, channel enlargement leads to increased sediment transport and bed-load, where the majority comes from the channel stream banks during high flow events. Bed-load is one of two main transport modes of material load, where the other mode is the suspended load. *The bed-load covers all particles that mainly move close to the riverbed by sliding, rolling and jumping* (Lysne et al., 2003). The velocity of the bed-load is often much less than the velocity of the water, and the particles are in frequent contact with the stable particles at the riverbed. Suspended particles are carried by the water flow, and may tend to settle and rest on the riverbed if the shear stress in the basin is reduced sufficiently. However, sedimentation problems in culverts are mostly related to bed-load.

Observations during a large storm in Australia in 1998 showed that sediments tend to block the culvert from the bottom up, reducing the capacity rather than blocking the pipe completely (Rigby et al., 2002). The degree of blockage was found to be more extensive for the smallest pipe openings, such that larger openings like bridge openings were less likely to block. Rigby, et al. found that no structure with an opening of 6 meters or more was fully blocked, compared to structures with a smaller opening, which experienced the full range from completely unblocked to fully blocked. From these structures, only 5 % were completely unblocked, whereas 58 % were fully blocked. The degree of blockage tended to be high for culverts with a diameter placed in the range between 1 and 2,5 meters. Further, no strong relations were found between the degree of culvert blockage and a range of other factors. These included material type, land use, stream slope, contributing catchment area, the number of culverts upstream and blockage of upstream culverts.

Field observations from Iowa show that sediment deposits in culverts grow rapidly (Ho et al., 2013). A new study of a multibarrel three-box culvert showed a considerable sediment deposition developing over only 1,5 years after complete removal of an earlier deposition. From this, a self-cleaning culvert inlet design was found possible to reduce the sedimentation in culverts. The sediment size used for the numerical and physical model was 0.45 mm. The self-cleaning was done by keeping the velocity distribution approaching the culvert as close as possible to the original one, before culvert construction. The self-cleaning culvert comprised a set of fillets that streamlined flow to the culvert entrance, ensured the continuity of sediment transport through the entrance, added turbulence where needed, did not reduce the culvert flow capacity and did not cause vegetation debris to accumulate at the culvert entrance.

In the Masters Thesis conducted by Sissel Alne Amundsen, with a similar physical laboratory model as in this Thesis, it was found that deposition of sediments in front of the culvert inlet was a less vulnerable strategy for transporting masses than a self-cleaning culvert (Amundsen, 2005). For the masses to be transported directly through the culvert, without depositing in the barrel, it was required an even and stable jet flow and a minimum critical water depth. It is rare for these criteria to be fulfilled in nature, since debris often blocks the water and form a hydraulic jump or changes the direction of the jet flow. This can induce an uncontrolled deposition of sediments in the barrel or near by the culvert inlet.

For the sediments to be deposited before the inlet, the most reliable strategy was found to be a displacement of the culvert in a distance of minimum 6 meters from the direction of the flow. This setup gave zero blockage of the culvert inlet or barrel, and the capacity was sufficient. In some situations the sediments were transported over the filing, but use of a high filling and a basin length of minimum 12 meters in nature would solve this problem. It was therefore recommended to deposit sediments in a basin to reduce the risk of blockage of the culvert, if the area of the location allowed it.

3 Model scaling

This chapter includes basic principles, concepts and equations that are used during the measurements, which are explanatory for physical modeling in general. The theory on how the measurements from the experiment are made dimensionless will also be included, since this is the foundation of the results presented in chapter 5.

3.1 Laws of modeling

A physical model is often a downscaled simulation of what happens in nature, and it is of importance to make the surroundings in the model as similar as possible to the prototype. It is also important that *the major dominant forces acting on the system are represented in correct proportion to the actual physical system* (Hughes, 1993). A physical model should act like a precision device, such that it is possible to predict the behavior of a physical phenomenon. The model can only be regarded as reliable when it is designed correctly, otherwise it will be wrong in principle. If the model is incorrect, even the finest instruments and methods of measurement are insufficient, and will only serve to increase the accuracy of wrong predictions. Nevertheless, a physical model is an important tool with its ability to visualize and observe the physical processes close at hand.

When speaking of physical modeling, there are several terms that are related to this topic. The more important terms are listed below.

- *The **prototyp**e is the situation that is being modeled. The model is often a downscaled version of the prototype, although modeling with the same size occurs. The prototype condition does not necessary have to be a "naturally-occurring" physical phenomenon.*
- *A **scale** is a ratio between a parameter value in the model and the same parameter value in the prototype. Scales are constant proportions of measurable characteristics between model and prototype.*
- ***Similitude (or Scaling) Criteria** are the formal mathematical conditions that must be met by the scale ratios between model and prototype. These criteria can be determined from mathematical representations of the physical properties, but they are only as good as the representation itself.*
- ***Scale effects** are the differences between the prototype and the model response that arise from the inability to simulate all relevant forces in the model at the proper scale dictated by the scaling criteria.*
- ***Laboratory effects** are the differences between the prototype and the model response that arise from limitations of the laboratory facilities. These can be wave and flow generation techniques, solid model boundaries or other limitations.*

- ***Similarity*** *is a word used for a condition that exists when a model gives a similar response as the prototype, even if the model is not in strict similitude with the prototype. It is possible to have model similarity without meeting similitude criteria when some macro scale feature of interest is satisfactorily reproduced in the model.*

(Hughes, 1993)

There are three criteria that have to be fulfilled for the model to achieve similarity, and these are listed below.

1. Geometric similarity
2. Kinematic similarity
3. Dynamic similarity

When using Froude´s law of similitude, each of the similarity criteria can be explained by the relationship in the following sections. The Froude number is a parameter that expresses the relative influence of inertial and gravitational forces in a hydraulic flow. It is given by the square root of the ratio of inertial to gravity forces, as shown in equation 2.1.

To make the Froude number dimensionless, it is required that the values are the same in model and prototype, such that

$$\frac{(\frac{V^2}{gL})_m}{(\frac{V^2}{gL})_p} = 1 \qquad or \qquad (\frac{V^2}{gL})_r = 1 \tag{3.1}$$

Equation 3.1 now shows Froude´s model law, which is normally expressed like equation 3.2.

$$(\frac{V}{\sqrt{gL}})_r = 1 \qquad or \qquad V_r = \sqrt{L_r} \tag{3.2}$$

The last expression in equation 3.2 is made possible by the assumption that g is equal in both model and prototype, because both systems function on earth where g is more or less 9,81 m/s^2 everywhere.

3.1.1 Geometric similarity

This is a similarity that exists between two objects or systems when the ratios of all the corresponding linear dimensions are equal. Examples of two such systems can be a prototype and its model. This type of similarity is called geometric because the relationship only involves similarity in form and is totally independent of any kind of motion (Hughes, 1993). These models are often called miniature versions because they represent the true geometric reproduction of the prototype. However, it can be challenging to reproduce every geometric detail correctly, so deviations must be carefully considered.

Equation 3.3 gives the length ratio when scaling according to this criterion.

$$L_r = \frac{L_m}{L_p} \tag{3.3}$$

where L_m represents a length in the model and L_p represents the same length in the prototype (Lysne, 1982). L is often expressed in meters.

3.1.2 Kinematic similarity

Kinematic similarity is characterized by a similarity of motion between particles both in model and prototype. This type of similarity is *achieved when the ratio between the components of all vectorial motions for the prototype and the model is the same for all particles at all times* (Hughes, 1993). A model can, as an example, achieve kinematic similarity to a prototype when the shape of the streamlines at any particular time is the same.

For this criterion the kinematic ratio, v_r, has to be constant. The kinematic ratio is here the ratio between all the velocities that occur in the model and prototype, as given in equation 3.4.

$$v_r = \frac{v_m}{v_p} = \frac{v_{k,m}}{v_{k,p}} \tag{3.4}$$

where v is the velocity of the water in model and prototype and v_k is the critical velocity (Amundsen, 2005). All these velocities are usually expressed in meters per second, m/s.

3.1.3 Dynamic similarity

In physical modeling the dynamic similarity criterion is the most important prerequisite. Dynamic similarity occurs between two geometrically and kinematically similar systems. To achieve dynamic similarity it is *required that the ratios of all the vectorial forces in the two systems are the same* (Hughes, 1993). This means that the ratios of all the masses and forces acting on the system must be constant, a so-called constant prototype-to-model ratio.

Equation 3.5 gives the scale ratio when scaling according to the dynamic similarity criterion.

$$F_r = \frac{F_m}{F_p} \tag{3.5}$$

where F represents the force acting in the model and prototype.

The requirements for dynamic similarity have their origin in Newton´s second law, which states the relationship between the vector sum of the external forces acting on an element and the elements mass reaction to those forces. Equation 3.6 shows how this relationship is expressed.

$$m\frac{dV}{dt} = \sum_n F_n \tag{3.6}$$

For mechanics problems on fluids, like water, Newton´s second law can be written as given in equation 3.7.

$$\widehat{F_\iota} = \widehat{F_g} + \widehat{F_\mu} + \widehat{F_\sigma} + \widehat{F_e} + \widehat{F}_{pr} \tag{3.7}$$

where

$\widehat{F_\iota}$= inertial force (mass x acceleration)
$\widehat{F_g}$ = gravitational force
$\widehat{F_\mu}$ = viscous force
$\widehat{F_\sigma}$= surface tension force
$\widehat{F_e}$ =elastic compression force
$\widehat{F}_{pr}$= pressure force

The hat symbols represent the vector quantities. Both the magnitude and direction of the force must be correctly represented (Hughes, 1993).

3.2 The importance of Froude Scaling

Forces associated with surface tension and elastic compression are relatively small when it comes to hydraulic flow problems, and can often be neglected from the calculations related to physical models. Hughes states in "Physical Models and Laboratory Techniques in Coastal Engineering" that *the Froude and Reynolds number are important to coastal engineers because similarity of one of these numbers, combined with geometric similarity, provides the necessary conditions for hydrodynamic similitude in an overwhelming majority of coastal models* (Hughes, 1993).

In this Masters Thesis the Reynolds number is disregarded because the flow in the model is always fully turbulent, such that it is not of interest. Accordingly, this thesis is based on similarity of the Froude number, and the forming of dimensionless products is also derived from these values.

3.3 Dimensionless numbers

Forming dimensionless numbers from selected important variables in a problem is important because of the following reasons

1. *It reduces the number of variables that must be investigated experimentally, numerically or via field measurements.*
2. *Dimensionless graphs provide more information than when dimensions are included, because of the possibility to cover a wider range of the parameters.*
3. *Points on dimensionless graphs can frequently be determined using models scaled in such a way that the dimensionless products are preserved at reduced scale.*
4. *Dimensionless products can be used as a basis for scale model design and interpretation of results.*
5. *Dimensionless products allow test to be planned and experimental results to be presented in a condensed and systematic manner.*

(Hughes, 1993).

The variables that were made dimensionless in this Masters Thesis were made using Froude scaling. Table 3.1 shows a list of the relevant parameters that are considered in the finding of the most important variables when forming dimensionless numbers. The Table is applicable for culverts with inlet control, and is made on the basis of which parameters that can influence the capacity.

The Buckingham π Theorem is a way of forming dimensionless products by using the fact that *the correlation between the number of independent dimensionless groups of variables (dimensionless parameters) and the variables in a given process is equal to n-m, where n is the number of variables involved and m is the number of basic dimensions included in the variables* (Crowe et al., 2010). Based on Table 3.1 there are 25 variables involved and 3 basic dimensions included. This makes the number of dimensionless groups, also called π-groups, equal to 22. From these 22 π-groups, it is possible to eliminate effects that will not affect the system.

Table 3.1 Important parameters for inlet control

Section	Parameter	Dimension	Description
Governing parameter	*Q*	m^3/s	Discharge
Culvert approach section	*S*	-	Slope of approach channel
	wa	m	Width of approach channel
	ha	m	Water depth in approach channel
	ka	m	Roughness of approach channel
Culvert basin	*h0*	m	Headwater depth
	lb	m	Basin length
	wb	m	Basin width
	hb	m	Culvert basin height
	Sc	-	Basin slope
	kb	m	Roughness of basin
Culvert inlet	*D*	m	Barrel diameter
	hD	m	Water depth in pipe (free surface flow)
	Shape	-	Inlet shape
	Barrel shape	-	Barrel shape
	Position	-	Position of drainpipe
Fluid	ρ	kg/m^3	Fluid density
	μ	kg/m/s	Dynamic viscosity
Gravitation	*g*	m/s^2	Gravitational acceleration
Sediments	*d*	m	Grain diameter
	ρs	kg/m^3	Sediment density
Sediment transport	*ma*	kg	Weigth of added sediments
	md	kg	Weight of deposited sediments
	mt	kg	Weight of transported sediments
	t	s	Time span of adding
Culvert details for outlet control	*lp*	m	Culvert pipe length
	kp	m	Pipe roughness
	hd	-	Downstream water depth

Basically, the approach channel can be disregarded because the control section will be in the basin at the hydraulic jump, and the culvert inlet will be the section controlling the discharge. Further, the effect of the sediments, the position of the culvert barrel, the roughness of the culvert basin and the culvert slope are neglected. The last two effects are neglected because there is no variation and the section is relatively short. Also, the water depth in the barrel is neglected, as it will be the critical one for which it is possible to find a corresponding relationship from the pipe geometry and discharge. Finally, the length and time are eliminated to make the discharge dimensionless. For the elimination of the time, the gravitational acceleration *g* can be used, and for the elimination of the length it is possible to use the constant pipe diameter *D*. Equation 3.8 shows the resulting dimensionless discharge, and what the parameter is a function of. The width of the basin is also eliminated because there is no variation in this parameter for this thesis.

$$\frac{Q}{\sqrt{g}D^{5/2}} = f(\frac{h_0}{D}, \frac{l_b}{D}, Shape) \tag{3.8}$$

Equation 3.8 will be used in the results by plotting the discharge and each of the functions in the performance curves. For the additional adding of the sediments, the ratio of the deposited sediments are also shown in a performance curve, along with the different sediment sizes and weights, feeding rate and feeding type.

For a better understanding of how the performance curves are made dimensionless and what they represent, two Figures in section 4.5 show an example of a curve before and after forming of the dimensionless product.

4 Experimental setup

The experimental setup chapter comprises a description of the culvert model setup, including calibration of the sensors that were used to measure the discharge and water levels in the model. It also describes how the tests were conducted, both with and without sediments, and how the performance curves were made with dimensionless numbers.

It should be called attention to the changes made during the project period. Originally, an intake model with a horizontal trash rack was supposed be constructed and tested. It was, however, found that this model would not be completed during the working period. The Master Thesis was therefore only based on the culvert model.

4.1 Laboratory setup and measurements

The model used in this study consists of a collecting reservoir leading to an approach channel to a basin, and a culvert with inlet from the basin. Figure 4.1 and 4.2 and Table 4.1 describe and specify the geometry of the model. As can be seen from the Table, the slope of the approach channel and the basin lengths were adjusted during the experiments. The other parameters were set to be constant. With these changes a clear water situation was studied, along with sediment transport. These situations were also measured on the basis of changes in the discharge, culvert inlet shape, sediment size and amount, and ways of adding sediments. The basin floor, walls and the approach channel were built from wood and painted white including a 10 times 10 cm grid to aid visualization of the flow conditions and the sediment deposition. For comparison with previous observations on the subject, the model was set to have a scale of 1:10.

Table 4.1 Technical specifications of the model

Physical dimensions	Length, l [mm]	Width, w [mm]	Height, h [mm]	Slope, S	Diameter, D [mm]
Collecting reservoir (cr)	785	535	420		
Approach channel (a)	2400	230	300	1:9	
				1:5	
Basin (b)	876 [1)]	1100	300	2 %	
	625 [2)]				
	315 [3)]				
Culvert barrel				2 %	100

[1)] Basin length l_{b1}, [2)] Basin length l_{b2}, [3)] Basin length l_{b3}

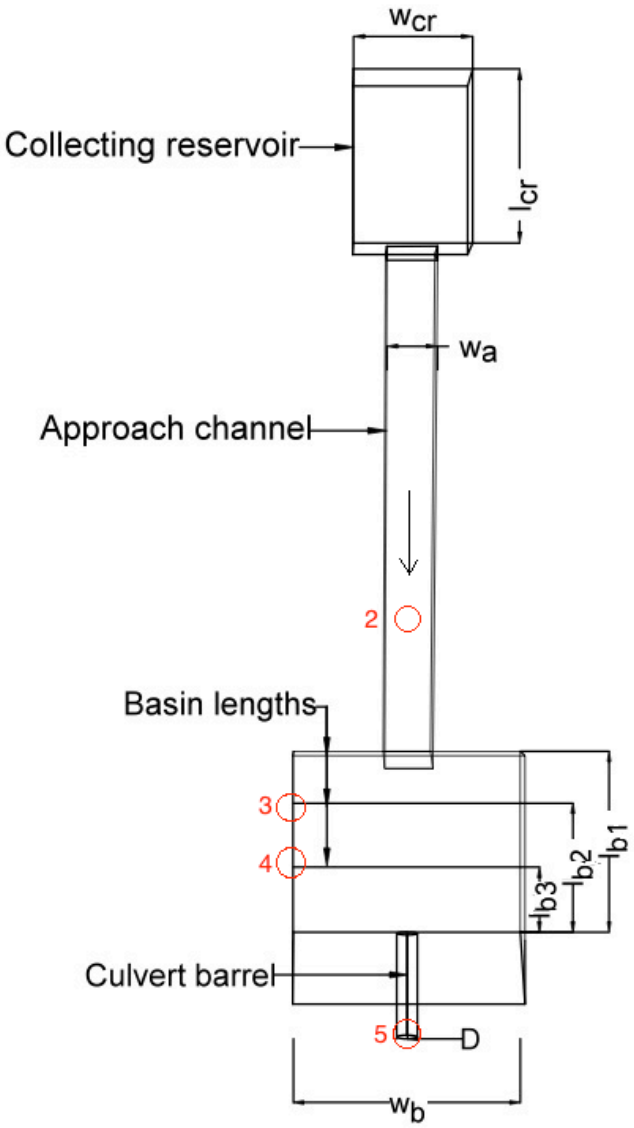


Figure 4.1 Top view of the model with sensors

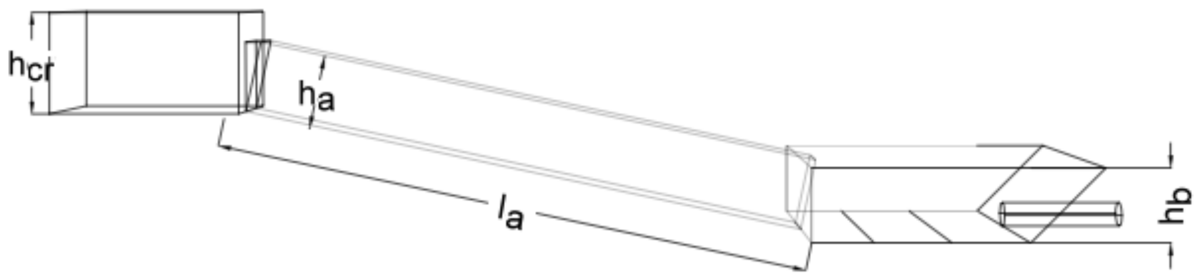


Figure 4.2 Side view of the model

When a culvert is inlet controlled, there are three conditions that will influence the capacity. These three conditions are the diameter of the pipe, the geometry and design of the basin and inlet, and the water depth at the inlet (Fergus et al., 2010). In the present experiments the pipe diameter was kept constant with 100 mm, so the changes centered on the geometry of the basin. It was expected that different basin geometries would affect the headwater elevation. Also the approach channel was made such that the slope could vary, by changing the length of the wood blocks placed underneath the collecting reservoir, as shown in Figure 4.3. It was chosen not to vary the placement of the culvert, because this was found to be a good solution in a previous Masters Thesis conducted by Sissel Alne Amundsen (Amundsen, 2005). The culvert barrel was placed in the middle of the basin width, in the flow direction from the approach channel, to see if there could be other solutions to the sediment deposition problem when varying other geometries and shapes.

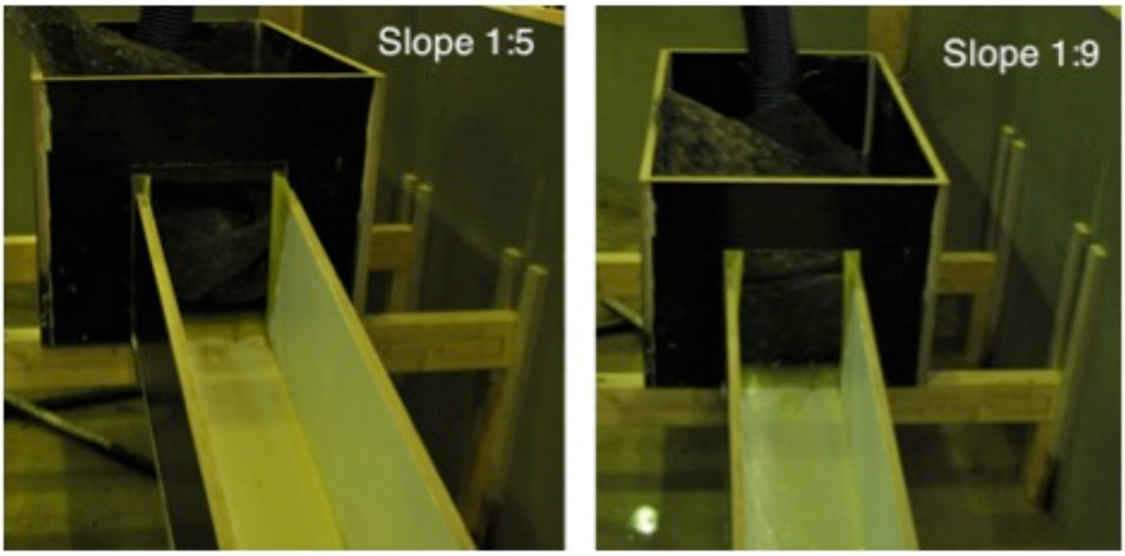


Figure 4.3 Changing the slope of the approach channel by varying the height of the upstream reservoir

Finally, three culvert inlet treatments were made. The first inlet had 45 degrees wingwalls, as shown in option A in Figure 4.4.

Figure 4.4 Culvert inlet shapes. A) Wingwalls, B) Cut inlet, C) Projecting inlet

Option B shows the second inlet treatment, a cut inlet with opening mitered to conform to the slope of the filling. Option C shows the third inlet shape, a projecting inlet out of the filling.

The length of the basin was 876 mm after the model construction, so this was chosen as the first length. Further, the approach channel ended at the line where the basin length was 625 mm, and this became the second length. As a third choice of the length it was naturally chosen half of the second length, equal to 315 mm. Also the slope of 1:5 was set after the construction of the model. Reducing the length of the wooden blocks underneath the collecting reservoir to half of the original length, the slope became 1:9.

4.2 Sensors and calibration

To measure the water depth, three microsonic mic+ Ultrasonic Sensors were installed. Two sensors were placed in the basin and one sensor was placed in the approach channel. Additionally, two pressure sensors were placed in the culvert barrel and in an external cylinder measuring the pressure in meter water column, and one sensor was placed beside the pump to measure the discharge. Table 4.2 summarizes the placement of the sensors and how they were numbered. The placement of the sensors can also be seen in Figure 4.1. The Figure does not show sensor 1 and 6, since they were located outside of the model area.

Table 4.2 Placement and numbering of the sensors

Sensor type	**Sensor number**	**Placement**	**Measures**
Flow instrument	1	Beside the pump	The discharge
Microsonic	2	In the approach channel	The water level in the channel
Microsonic	3	In the basin, near the channel	The water level in the basin
Microsonic	4	In the basin, near the culvert	The water level in the basin
Pressure	5	In the culvert	The water level in the culvert
Pressure	6	In the cylinder	The water level in the culvert

The microsonic sensor has one analogue output that measures the distance to the water within the detection zone. The sensor has a blind zone from 0 to 65 mm, an operating range of 350 mm and a maximum range of 600 mm. The accuracy of the sensors is ± 1 % when the sensors are internal temperature compensated, which they were in this experiment. That the sensors are temperature compensation means that they heat up on their own when they are turned on. It takes approximately 30 minutes of operation for the temperature compensation to reach its optimum working point. The sensors were therefore always turned on 30 minutes or more before the experiments started. Figure 4.5 shows a picture of the sensors.

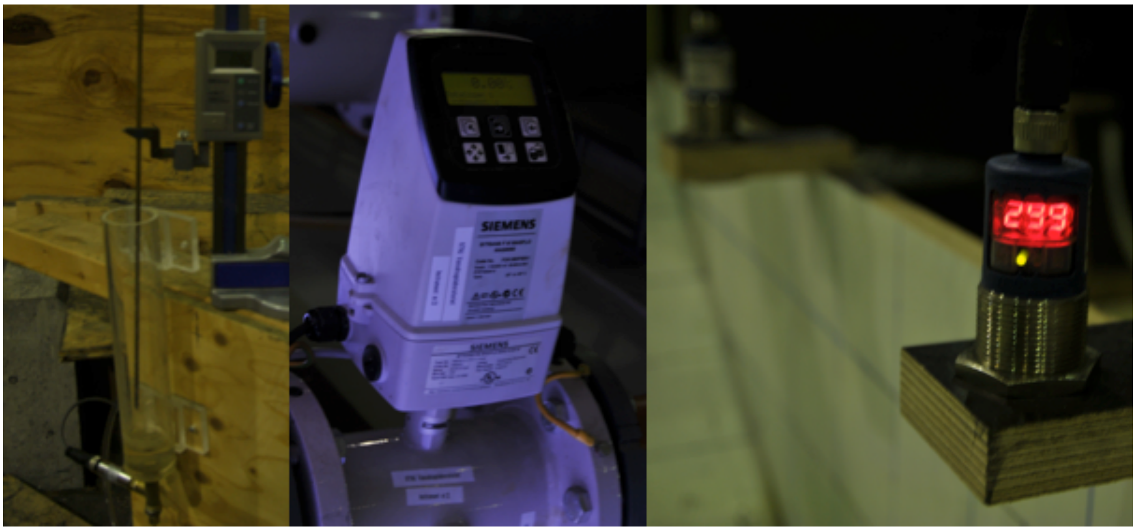


Figure 4.5 Sensor 6 to the left, sensor 1 in the middle and sensor 3 to the right

To log all the measurements on the computer, a logging device called Agilent was used. The six sensors were all logged in a computer program named Agilent Measurement Technologies. This program gives all its incoming measurements in millivolt, so the results had to be calibrated. The discharge was calibrated from volt to liters per second (l/s), and the distance and pressure was calibrated from volt to millimeters (mm). The calibration was done using a voltmeter, a calculator and a wooden block. The voltmeter was connected to the microsonic sensors, placed in the correct position and the distance to the basin floor was measured in volt. Putting a 100,2 mm thick wooden block under the sensor another distance value was measured. The difference in the voltage from the two distances was then divided by the distance difference of 100,2 mm, and further multiplied by a thousand to get the correct relationship between millimeters and millivolt. The result was a calibrated number giving how many millimeters one millivolt corresponds to, also known as the sensors offset. The offsets unit was then mV/mm. Further, the sensitivity of the sensors was the value given from the measured distance down to the basin floor divided on the sensors offset. The unit for the sensitivity became mm.

Calibration of the discharge was simply to program the analogue discharge logger, MAG 5000, to start the measurements at 0 l/s. Figure 4.5 shows a picture of the logger. The pressure sensors were calibrated from volt to meter water column (mWC), and then to millimeters. The sensors have a range from –1 bar to + 1 bar, and so 2,5 volts equal 10 mWC, and further one millivolt will correspond to 0,25 mm. The offset was set to -10 000 mm, since the positive value is equal to 10 mWC. It should be known that the values from sensor number 2, 5 and 6 were not used in this Masters Thesis. Sensor 2 was used for checking that the water flow in the channel was stable. When it comes to sensor 5 and 6, the pressure sensors were new, and the goal was to verify that they worked properly. Additionally, the pressure sensors were supposed to measure the water level in the culvert barrel, such that inlet coefficients could be found for the different inlet shapes. Since errors were found in the pressure measurements, the results would not have become accurate and it was chosen not to include them. The values from sensor 1, 3 and 4 were therefore found sufficient for the analysis.

The computer was set to log all the sensors at a rate of 1000 hertz. All the sensors were enabled such that the thousand measurements per second were averaged. When logging every discharge series for one minute, the result was a data sheet with 60 measurements. Also these measures were averaged to get a comparable value for both water depth and discharge, in the comparison of the different inlet and basin designs.

4.3 Clear water experiments

Experiments in the laboratory model were first conducted with clear water to establish how the changes in the geometry and inlet affected the culvert hydraulics and headwater. For each discharge the clear water was measured for 60 seconds after stabilization of the flow conditions. The discharge was increased with 2 l/s each time, until the basin was overtopping and the limit was reached. In conversation with Harald Norem from NRPA, the limit for overtopping was defined as two times the culvert diameter (over the culvert inlet, as shown in Figure 4.6), which is the culvert super elevation NPRA use for a filling when building roads and railways.

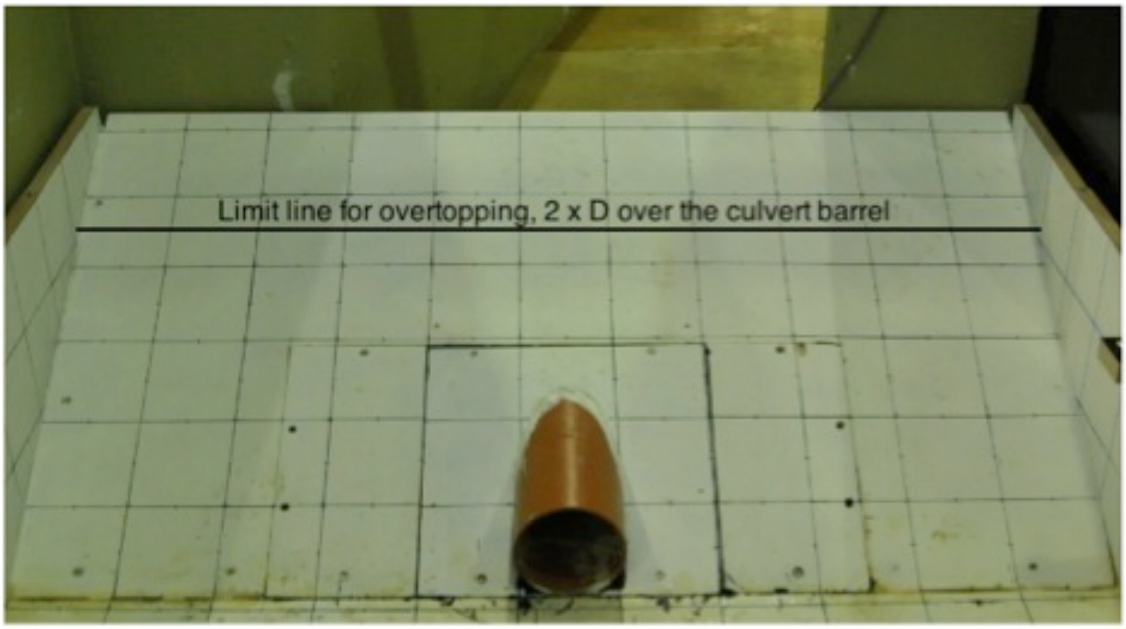


Figure 4.6 Limit for overtopping

Also a “zero measurement” was necessary because of the possible changes in the hydrostatic pressure in pressure sensors 5 and 6. This kind of measurement consisted of a regular measurement of the sensors with 0 l/s discharge. The zero-values from sensor 5 and 6 were subtracted from the values of the higher discharges. It was these measurements that were found to be inaccurate. Table 4.3 summarizes the experiments conducted with clear water.

Table 4.3 Experiments carried out with clear water

	Inlet types			Slopes	
Parameter changes	*Cut*	*Projecting*	*Wingwalls*	*1:5*	*1:9*
Slope [2)]					
1:5	X	X	X		
1:9	X	X	X		
Basin length [mm] [2)]					
876	X	X	X	X	X
625	X	X	X	X	X [1)]
315	X	X	X	X	-

[1)] Only for the projecting inlet with walls, [2)] Basin width 1100 mm

4.4 Sediment experiments

Sediments were added for selected geometries to determine the sediment effect on the headwater and culvert hydraulics. The sediments were added to the approach channel in two ways. First, approximately 5 kilograms were weighed and added to the approach channel all at once to simulate a landslide. A bucket was placed in the end of the culvert outlet to trap all the sediments coming out from the model. The sediment deposition in the basin and the sediments that went through the culvert were weighed separately, and the total weight of the sediments added was found. From this the percentage of sediments added in the basin was determined, and the sediment transport could be accurately quantified.

Figure 4.7 Vibrating machine

Alternatively, sediments were fed gradually with a vibrating machine, as shown in Figure 4.7. A scale was set to fit such that both 5 and 7 kilograms were added continuously during the time of adding. For both methods, clear water flow conditions were established first (and measured for 60 seconds) before sediments were added. The headwater and discharge were measured for 900 seconds during the adding of sediments. In total 16 minutes of clear water and sediments were measured for each discharge for a given geometry.

The measurements were carried out when the discharge and water level in the basin were stable. However, the measurements in total endured longer than 16 minutes. It was necessary to wait for 10 to 15 minutes before the water level in the cylinder connected to the culvert barrel was stabilized. This was required for all the discharges, and it could take up to one working day to finish a set of measurements. A total set of measurements included all discharges for a chosen culvert inlet, slope, basin length, sediment size and amount of sediments added. When adding sediments, the time it took to carry out a series was further prolonged because of weighing of the sediments. In Table 4.4 the experiments carried out with sediments are summarized.

Table 4.4 Experiments carried through with sediments

	Inlet types			**Lengths [mm]**		
Parameter changes	*Cut*	*Projecting*	*Wingwalls*	876	625	315
Sediment size [mm] 1)						
8 - 16	X	X	X	X	X	X
16 - 32	X	X	X	-	X	-
Sediment amount [kg] 1) 2)						
5	X	X	X	X	X	X
7	X	X	X	X	-	-
Ways of adding 1) 2)						
Gradually	X	X	X	X	X	X
All at once	X	X	X	X	X	X

1) Slope 1:5, 2) Sediment size 8 – 16 mm

In the Masters Thesis conducted by Sissel Alne Amundsen, two grain sizes were used (Amundsen, 2005). The smallest fraction was 8 – 11 mm, and the biggest fraction was 16 – 22 mm. The aim was to choose similar grain sizes as the ones previously used by Sissel. Since the sieves only had openings for 8 – 16 mm and 16 – 32 mm, these sizes were selected. The weights of 5 kg and 7 kg were chosen randomly. Sediments were collected and sieved to get the right grain size of 8 – 16 mm. The first sieving gave a total weight of the sediments equal to 5 kg, and this was chosen as a start weight. Further in the test it was found that the amount of sediments added should be tested for influence on the capacity, and more sediment were added to the sieve. The total amount of sediments after sieving was found to be 7 kg.

From the observations in Australia in 1998 it is likely to believe that sediment experiments conducted in the laboratory during this Masters Thesis will give a similar sediment behavior as the field observations. This meaning that the sediments will tend to block the culvert, since the pipe diameter is in the range of 1 to 2,5 meters.

4.5 Making of dimensionless curves

This section shows an example of a performance curve changing from regular dimensions to dimensionless numbers. Figures 4.8 and 4.9 represent the curve before and after, respectively.

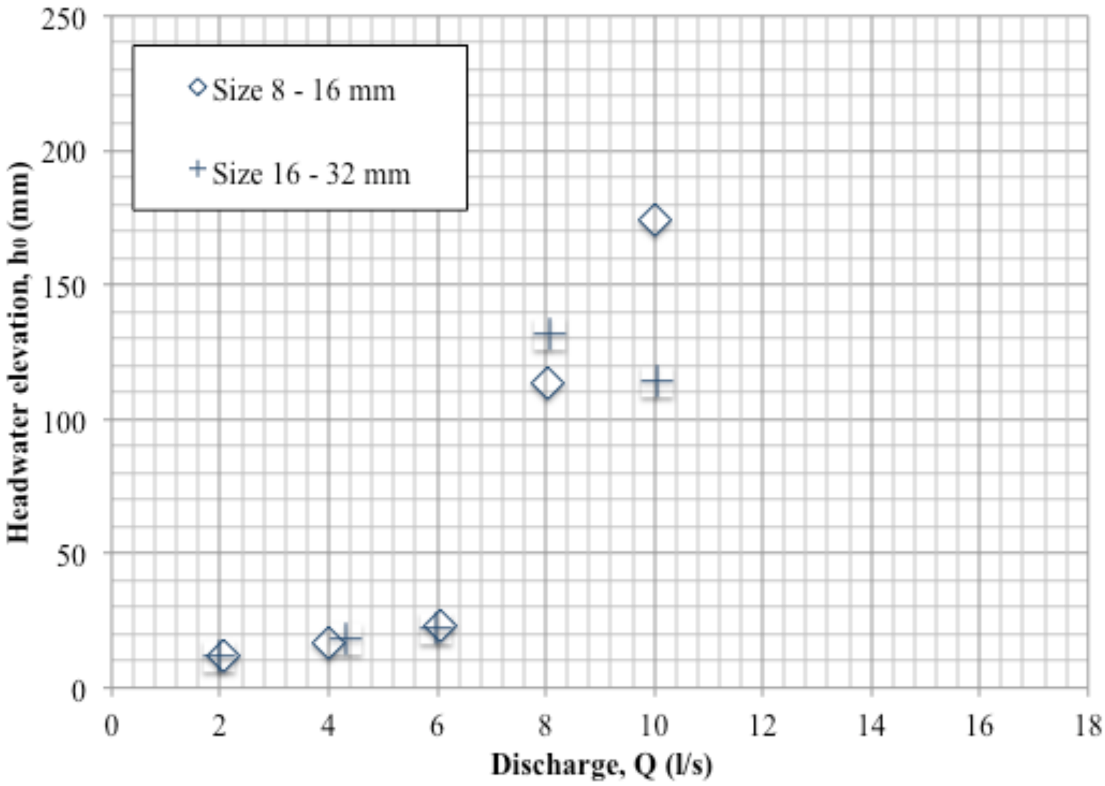


Figure 4.8 Performance curve with normal dimensions for different sediment sizes

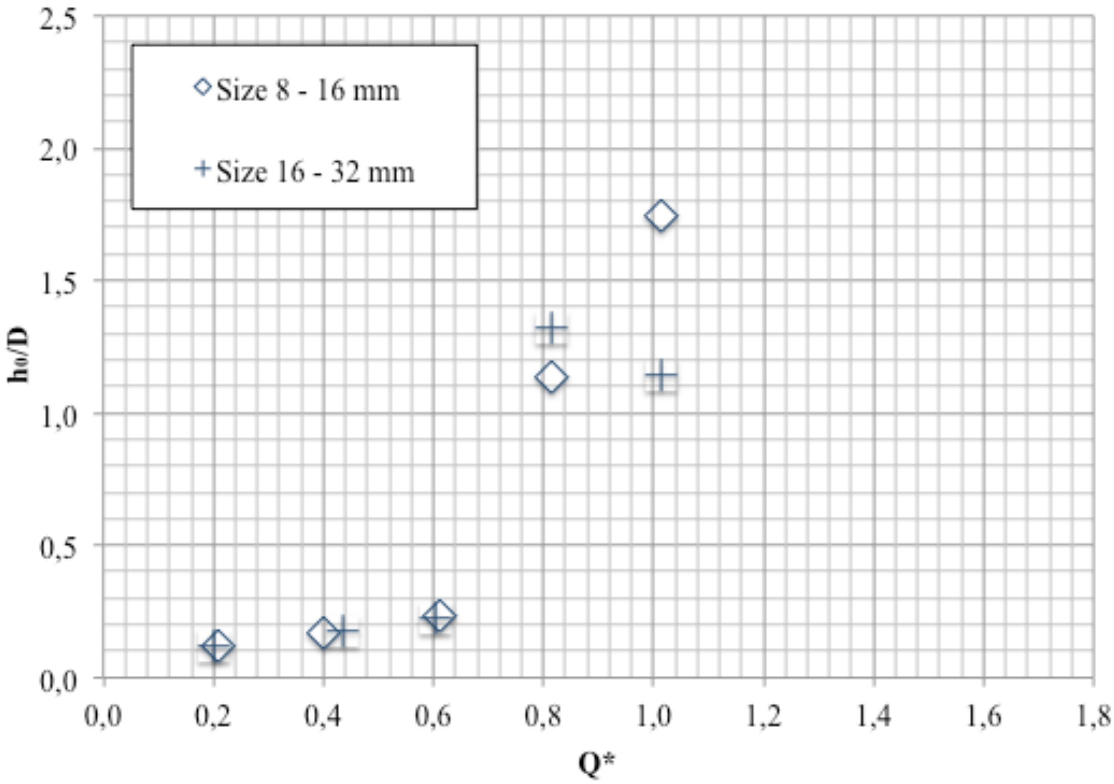


Figure 4.9 Dimensionless performance curve for different sediment sizes

Figure 4.9 shows how the headwater elevation is made dimensionless by dividing it on the culvert diameter, D. The discharge is also dimensionless as $Q^* = \frac{Q}{\sqrt{g}D^{5/2}}$. From the two graphs it is obvious that the pattern of the curves is the same. The difference between them is that the curves in Figure 4.8 only apply for the laboratory model with the given geometry, whilst the curves in Figure 4.9 can apply for other, up-scaled models and real life situations.

Table 4.5 Color codes and signs for the performance curves

Effect	**Description**	**Color/Sign**
Inlet shape	Wingwalls	Red
	Cut inlet	Blue
	Projecting inlet	Green
Basin length	876 mm	○
	625 mm	△
	315 mm	□
Slope of approach channel	1:5	Filled sign
	1:9	Non filled sign
Sediment size	8 - 16 mm	◇
	16 - 32 mm	+
Adding of sediments	Gradually	⬭
	All at once	⬭
	Clear water	×
Total weight added	5 kg	⬭
	7 kg	⬬

All the graphs presented in the results were made with color codes and different signs. These are shown in Table 4.5 and can be used as guidance when interpreting the corresponding graphs.

5 Results

Several experiments were conducted in the laboratory model shown in Figure 4.1. From these experiments different effect graphs were made, depicting how changes in the model design influenced the culverts capacity. In all the plots it is shown where the culvert went from inlet to outlet control. The headwater elevation is then higher than the critical depth in the basin for the given discharge.

The effects that were studied were the inlet shape, basin length, slope of the approach channel, how the sediments were added to the approach channel, the sediment size and the amount of sediments added during the time of measurement.

5.1 Inlet shape effect

The inlet shape effect, shown in Figure 5.1, consists of three performance curves indicating how the three different culvert inlet shapes influences both the headwater elevation and the culverts capacity. The curves were made on basis of experiments with a slope S =1:5, basin length l_b = 876 mm and clear water conditions, so no sediments were added to the approach channel.

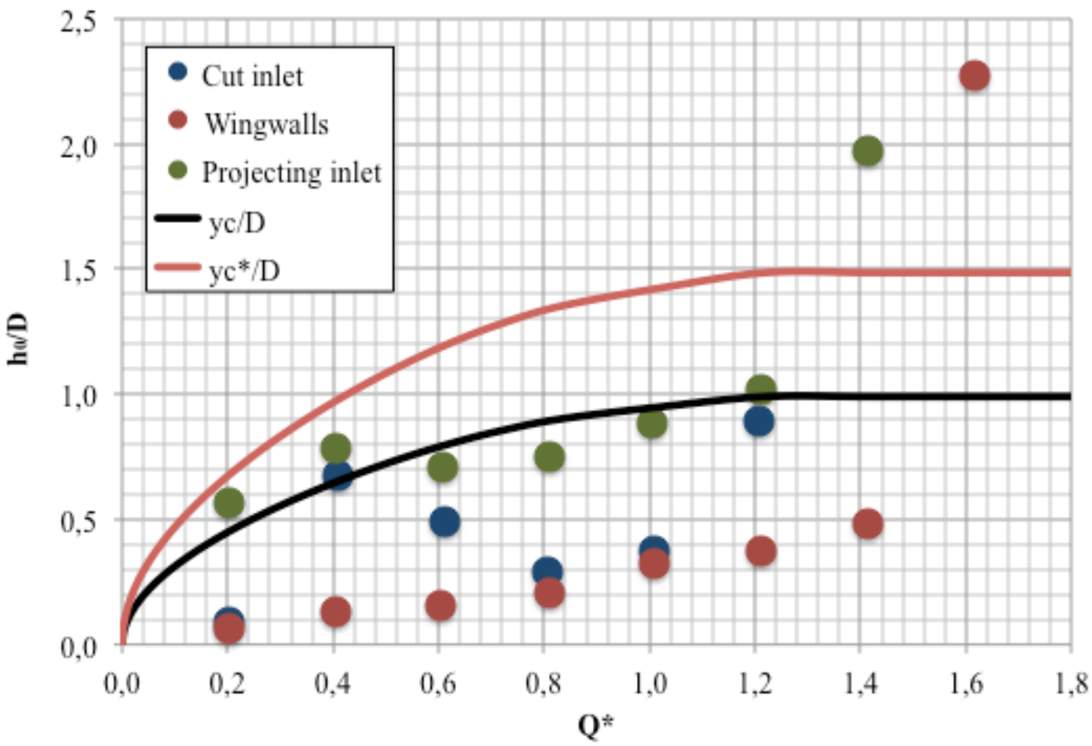


Figure 5.1 Inlet shape effect with slope 1:5, basin length 876 mm and clear water situation

Based on the results from the Figure, the inlet with wingwalls gives the best culvert capacity. As can be seen from the Figure, the last two data points at h_0/D = 1,9 for the projecting inlet and at h_0/D = 2,3 for the inlet with wingwalls, shows that the culvert is outlet controlled. These plots are difficult to compare with the plots that are inlet controlled, because they represent two different flow situations. However, it can be used to describe the capacity of the culvert. If the culverts capacity is too low to swallow the water, it changes from inlet to outlet control such that more water can be forced out with pressure flow. The outlet control plots therefore represent a reach in the capacity.

The curve for y_c* indicates, as described in section 2.1.4, where the culvert goes from inlet to outlet control, but it is not directly accurate to compare y_c*/D with h_0/D. When the water flows through the culvert inlet, the water height will decrease through the barrel. The critical depth will therefore be lower than the headwater elevation. Even though y_c* is compensated for this reduction in the water depth by the factor 3/2, this is still a theoretical value, which assumes zero head loss through the barrel. However, the line can be used as an indication for the transition between inlet and outlet control.

It is also noticeable that the cut inlet has a decrease in the headwater from Q = 4 l/s. This is due to an oscillating pattern that appeared at the next point, Q* = 0,6 (Q= 6 l/s), as shown in Figure 5.2. The oscillation suddenly appeared after some time of running the model, and it is uncertain what caused this to occur. At this stage it can only be speculated that the geometry of the model in combination with the inlet shape was the reason.

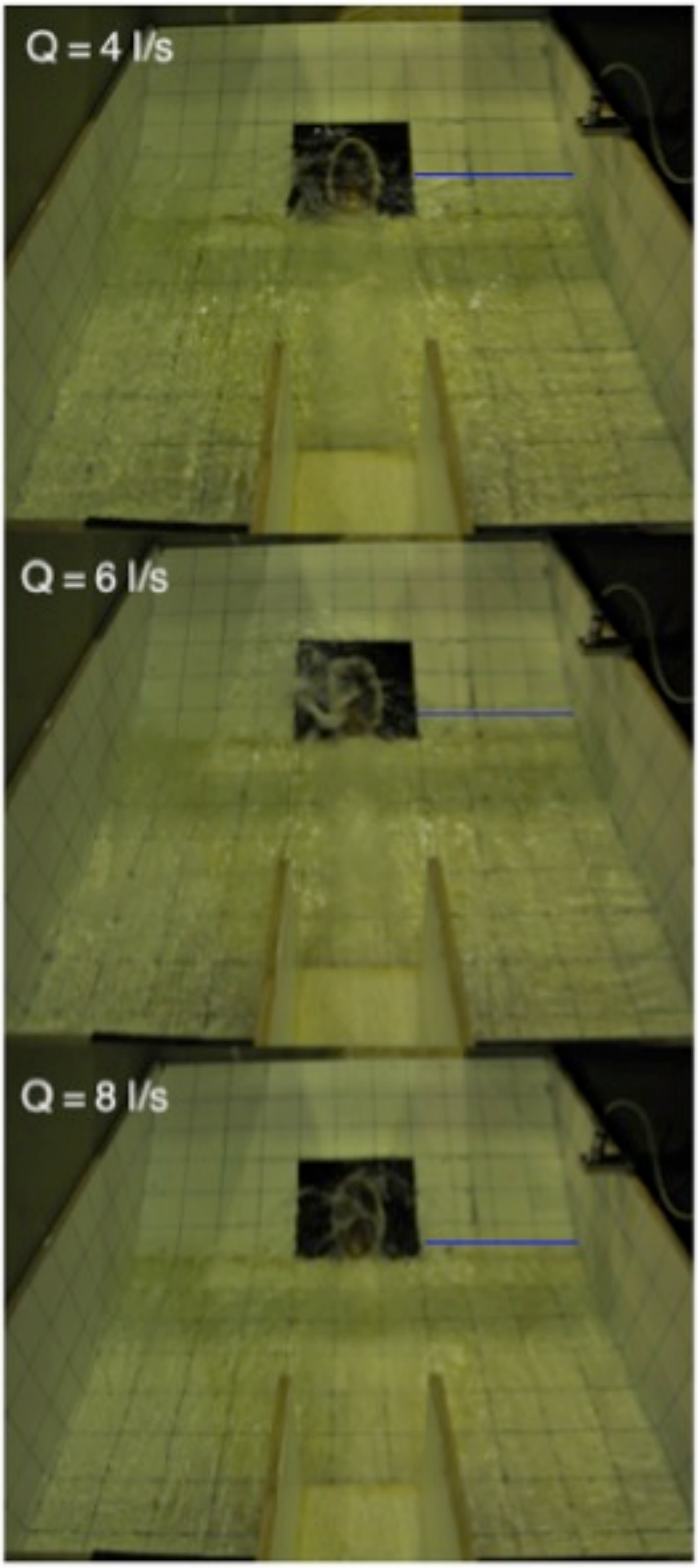


Figure 5.2 Water flow towards a cut inlet at Q = 4 l/s, Q = 6 l/s and Q = 8 l/s, with oscillation at Q = 6 l/s. The blue line to the right represents the decreasing water level in the basin

During the oscillation, the culvert experienced a higher amount of air entrance through the barrel and the water velocity increased. More water was pushed through the culvert, causing the basin to drain and the headwater elevation to decrease. For the cut inlet, this situation endured until the oscillation stopped around Q* = 0,8 (Q = 8 l/s), when the water behaved as a supercritical flow straight through the culvert. Further, the water level in the culvert increased gradually, and the headwater elevation rose accordingly until the limit for overtopping was reached at Q* = 1,2 (Q = 12 l/s). An oscillating pattern also occurred at Q* = 0,4 (Q = 4 l/s) for the projecting inlet, but the flow for this inlet was more stable than for the cut inlet.

5.2 Basin length effect

The basin length effect represents how three different basin lengths influence the culvert capacity and headwater elevation for each of the three inlet shapes. Figure 5.3, 5.4 and 5.7 shows the length effect on the cut inlet, projecting inlet and inlet with wingwalls respectively. The performance curves are all based on a clear water situation with a slope of the approach channel equal to 1:5.

Cut inlet

From Figure 5.3 two data points can be observed for basin length l_b = 625 mm and Q* = 1,0 (Q = 10 l/s). These points are a result of an oscillating pattern, which occurred with 10 minutes interval during the measurements. When the oscillation began, the water level in the basin sank and further the headwater elevation was reduced. After 5 minutes the oscillation disappeared, the culvert experienced full flow and the water level was raised over the limit for overtopping, also overtopping the edge of the basin above the culvert. Similarly, after 5 minutes of full flow the oscillation started again.

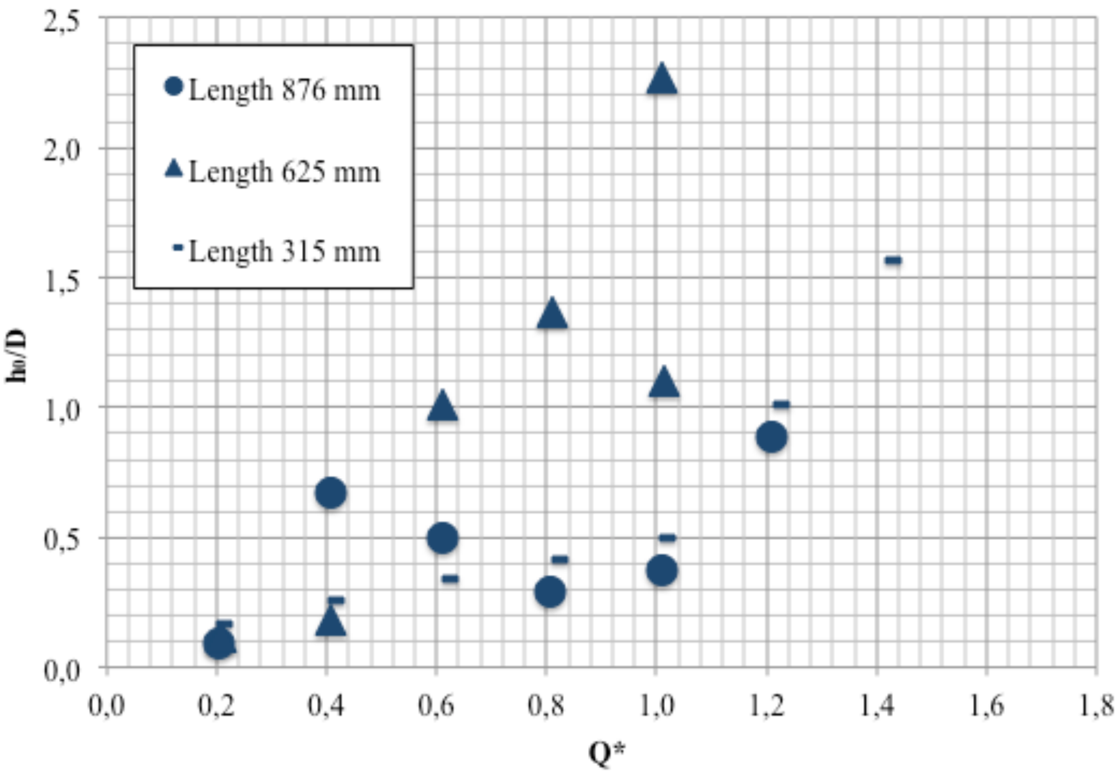


Figure 5.3 Basin length effect on culvert with cut inlet, slope 1:5 and clear water situation

For the cut inlet shape the basin length of 315 mm represents the best length when it comes to the culverts capacity, having low headwater values and stable flow. The curve for basin length l_b = 876 mm is the same as the curve for the cut inlet in Figure 5.1, and therefore show the same local peak at Q* = 0,4 because of the oscillation.

Projecting inlet

Figure 5.4 shows how the different basin lengths affect the projecting inlet. It can be observed that also for this inlet the shortest basin length of 315 mm seems to give the best capacity and has the smoothest performance curve.

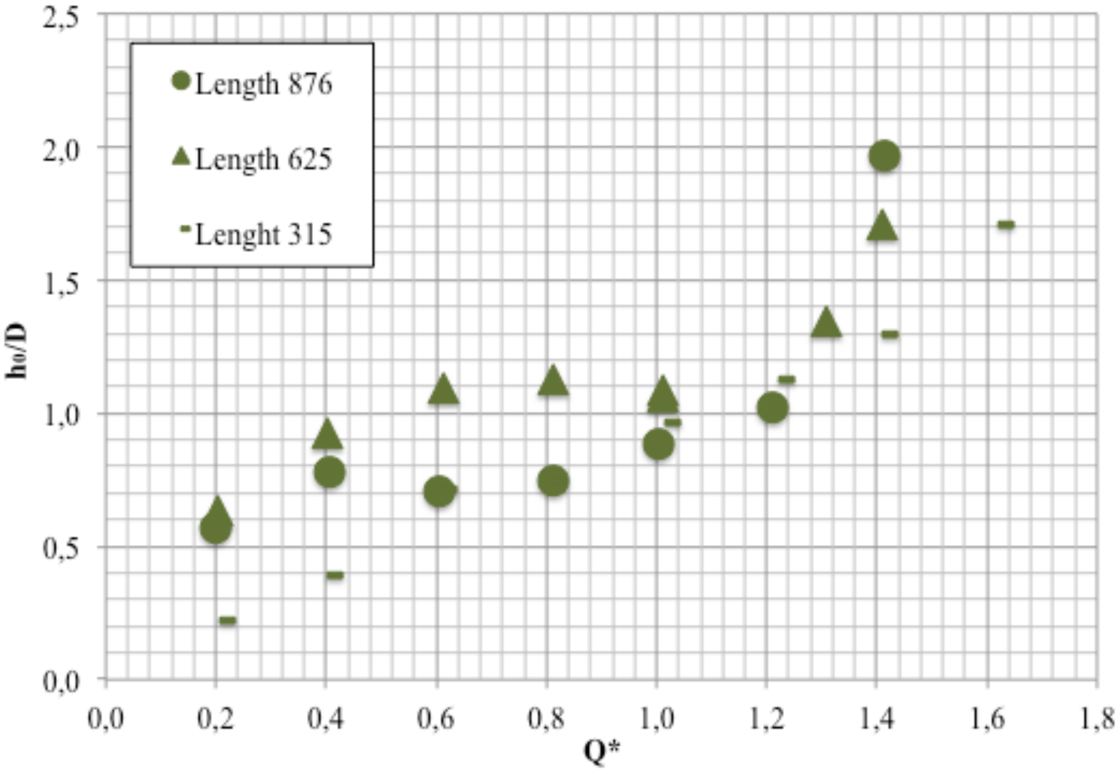


Figure 5.4 Basin length effect on culvert with projecting inlet, slope 1:5 and clear water situation

An oscillating pattern occurred for basin lengths 876 mm and 625 mm, both at Q* = 0,4 (Q = 4 l/s). This endured until the basin was overtopping for l_b = 625 mm and until Q = 6 l/s for l_b = 876 mm. For l_b = 625 mm the headwater elevation at 2 l/s started at a low level when the water flowed straight towards the culvert. During the time of waiting for the system to stabilize, the water level suddenly increased from 10 to 50 mm height above the basin floor. Here, the measurement from the highest water level was chosen, when this was a stable level. Figures 5.5 and 5.6 show the sudden increase in the headwater at 2 l/s and an oscillating pattern at 8 l/s respectively, both for length 625 mm.

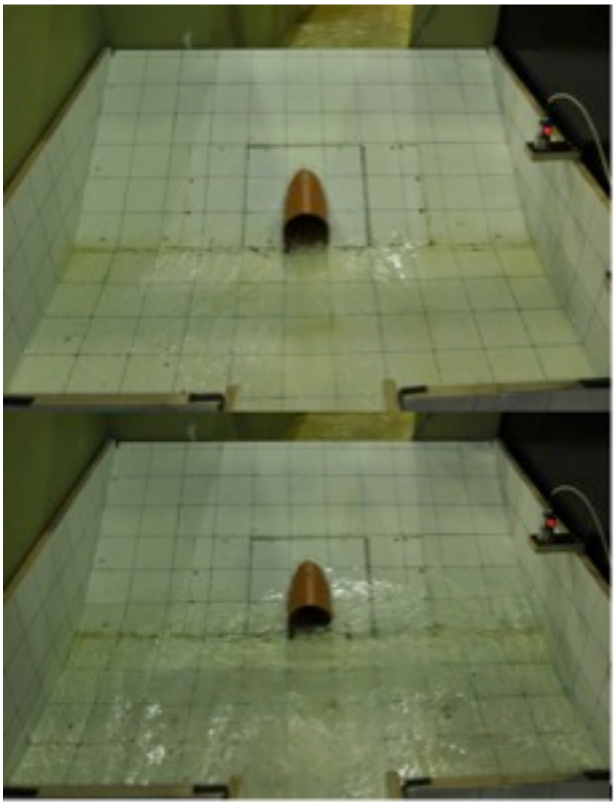


Figure 5.5 Increased water level in basin with projecting inlet and Q = 2 l/s and basin length 625 mm

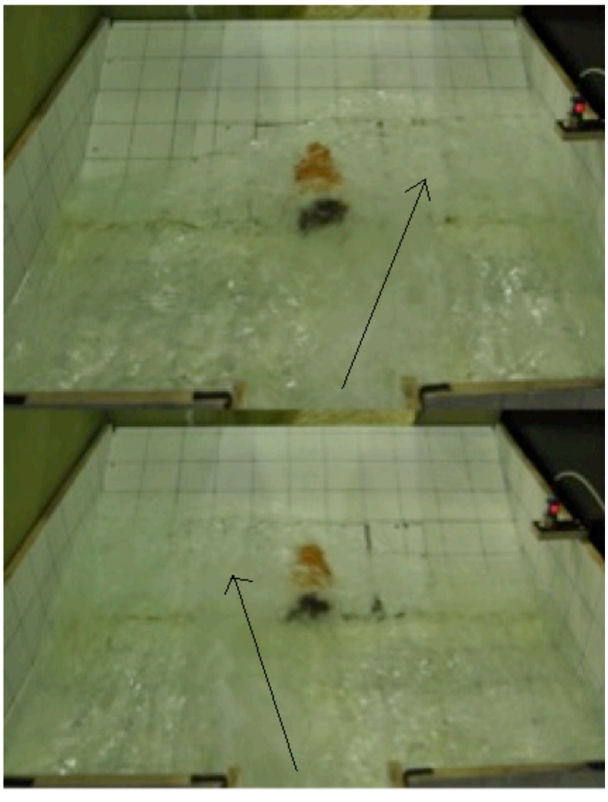


Figure 5.6 Oscillating pattern for projecting inlet with Q = 8 l/s and basin length 625 mm

Wingwalls

From Figure 5.7 it is evident that the basin length does not make a significant difference on the capacity for the lowest discharges for the experiments with wingwalls. On the other hand, the culvert for all three lengths reached outlet control at the highest discharges, where the limit for overtopping was reached. For basin lengths l_b = 315 mm and l_b = 876 mm, the capacity was reached at different headwater values. In general, the lowest capacity can be found for basin length l_b = 625 mm.

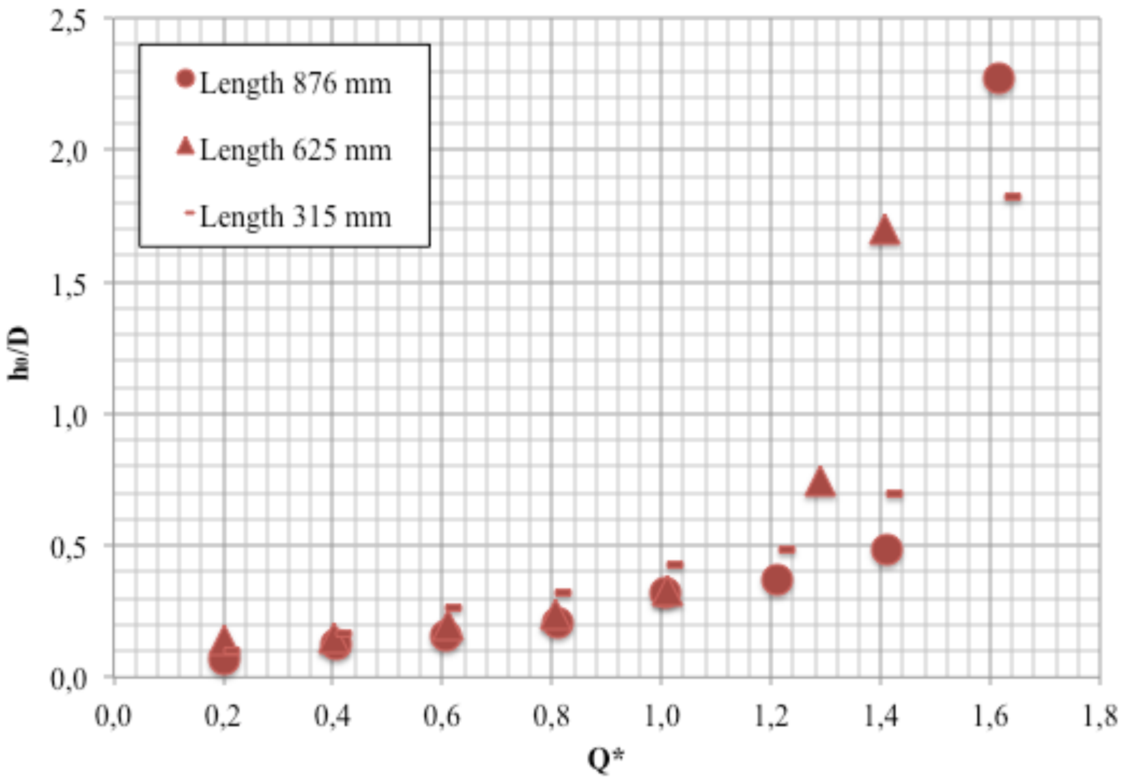


Figure 5.7 Basin length effect on a culvert with wingwalls, slope 1:5 and clear water situation

The circular data point at outlet control, applying to the longest basin length, is higher than the rest of the overtopping plots because the discharge was too high. This resulted in a overtopping of the basin edge above the culvert at Q = 16 l/s, and the water level would probably overtop the limit at a lower discharge. Figure 5.8 shows how overtopping of the basin edge looked like.

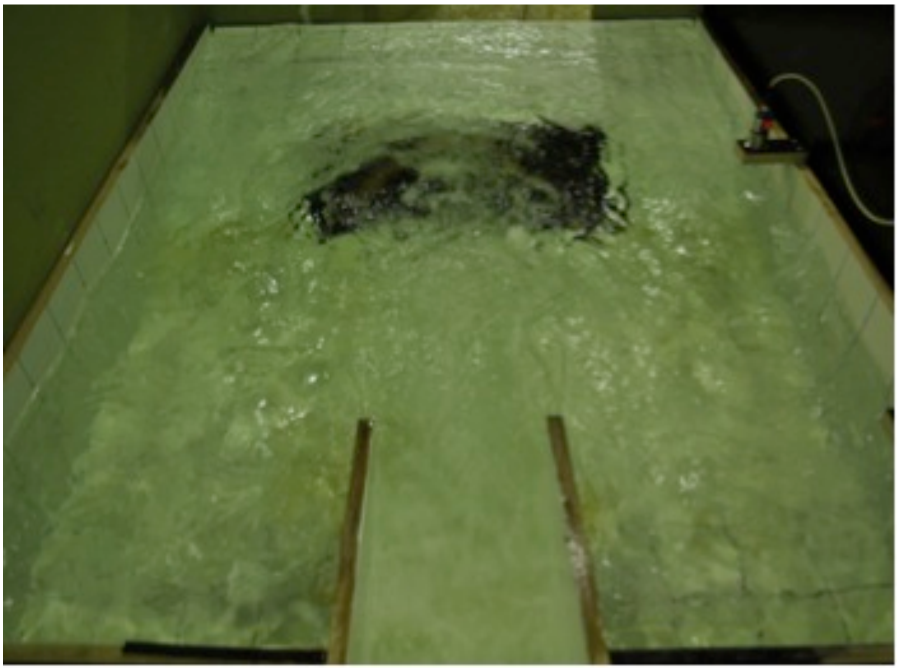


Figure 5.8 Overtopping basin edge for inlet with wingwalls and Q = 16 l/s

5.3 Slope effect from the approach channel

The slope effect consists of two performance curves showing how the slope of the approach channel affects the culvert capacity and headwater for all three shapes of inlets. These performance curves are based on a basin length of 876 mm during a clear water situation, and the slopes that were tested were S = 1:5 and S = 1:9.

Cut inlet

Figure 5.9 indicates that the slope S = 1:5 gives a better culvert capacity than slope S = 1:9. The culvert reaches a discharge of 12 l/s when the slope is at its steepest. For slope 1:9 the discharge only reached 8 l/s before the water level overtopped the limit line and the capacity of the culvert was reached. The headwater elevation is much higher at overtopping for slope 1:9 compared to the headwater for slope 1:5 at overtopping. It is therefore difficult to compare those two values, but the culvert at slope 1:5 still reach a higher discharge before the limit line is reached. It therefore seems like the culvert capacity is better for slope 1:5.

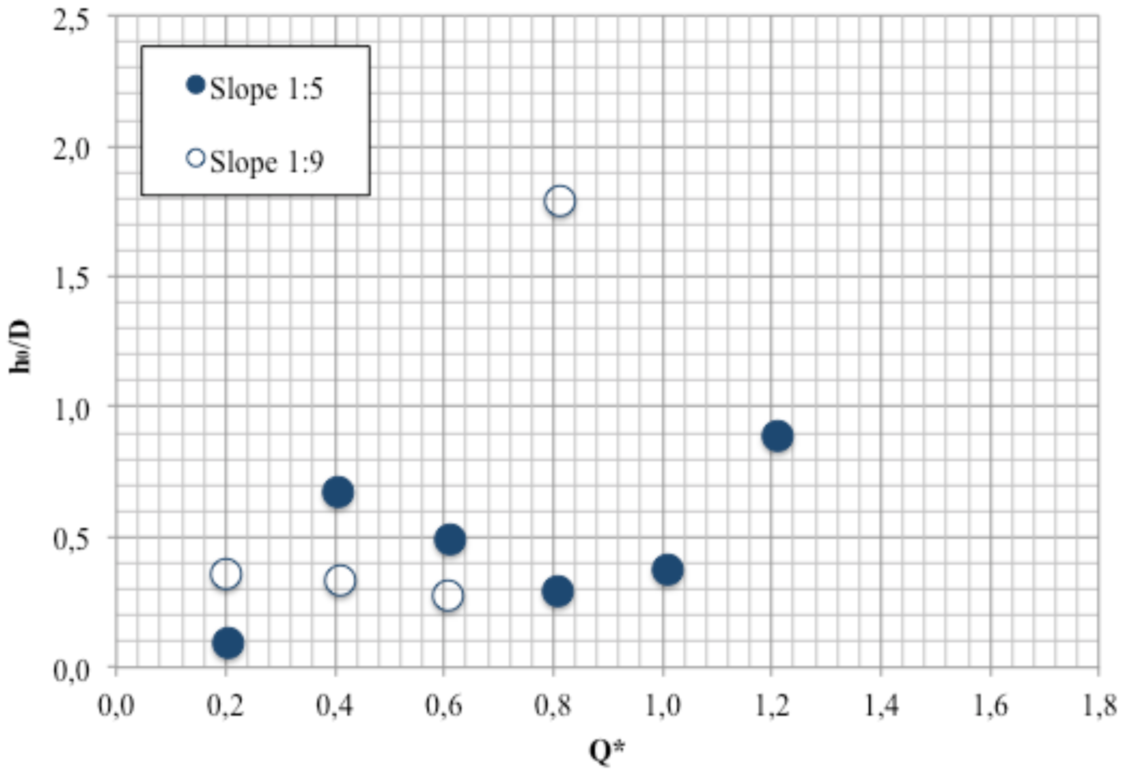


Figure 5.9 Slope effect on a culvert with cut inlet, basin length 876 mm and clear water situation

From the Figure a local peak at Q* = 0,4 is observable. This is due to the oscillation at Q* = 0,6, which did not occur for slope 1:9. The latter has a slightly decrease in the headwater from Q* = 0,2 to Q* = 0,6. This can be explained by the fact that the flow from the approach channel to the culvert inlet changes with the water velocity. For higher discharges the velocity increases in the approach channel, causing the flow to go straight through the culvert barrel at supercritical flow conditions. For this geometry at slope 1:9, the water flow went straight through the culvert until the capacity was reached and the culvert experienced both outlet control and overtopping.

Projecting inlet

From Figure 5.10 it is clear that the slope has close to no influence on the headwater elevation for culverts with projecting inlets. The last data point for the curve with slope 1:9 is hidden behind the plot for slope 1:5, but both slopes reach 16 l/s at overtopping.

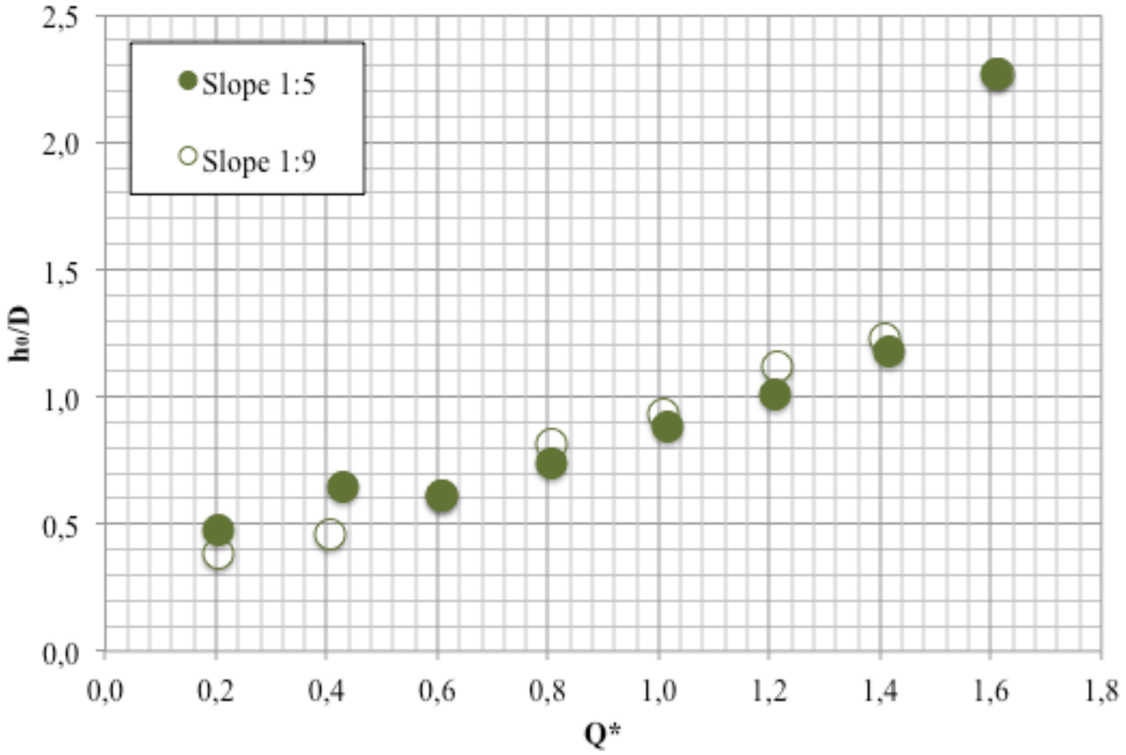


Figure 5.10 Slope effect on a culvert with projecting inlet, basin length 876 mm and clear water situation

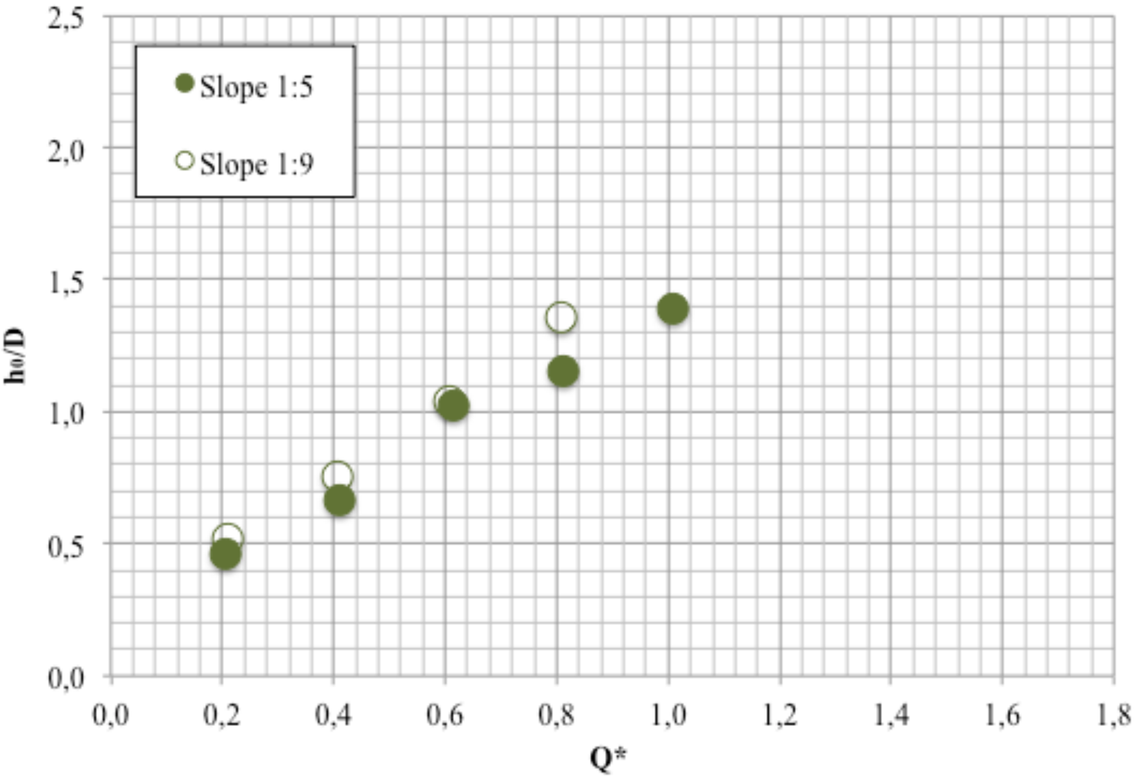


Figure 5.11 Slope effect on a culvert with projecting inlet, basin length 625 mm and clear water situation

Figure 5.11 shows two performance curves for both slopes when the basin length is 625 mm. For the projecting inlet with slope 1:9, one more test was conducted, including two walls placed in the middle of the basin reducing the basin width, as shown in Figure 5.12. The system was then working as a prolonged approach channel directing the water straight into the culvert. These curves also show that the slope does not influence the headwater of the culvert. The difference from basin length 876 mm and full width of the basin is the reduction of the culvert capacity, which is much lower when the width and length are reduced.

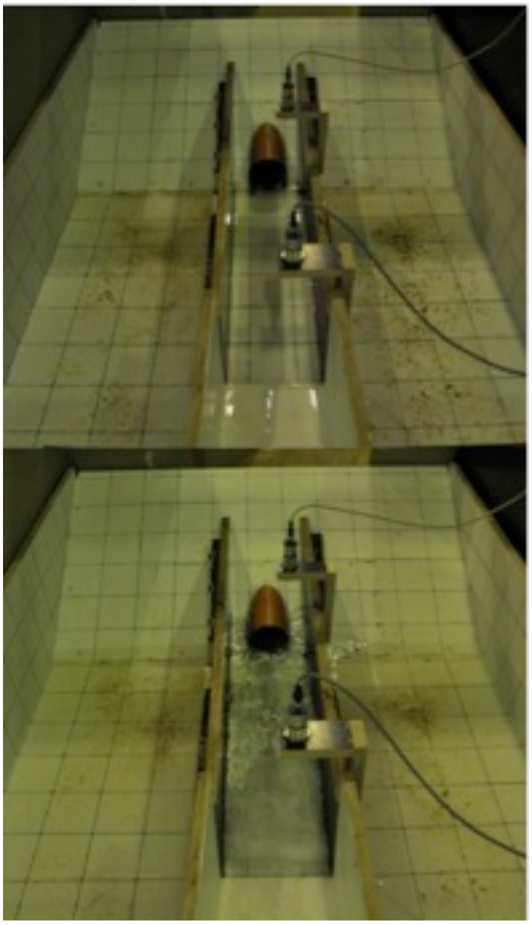


Figure 5.12 Projecting inlet with walls placed in the basin

The test with the walls was only done for the cut inlet shape and slope 1:9 because of the time frame. It will be discussed further in the discussion chapter whether more tests should be conducted.

Wingwalls

Figure 5.13 shows that for the lowest discharges, the slope has no influence on the headwater elevation. The difference in the headwater can be seen when the discharge reach Q = 8 l/s, because the culvert has a much lower capacity when the slope is 1:9 compared with when the slope is 1:5. For S = 1:9, the culverts capacity is reached somewhere between 6 l/s and 8 l/s, even though the water level overtops at Q = 10 l/s, because the culvert is outlet controlled at Q* = 0,8. The steepest slope of 1:5 has a greater culvert capacity, overtopping at 16 l/s.

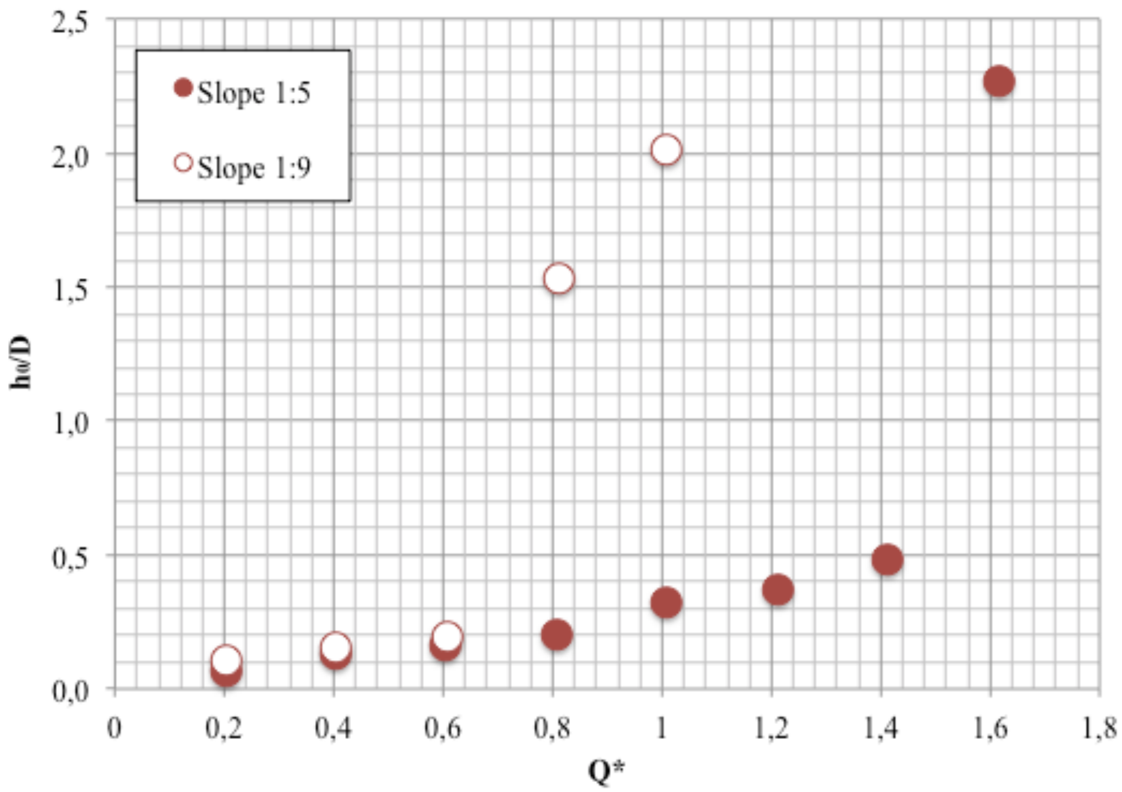


Figure 5.13 Slope effect on a culvert with wingwalls, basin length 876 mm and clear water situation

The Figure also indicates that the culverts capacity for S = 1:5 is actually lower than 16 l/s. At this point the headwater elevation is too high, resulting in an overtopping of the basin edge, as shown in Figure 5.8. This means that the water level would actually reach the limit for overtopping at a lower discharge, between 14 l/s and 16 l/s. It can be observed that the hydraulic jump is at the inlet for both slopes at inlet control. When the culvert reaches outlet control, it is noticeable that the hydraulic jump moves up in the channel end.

5.4 Sediment adding effect

The sediment adding effect shows how the different ways of adding the sediments affect the headwater and culvert capacity. For all the three inlet shapes and lengths, the sediments were added both gradually with a vibrating machine and all at once to the approach channel. The tests were conducted with a slope of 1:5, sediment size of 8 – 16 mm and a total weight of the sediments added equal to 5 kilograms. For both ways of adding the sediments, the discharge and headwater were measured for 15 minutes in total. The clear water curves are also included for a better overview of how the sediments in general affect the headwater and capacity. For the evaluation of the performance curves it is chosen to focus only on the basin length of 876 mm, because the other two lengths gave similar curves. Additionally, the curves for l_b = 876 mm had the best outcome in capacity when sediments were added. The performance curves for the other lengths can be found in Appendix A.

Cut inlet

From Figure 5.14 it is clear that there are some differences between the three curves. Looking at how the sediments were added, it is noticeable that adding the sediments gradually gives a better culvert capacity compared to adding the sediments all at once. It can also be seen that all three curves have a local peak around Q^* = 0,4 (Q = 4 l/s), and that when adding sediments gradually this occurs at Q^* = 0,8 as well. Of course this point could be an error since it only applies when sediments are added gradually, but the time frame made it difficult to validate the measurement.

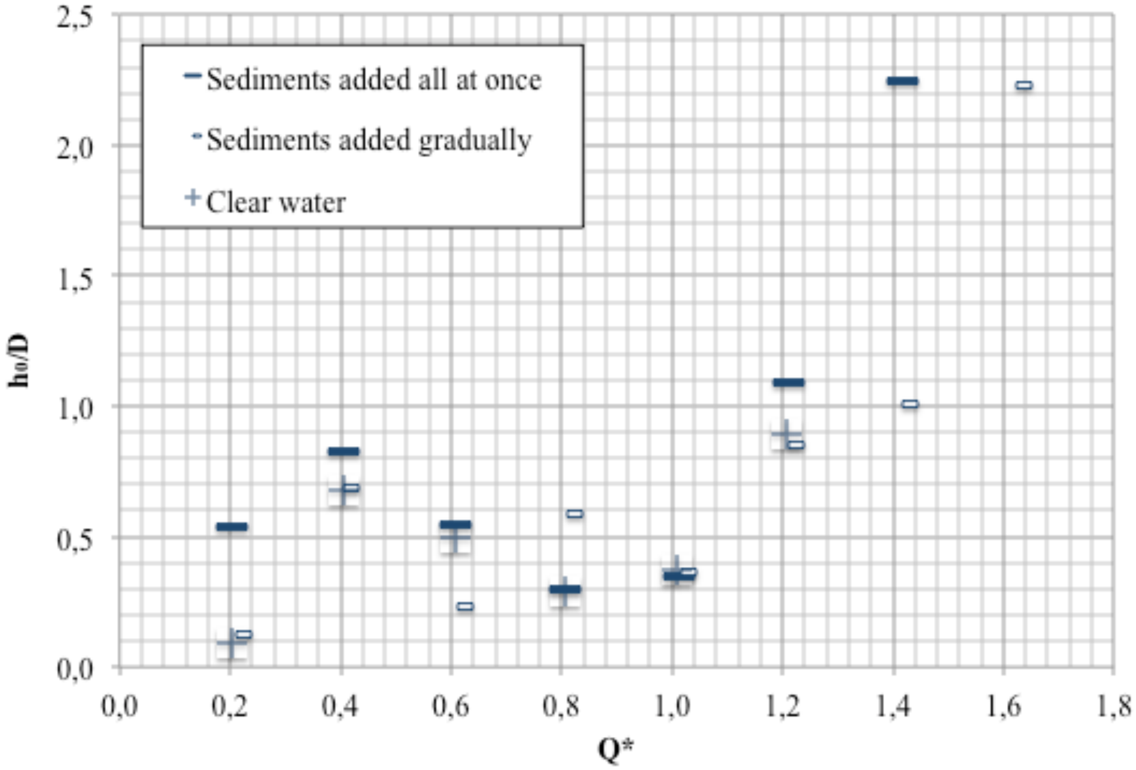
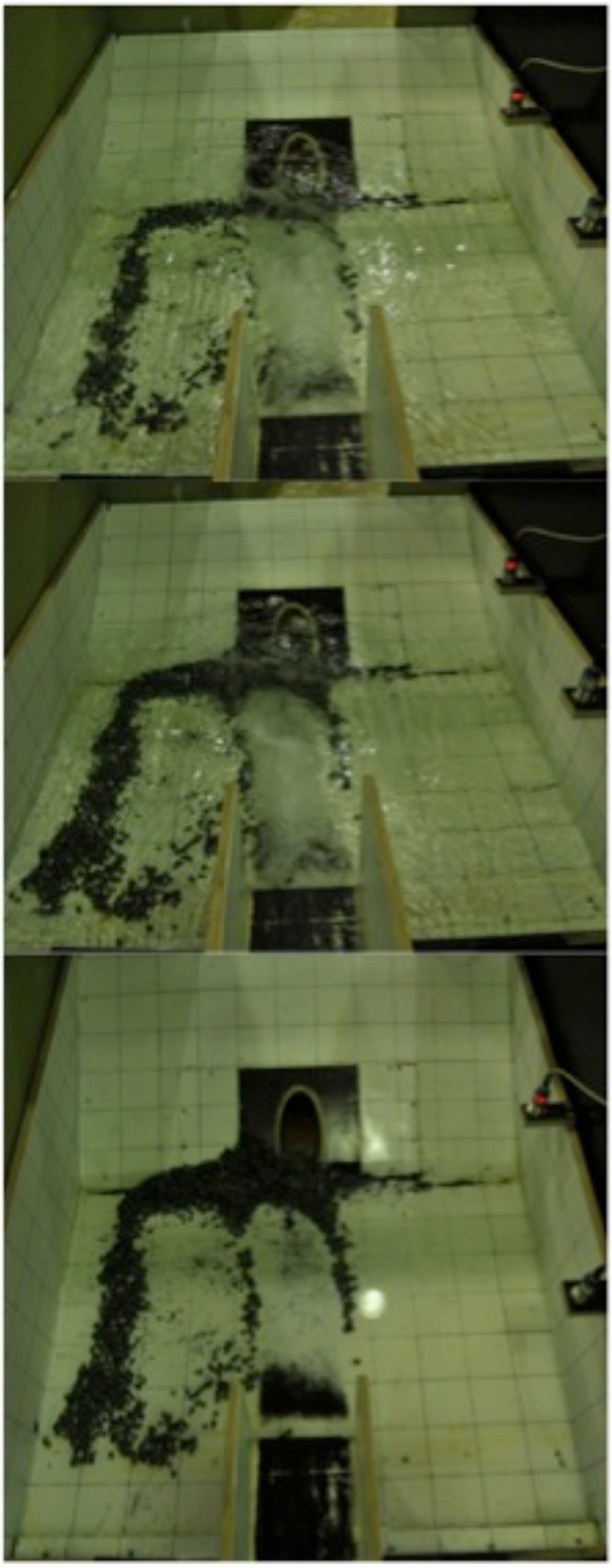


Figure 5.14 Sediment adding effect on a culvert with cut inlet, basin length 876 mm, slope 1:5 and 5 kg of 8 – 16 mm added

For the sediments added gradually, a jet flow directed to the left appeared at Q = 4 l/s. This caused a reduction of the water flow through the barrel and an increase of the headwater elevation. It also made the sediments deposit at the left side of the inlet, as shown in Figure 5.15.

Figure 5.15 Sediment added gradually deposited in front of a culvert with cut inlet and Q = 4 l/s



From the last picture in Figure 5.15 it can be seen that the sediments deposited in front of the culvert inlet, causing the headwater elevation to increase further. The oscillation continued throughout the experiment when the sediments were added gradually, but from Q = 6 l/s it started alternating from left to right, making the pattern of the deposited sediments look more like symmetric wings on each side. The local peak at Q* = 0,8 was caused by drainage of the basin at Q* = 0,6 and Q* = 1,0 because of the change in the flow. At 16 l/s the water overtopped the limit line and the culvert reached its capacity and became outlet controlled. When looking at the pictures it can be observed that the water reached the limit for overtopping at Q = 14 l/s in the beginning, but when adding the sediments, the basin drained.

The performance curve for the sediments that were added all at once and the clear water has the same peak at Q* = 0,4 as the sediments added gradually. For the clear water this is also due to an oscillating pattern occurring at Q = 6 l/s. For the sediments added all at once, the increase in the headwater elevation at Q = 4 l/s was caused by the sediments depositing in front of the culvert inlet and blocking the entrance. A hydraulic jump was induced at the deposition, and the water velocity was not high enough to break the deposited masses, resulting in an increased water level in the basin. At the higher discharges, the velocity was increased such that the water broke through the masses. The headwater elevation then decreased until the capacity of the culvert was reached and the basin overtopped. Figure 5.16 shows a picture of the masses deposited in front of the culvert and how the sediments were deposited when the water broke through.

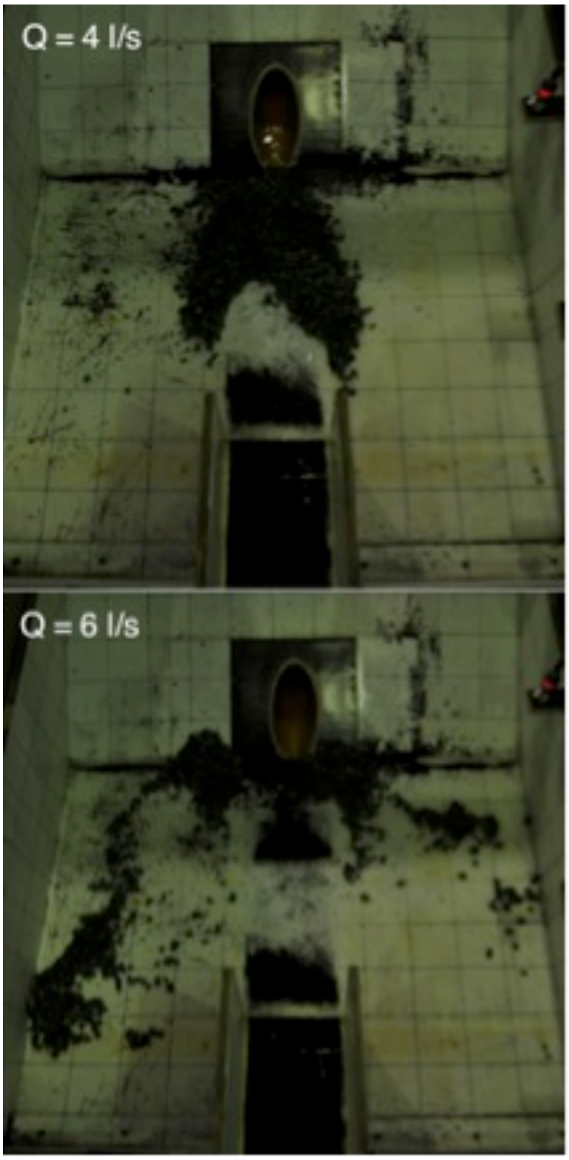


Figure 5.16 Sediments added all at once deposited for a cut inlet at Q = 4 l/s and Q = 6 l/s

For the highest discharge Q = 14 l/s, when the sediments were added all at once, the water level in the basin reached the limit for overtopping in the beginning, but after 1 – 2 minutes the water was overtopping the basin edge. The hydraulic jump moved from the basin to the approach channel, around 20 – 30 centimeters up from the channel end. Again, the water velocity was not high enough to break through the deposited masses, and the sediments were deposited as the upper picture in Figure 5.16. Also for this curve it can be observed that the capacity of the culvert is not at Q = 14 l/s. At this point the basin is overtopping, and the culvert is outlet controlled with pressure flow through the barrel. The culverts capacity at inlet control should be somewhere between 12 l/s and 14 l/s, when the water level is stable at the limit line.

Looking at the pictures of the deposition, the amount of the deposited sediments in the basin is naturally higher when the sediments are released all at once compared to when they are added gradually. This coincides with the values shown in Table B.1 and B.2 in

Appendix B, which gives a summary of the amount of sediments that deposited in the basin and the amount that went through the culvert. In general high amounts of sediments deposited in the basin for the cut inlet.

Projecting inlet

From Figure 5.17 it can be seen that the two ways of adding sediments for the projecting inlet coincide well with both each other and with the clear water situation. The performance curve for the sediments added gradually has a smooth increase in the headwater elevation, which corresponds to the increased discharge. From the pictures taken during the measurements it can be observed that some oscillation occurs from the beginning, but does not influence the headwater elevation. For all discharges, except 2 l/s, sediments deposit as wing on the culvert sides.

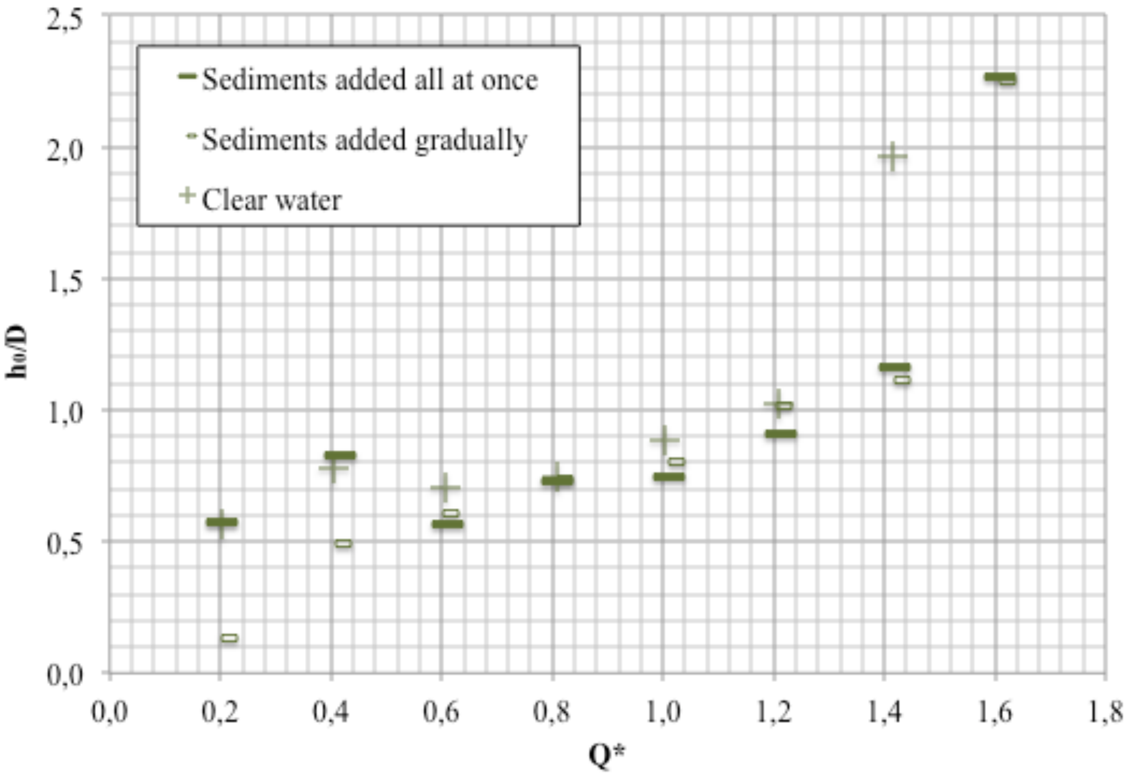


Figure 5.17 Sediment adding effect on a culvert with projecting inlet, basin length 876 mm, slope 1:5 and 5 kg of 8 – 16 mm added

The curves for the clear water situation and the sediments added all at once both have a local peak at $Q^* = 0,4$. For these situations, an oscillating pattern occurred at Q = 6 l/s before it disappeared at Q = 8 l/s. The sediment deposition formed as more or less symmetric wings for most of the discharges, as shown in Figure 5.18. The sediments deposited in front of the culvert inlet for the lowest discharges, blocking the lower area of the basin. This made the headwater elevation increase to the same level as for the clear water situation. When looking at the pictures, the water level seems to be at this height because of a hydraulic jump in the basin, near the channel. This hydraulic jump was also present when the sediments were added gradually and deposited in front of the inlet, so it is difficult to explain the difference in the headwater at 2 l/s.

Figure 5.18 Symmetric deposition of sediments added all at once for a projecting inlet with Q = 12 l/s

For the projecting inlet, the two ways of adding the sediments reach the same culvert capacity at the same headwater elevation at outlet control. This high discharge is caused by pressure flow, so this does not represent the culverts capacity at inlet control. The capacity should be somewhere between 14 l/s and 16 l/s for both ways of adding the sediments. Still, it can be observed that adding the sediments improves the capacity compared to the clear water situation.

The amount that deposited in the basin for the projecting inlet was higher at the lowest discharges when the sediments were added all at once compared to when they were added gradually. When the discharge reached 6 l/s and higher, the difference between the two was not observable. Table B.1 and B.2 summarizes the amounts that deposited and went through.

Wingwalls

Figure 5.19 shows that the clear water situation, and the two ways of adding the sediments, coincide more or less perfectly for the lower discharges. The deviation for the headwater at $Q^* = 0,2$ for the curve with sediments added all at once, is caused by a sediment mass building up at the end of the approach channel. This deposition inhibits the water to flow directly through the culvert barrel, causing an increase in the water level in the basin.

At $Q^* = 1,6$ there is an obvious variation in the headwater elevation between the three curves. At this point the culvert reaches its capacity when sediments are added all at once.

The culvert has already reached its capacity for the clear water situation, between 14 l/s and 16 l/s at inlet control. When sediments are added gradually, it is noticeable that the capacity is still sufficient, and the capacity is reached somewhere between 16 l/ and 17 l/s during inlet control.

Figure 5.20 shows a picture of how the basin suddenly flowed full from 14 l/s to 16 l/s discharge for the clear water situation. The curve with sediments added all at once overtops at Q = 16 l/s, due to the water jet from the approach channel, which hit the top of the culvert inlet causing waves to appear in the basin. These waves always overtopped one side of the culvert, and the limit was reached.

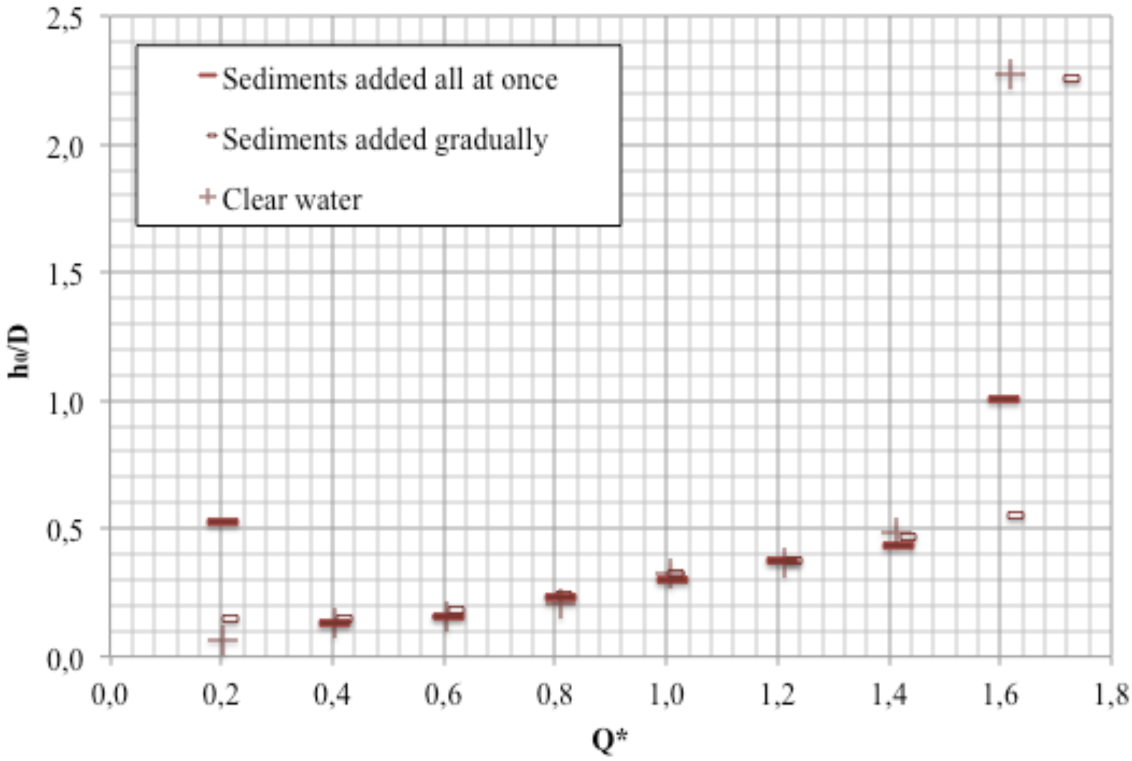


Figure 5.19 Sediment adding effect on a culvert with wingwalls, basin length 876 mm, slope 1:5 and 5 kg of 8 – 16 mm added

The sediment deposition for the two adding methods was most frequently symmetric wings on each side of the culvert. For some discharges the sediments deposited as asymmetric wings or as a mass in front of the inlet.

For the wingwalls, the sediment amount that deposited in the basin was lower than for the other inlets. The amount was higher when the sediments were added all at once compared to when they were added gradually, and a summary can be found in Table B1 and B.2 in Appendix B.

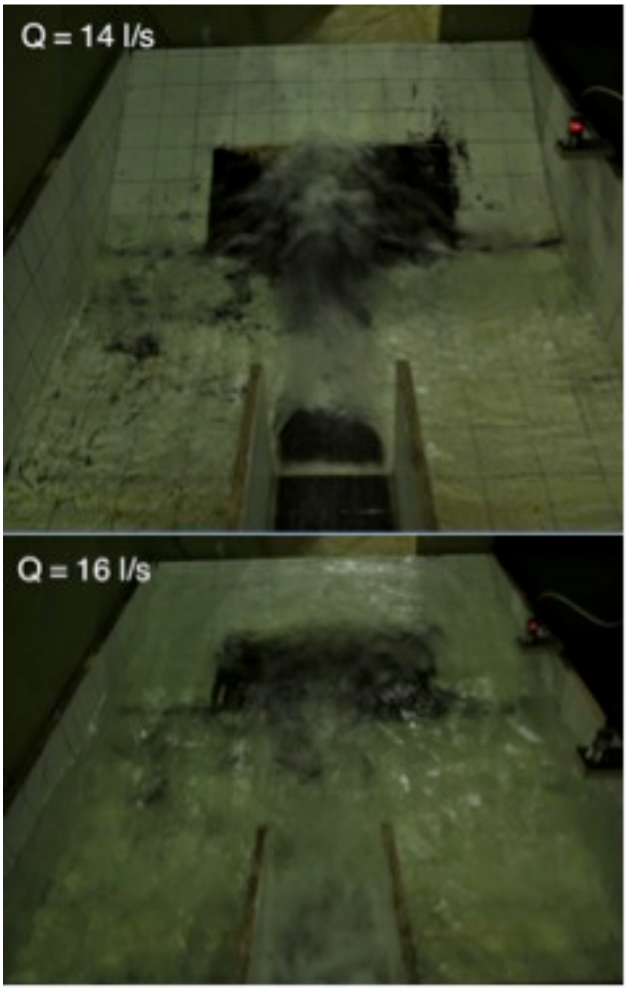


Figure 5.20 Culvert with wingwalls going from not overtopping at Q = 14 l/s to overtopping the basin edge at Q = 16 l/s for clear water situation

From the second the sediments were released and until the measurements were finished 15 minutes later, the headwater in the basin changed over time. To find the value that is used in the effect graphs, several values were averaged over a time where the headwater level was stable. Figure 5.21 and 5.22 show an example of how the headwater developed over time, and from where the stable values were found.

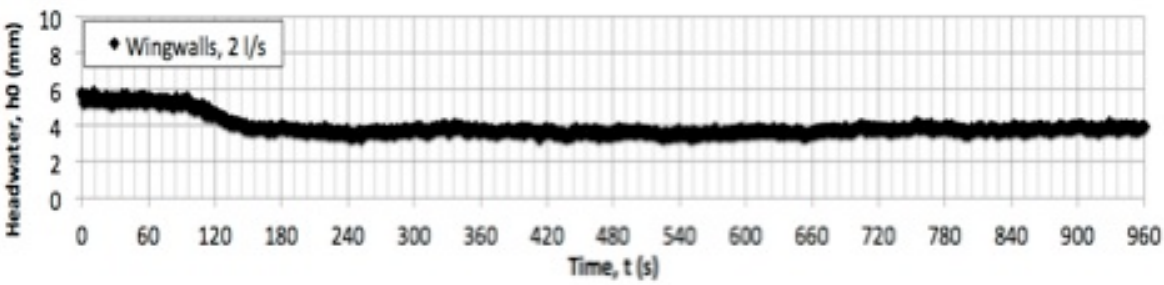


Figure 5.21 Headwater over time for a culvert with wingwalls, Q = 2 l/s, basin length 625 mm, slope 1:5 and 5 kg sediments of 8 – 16 mm sediments added gradually

From Figure 5.21 it can be seen that the headwater reaches a stable level after about 150 seconds. The values for this headwater elevation were therefore averaged over the last 810 seconds of the measurement. This procedure was done for all the measurements, such that a stable value for the headwater was found for all discharges.

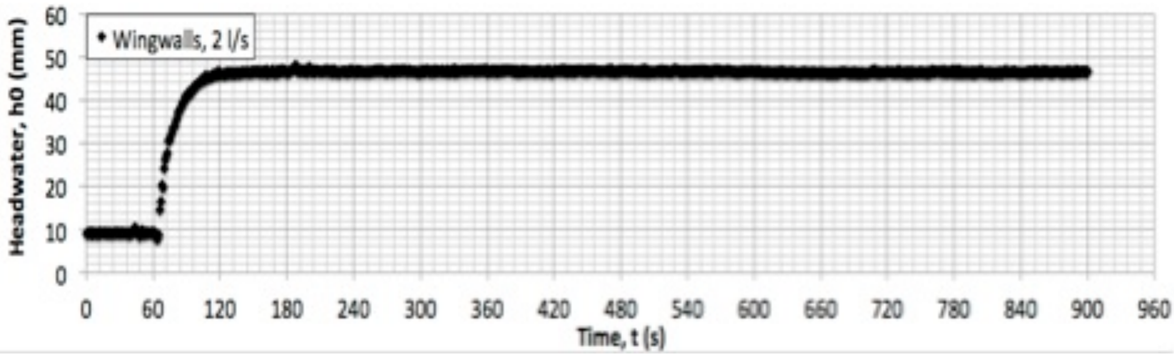


Figure 5.22 Headwater over time for a culvert with wingwalls, Q = 2 l/s, basin length 625 mm, slope 1:5 and 5 kg sediments of 8 - 16 mm added all at the same time

Figure 5.22 shows that when the sediments are added all at once, the development of the headwater over time can be different from when the sediments are added gradually. Similarly, this counts for the other two inlets and for higher discharges. It can also be observed that the headwater is stable after 120 seconds, making the headwater elevation averaged over the last 830 seconds of the measurements. This wingwall test was measured over a time frame of 15 minutes in total, because the 60 seconds of clear water was included in the first sediment measurements. It was later found that the sediments should be added and measured for 15 minutes alone, making the measurement 16 minutes in total with the 60 seconds of measurements before adding sediments.

It is noticeable that the headwater in the beginning with clear water is not the same for the two graphs in the Figures. When looking at the pictures, it seems like this could be an effect of a hydraulic jump at the channel end before the sediments were added all at once. From the pictures taken before the sediments were added gradually, such a hydraulic jump is not visible.

5.5 Sediment size effect

The sediment size effect shows the difference between two sediment sizes and how they affect the headwater elevation and culvert capacity for all of the three inlet shapes. The sediment sizes that were tested were in the range of 8 to 16 mm and 16 to 32 mm. For all three inlet shapes the basin length was 625 mm, the slope was 1:5 and the sediments were added gradually. The scale on the vibrating machine altered depending on the size, but the total weight added to the approach channel during the 15 minutes of adding was 5 kilograms.

Cut inlet

From Figure 5.23 it can be seen that the difference in the capacity at inlet control is insignificant for the two sizes. The slightly difference is indicated by the headwater elevation at 10 l/s during outlet control, which is higher for the smallest sediment size range at overtopping. This was due to an increase of the water level in the middle of the measurement. When the measurement started, the water flow had an oscillating pattern from one side of the basin to the other. After about 5 minutes of adding the sediments, the basin overtopped completely making the sediments deposit in front of the culvert inlet. In the last 5 minutes the basin drained again, but the water flow did not oscillate. It was chosen to take the average of these three situations, resulting in the plot at Q* = 1,0 and h_0/D =1,75. The last plot for the bigger sediment size had an opposite behavior, because it started with overtopping of the basin and ended with an oscillating flow. The last behavior endured for the longest period of the measurement, making the headwater value averaged over this time. The sediments deposited as symmetric wings on each side of the culvert inlet.

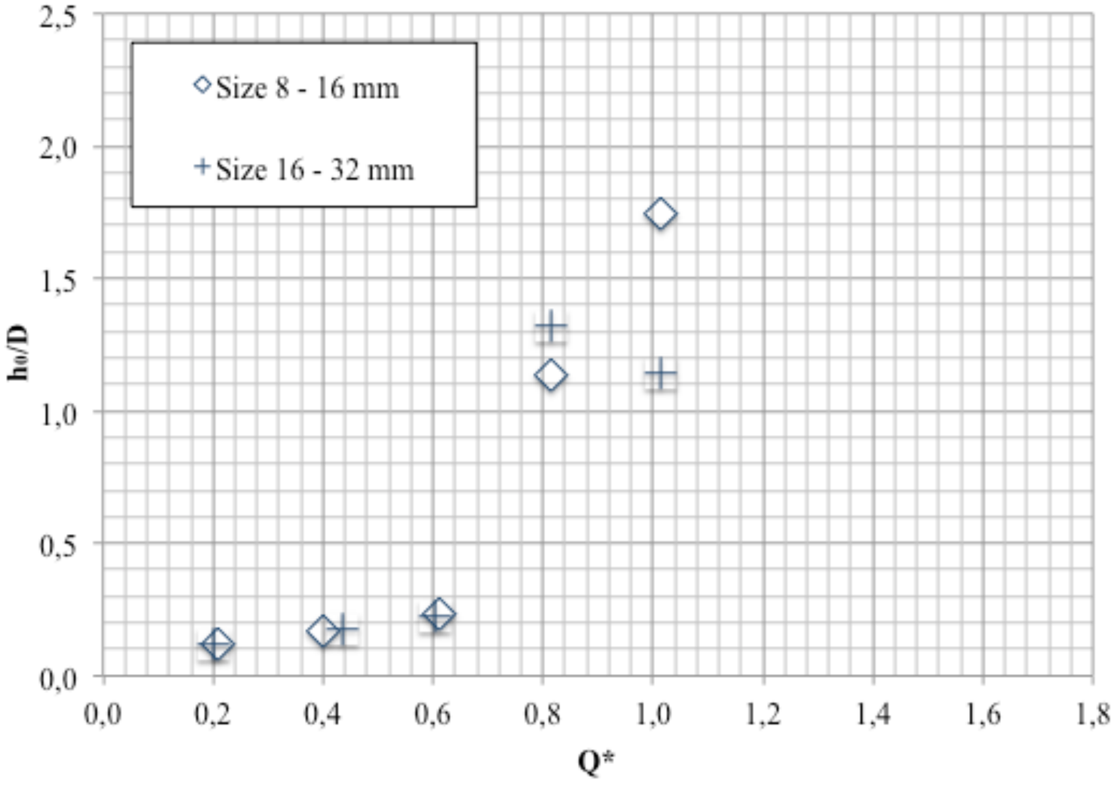


Figure 5.23 Sediment size effect on a culvert with cut inlet, basin length 625 mm and 5 kg of sediments added gradually

From Table B.7 and B.8 it can be seen that the sediment size has little influence on the amount of deposited sediments in the basin. The amount in percentage is more or less the same for the two sizes.

Projecting inlet

Figure 5.24 shows that the two sediment sizes coincide more or less perfectly for the projecting inlet. When looking at the pictures from the experiments, the deposition for the two curves is close to identical. For Q = 2 l/s the sediments deposit in front of the culvert inlet, initiating an increase in the headwater elevation from the beginning. Further, the deposition follows a symmetric pattern on each side of the culvert inlet, as shown in Figure 5.25.

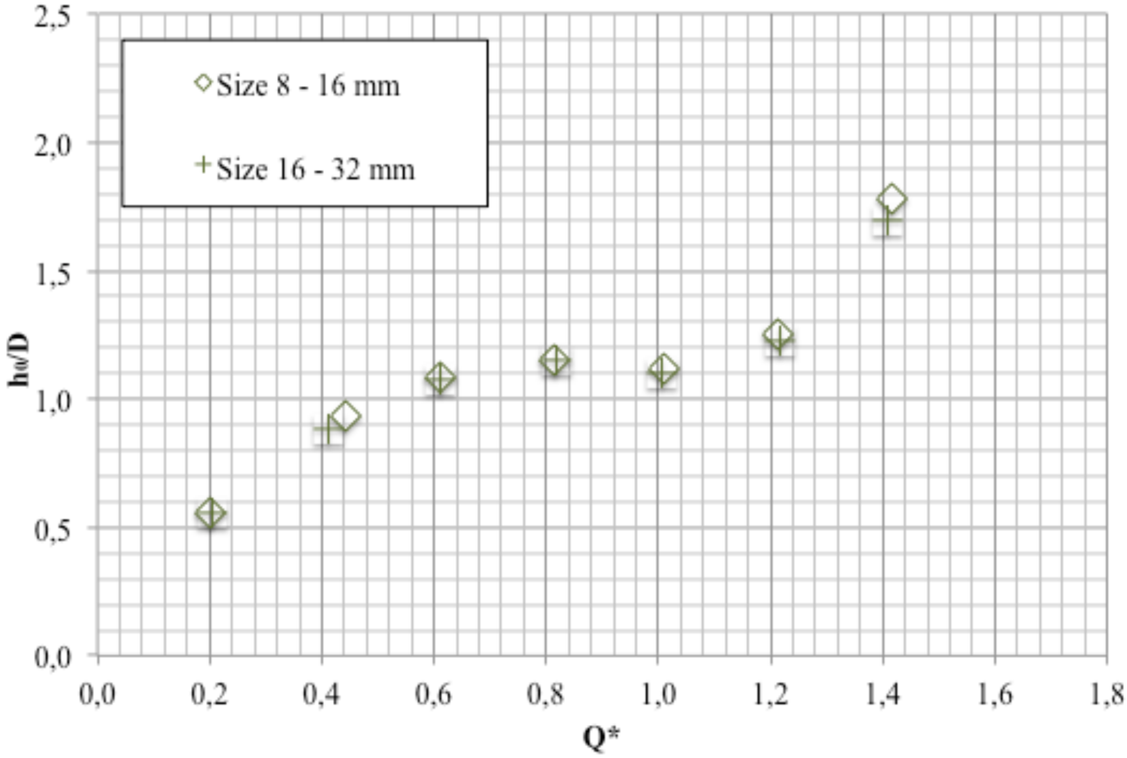


Figure 5.24 Sediment size effect on a culvert with projecting inlet, basin length 625 mm and 5 kg of sediments added gradually

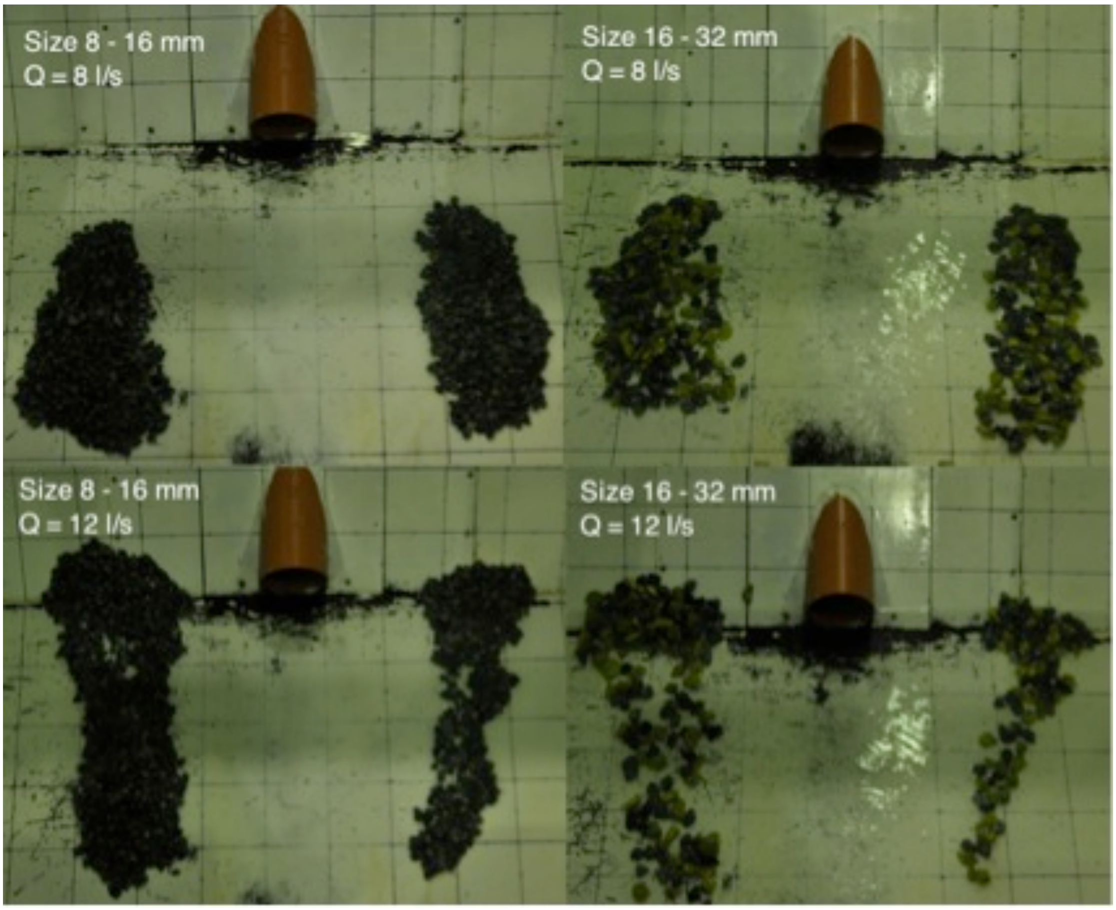


Figure 5.25 Sediment deposition for a projecting inlet when adding the sediments gradually

The difference between the pictures in Figure 5.25 is the amount of sediments deposited. Even though the bigger fraction weighs more than the smaller fraction, the weight of the deposited sediments in the basin was somewhat higher for size 8 – 16 mm for most of the discharges. In percentage of the total amount added, the smallest fraction size had the highest deposition in the basin for all discharges. Table B.7 and B.8 gives a summary of these amounts.

Wingwalls

Also for the wingwalls the two sizes coincide very well, as shown in Figure 5.26, and the size has very little influence on the culverts capacity or headwater. The capacity is reached between Q = 12 l/s and 14 l/s for both sizes at inlet control. Looking at the pictures it can be observed that the sediments deposit as asymmetric wings on each side of the culvert inlet for both sizes, even though the deposition is more uneven for the bigger size at the lowest discharges. In general the weight of the sediments deposited in the basin is low, hence most of the sediments added were transported through the culvert for both sizes. A summary of the amounts is given in Table B.7 and B.8.

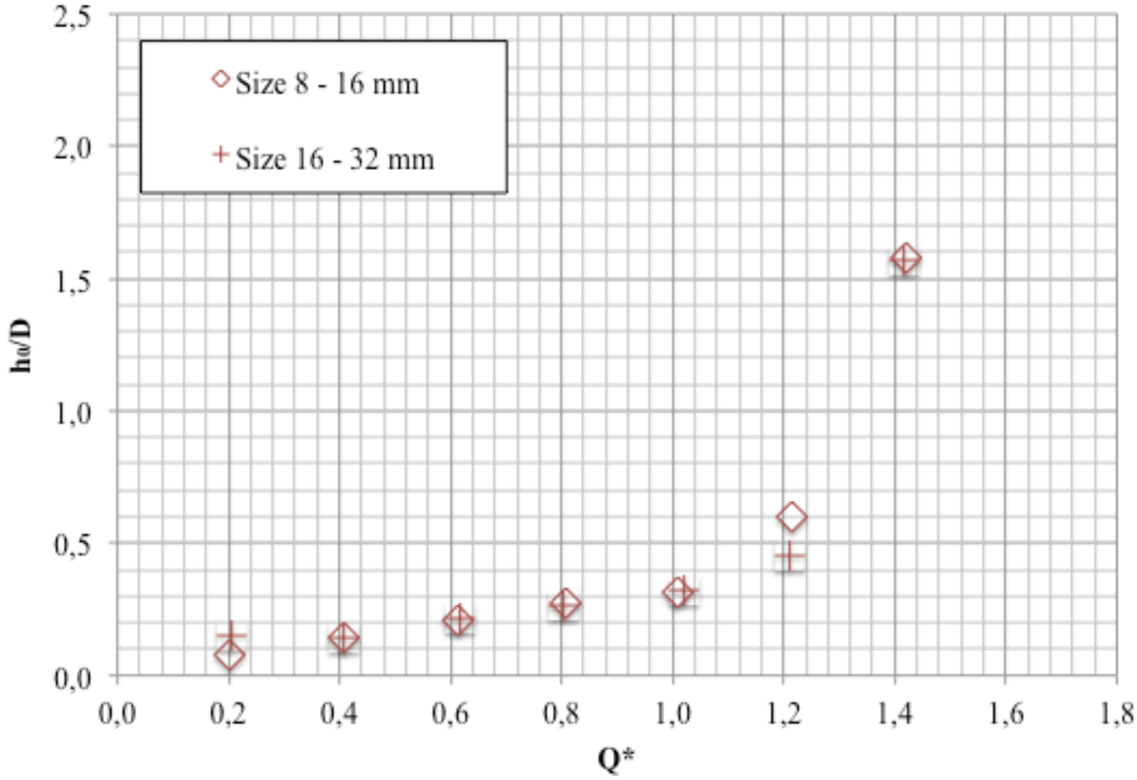


Figure 5.26 Sediment size effect on a culvert with wingwalls, basin length 625 mm and 5 kg of sediments added gradually

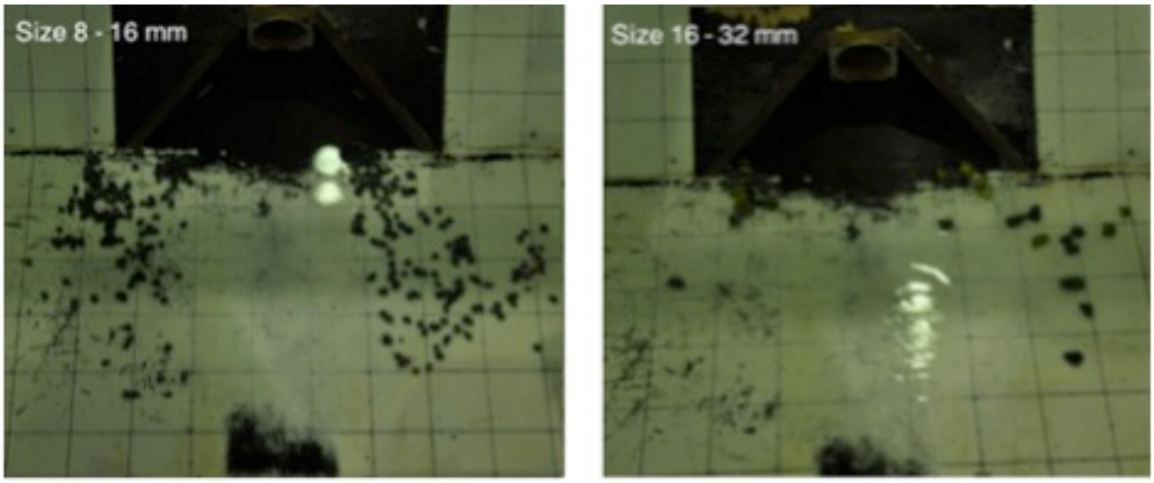


Figure 5.27 Sediment deposition for a wingwall with Q = 8 l/s and sediments added gradually

Figure 5.27 shows the difference between the deposited sediments both in amount and pattern for Q = 8 l/s.

5.6 Effect of added mass

The effect of added mass shows the effect on how the total amount of sediments added to the approach channel influence the headwater and capacity of the culvert. For all the three inlet shapes the tests were conducted with a basin length of 876 mm, slope 1:5 and sediments added gradually. The total amount of the sediments that were added had a weight of 5 kg and 7 kg, added from the vibrating machine. The scale was set to be 42,5 when adding 7 kg of sediments, and 36 when adding 5 kg.

Cut inlet

From Figure 5.28 it can be observed that for most of the discharges the amount of sediments added has little influence on the capacity. It can be a little difficult to see, but the plots with no fill are the ones representing the 5 kg added, as described in Table 4.5. The pictures show an oscillating pattern to the left of the culvert at Q = 4 l/s when 5 kg were added. This made the sediments deposit at the left side and in front of the inlet, making the water level in the basin higher than for Q = 2 l/s and Q = 6 l/s.

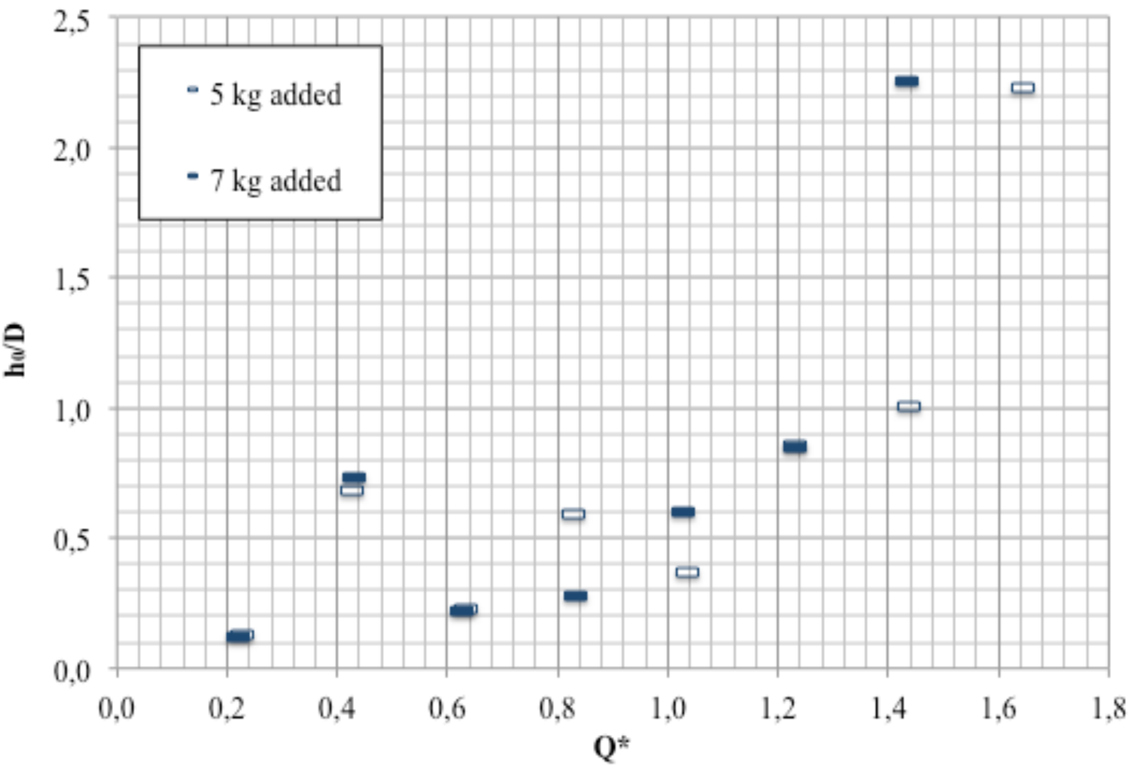


Figure 5.28 Sediment weight effect on a culvert with cut inlet, basin length 876 mm and sediments added gradually

The local peak at Q* = 0,8 was caused by a change in the flow at Q = 10 l/s, which changed from a slightly oscillation pattern to the left to a jet straight through the culvert. This caused the basin to drain and the headwater elevation to sink. As described in the sediment adding effect for the cut inlet, the water level reached the limit for overtopping at

Q = 14 l/s but decreased when the sediments were added. This also applies for the curve with 5 kg sediments added, and the capacity of the culvert should be between 14 l/s and 16 l/s, since the culvert overtops the basin at Q = 16 l/s and is outlet controlled.

The curve for the 7 kg added sediments also show a local peak at Q* = 0,4, which similarly to the 5 kg added was caused by an oscillating pattern to the left and made the sediments deposit in front of the inlet. For the other discharges the headwater elevation follows the increase until the basin is overtopping at 14 l/s. At Q = 12 l/s the water level touched the limit line a few times, but not always. It was therefore chosen to increase the discharge to 14 l/s, where the culvert became outlet controlled, and the capacity of the culvert should be somewhere between 12 l/s and 14 l/s.

The sediment deposition for the two amount of sediments added were more or less asymmetric wings on each side of the culvert, or a mass of sediments in front of the inlet. The exception was for discharge 12 l/s and 14 l/s for the amount of 7 kg, and 16 l/s for the amount of 5 kg, where the wings on each side were symmetric.

When it comes to the amount of sediments deposited in the basin, the amount was close to the same. For most of the discharges, more sediments deposited in the basin when 5 kg were added compared to when it was added 7 kg, as can be seen in Table B.2 and B.9.

Projecting inlet

Figure 5.29 indicates higher headwater values for the lower discharges when the total sediment amount added is equal to 5 kg compared to a total amount of 7 kg, especially for the two lowest discharges. At Q = 2 l/s this was due to sediment masses, which deposited in front of the culvert inlet and hindered the water to run properly through. At Q = 4 l/s the flow was oscillating, but it was also oscillating for the higher discharges. There were no signs during the measurement or in the pictures of anything that could describe why the headwater elevation was higher for 5 kg added compared to 7 kg added. For the other discharges, the sediment deposited as asymmetric wings on each side. The limit for overtopping was reached at Q = 14 l/s, when the waves in the basin altered from one side to the other.

For the performance curve representing the total sediment amount of 7 kg added, the increase in the headwater elevation corresponds to the increase of the discharge. At Q = 4 l/s and Q = 6 l/s the flow was oscillating to the left and to both sides respectively, making the sediment deposition look like asymmetric wings. For Q = 2 l/s and the higher discharges the sediments deposited as symmetric wings on each side. The difference between the two sediment depositions at Q = 2 l/s and Q = 4 l/s can be seen in Figure 5.30.

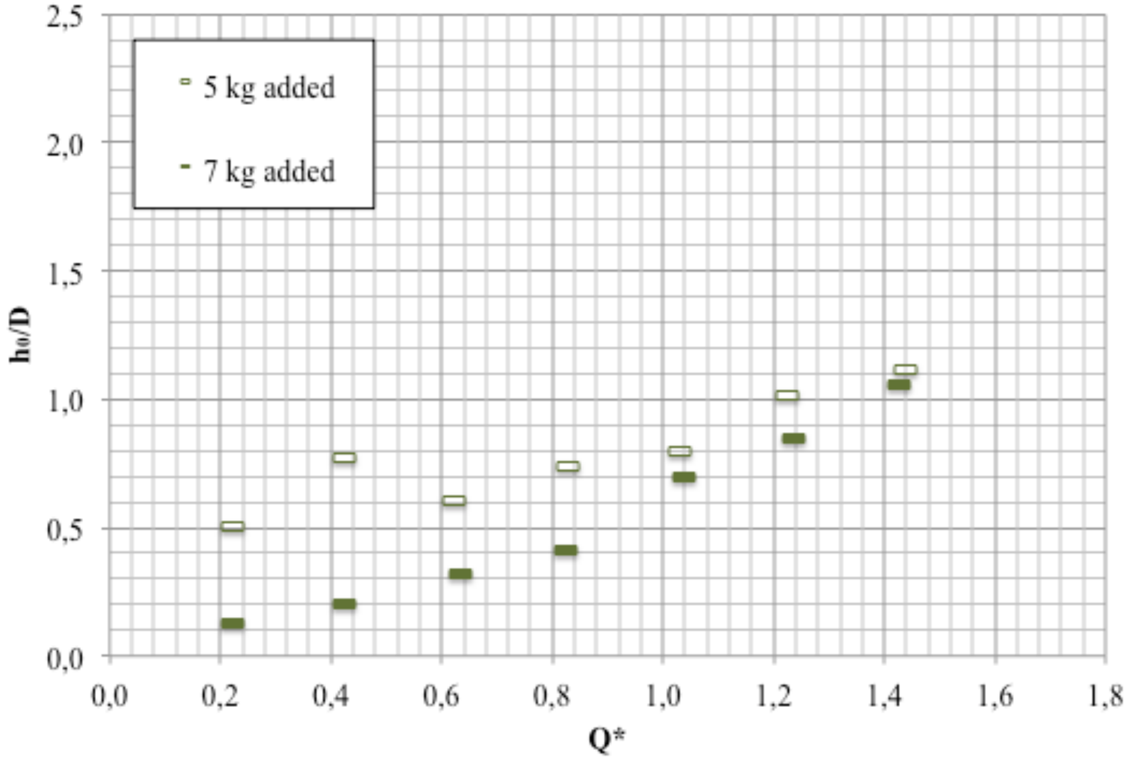


Figure 5.29 Sediment weight effect on a culvert with cut inlet, basin length 876 mm and sediments added gradually

It is strange that the headwater elevation is higher when a lower amount of sediments are added. When 7 kg were added, the amount per minute were higher compared to when adding 5 kg, so naturally one would think that more sediments should deposit when adding more. The reason for the high deposition when adding 5 kg seems to be a hydraulic jump in the channel end, which lowered the velocity of the sediments and made them deposit in the basin as a mass in front of the inlet. When the amount of 7 kg was added, the water behaved as a shooting jet flow without the hydraulic jump, and most of the sediments went straight through the culvert. The ones that deposited in the basin were left as small wings on the sides of the inlet, not influencing the headwater elevation.

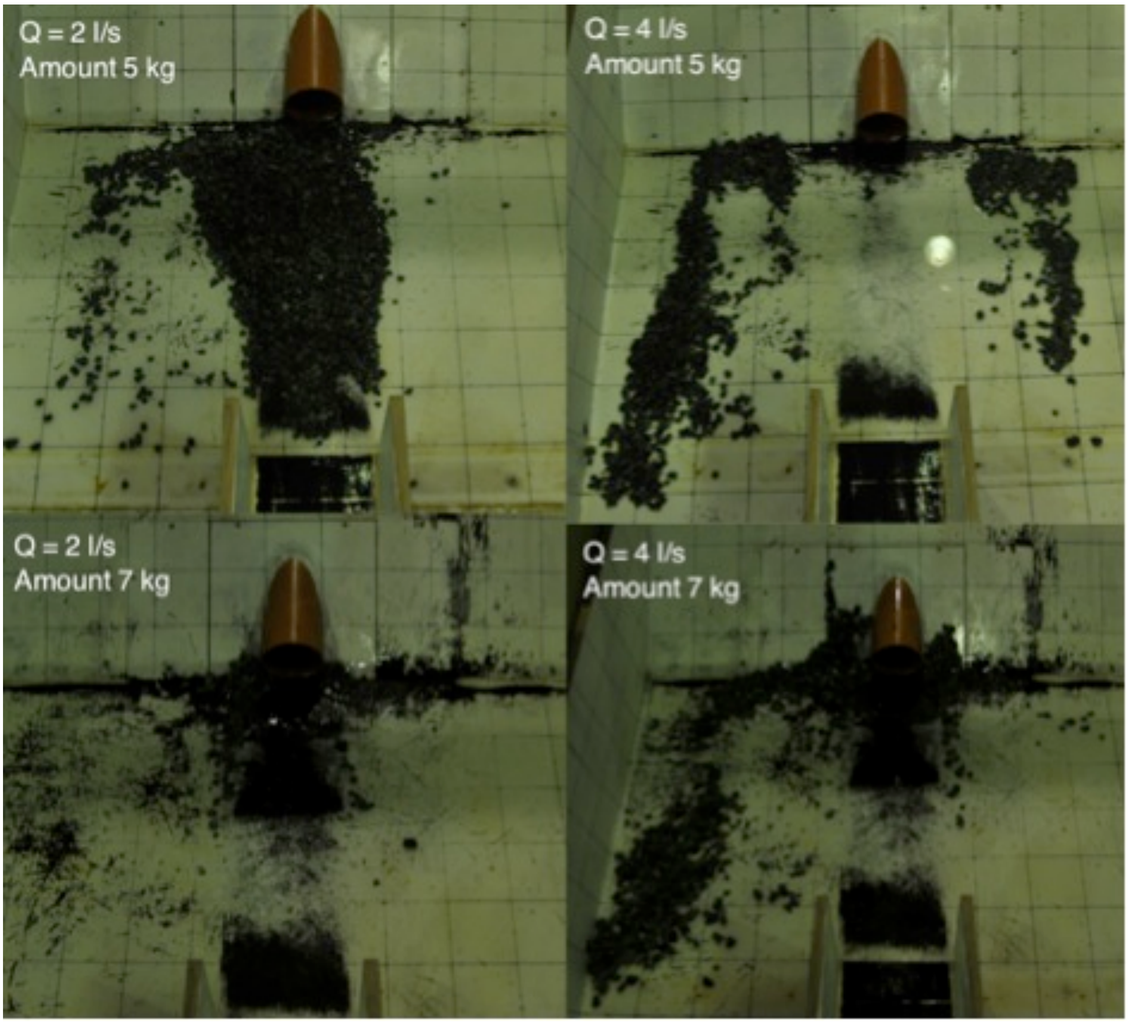


Figure 5.30 Sediment deposition for a projecting inlet with different amounts of sediments added and different discharges

The deposition of sediments in the basin was then higher when the total amount of sediments added to the approach channel was 5 kg compared to 7 kg added. The difference was especially noticeable at 2 l/s, when the amount deposited was 95,36 % of the 5 kg that were added and only 6,32% of the total when adding 7 kg. For the other discharges, it is referred to Table B.2 and B.9.

<u>**Wingwalls**</u>

From Figure 5.31 it is clear that the amount of sediments added to the approach channel has no influence on the headwater elevation for the lowest discharges. At Q^* = 1,2 and Q^* = 1,4, for the curve with 7 kg added, the headwater values are higher than for 5 kg added because the capacity of the culvert is close to be reached, and the water level is overtopping the limit at Q = 14 l/s. The sediments deposited as quite symmetric wings, but the amount of sediments left in the basin after the measurements was low. For all the discharges, the amount deposited in the basin was lower than 18 % of the total amount of 7 kg added.

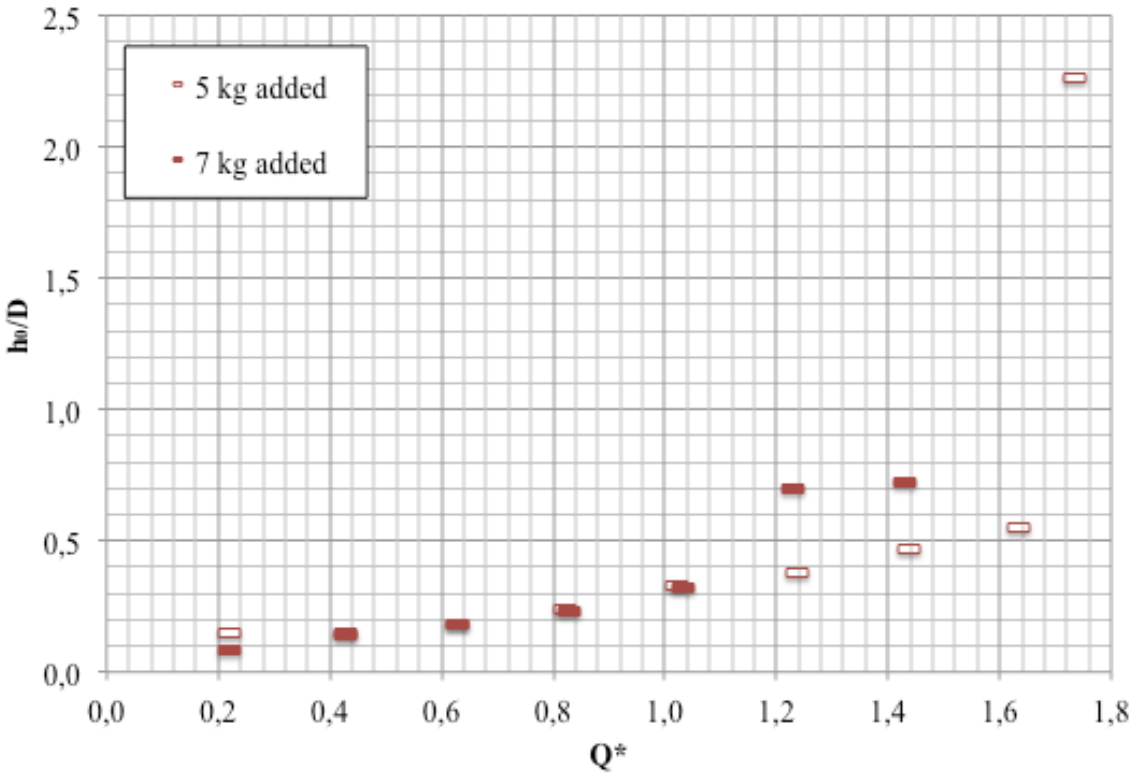


Figure 5.31 Sediment weight effect on a culvert with wingwalls, basin length 876 mm and sediments added gradually

When it comes to the curve for the sediment amount of 5 kg added, the overtopping does not happen until Q = 17 l/s. At this point the water level reached the limit accurately in the beginning of the measurement, but increased after 5 minutes and overtopped the basin completely. The culvert changed from inlet to outlet controlled when the discharge increased with 1 l/s, and the capacity of the culvert should therefore be between 16 l/s and 17 l/s. The sediments deposited as more or less symmetric wings for all discharges, as for adding 7 kg, even though the amount of sediments deposited in the basin generally was higher. The amount deposited in the basin when adding 5 kg sediments was a couple of percent higher than for 7 kg added for almost all the discharges.

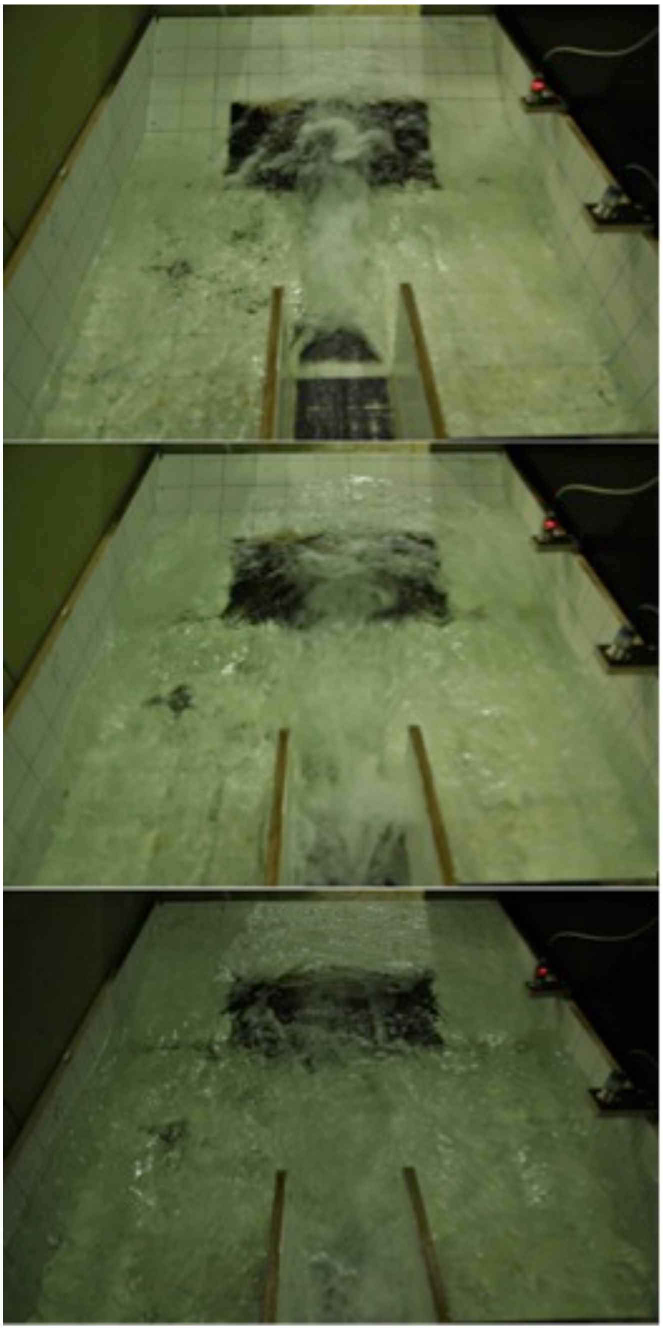


Figure 5.32 Overtopping process at Q = 17 l/s for a culvert inlet with wingwalls

Figure 5.32 show a picture of how the basin suddenly overtopped completely when the discharge was 17 l/s for the experiment with 5 kg sediments added to the approach channel. In the upper picture the water level is at the limit line, in the picture in the middle the water level has increased and in the lower picture the water is overtopping the basin edge.

6 Discussion

In this chapter, observations and experiences gained during the physical model tests in the hydropower laboratory will be used to evaluate which of the effects presented in the results that have the most influence on the culvert capacity. The studied effects were

- The shape of the culvert inlet
- The basin length
- The slope of the approach channel
- How the sediments were added
- The sediment size
- The total amount of added sediments

Further, the effect of adding sediments, as apposed to not adding sediments, will be discussed, and the results will be compared with previous knowledge on this subject, described in chapter 2. It will also be discussed whether the duration of the measurements should be extended, and how the results from these experiments can be adapted in real culvert design and handling of sediment problems in culverts.

Uncertainties in the experiments will also be presented, and relevant work for further studies on the subject will be discussed.

6.1 Effect graphs

For a better comparison of the effect graphs, each of the effects will be discussed separately. A summary will be given at the end of this section, to sum up which of the effects that has the most influence on the capacity, and which of the effects that can be neglected in further studies of the subject.

Inlet shape effect

From the results it is clear that the inlet with wingwalls is the best inlet shape when looking at both the capacity and the headwater elevation. It is also the most stable inlet shape, swallowing high amounts of water for each increase in the discharge. The culvert is inlet controlled for almost all discharges with wingwalls, making the culvert reach a capacity between 14 l/s and 16 l/s.

It can be difficult to say which of the other two inlets that are the worst and give the lowest capacity. The cut inlet has lower headwater values than the projecting inlet, and swallows more water for all discharges. However, it has a very uneven flow pattern because of the oscillation at 6 l/s. These types of flow can be very unstable and cause waves, which can overtop the filling. If the filling overtops, the culvert loses its function and the capacity is reached. The projecting inlet is a better inlet shape with a more stable flow pattern, and reaches a capacity between 12 l/s and 14 l/s.

When comparing the results from the experiments with NRPAs Table 2.3, differences are noticeable. NRPAs manual states that the inlet with wingwalls gives the highest capacity, and that the cut inlet is the second best and the projecting inlet the worst. Additionally, they found that when increasing the pipe diameter to 1 meter or more, the cut inlet would give the best capacity. It is challenging to compare NRPAs results with the test results from the model, because the manual does not clarify the geometries used for testing of the inlets. In that way, the basin length and slope of the approach channel could be very different from the tests conducted in the laboratory model. However, all the inlets in the model experiment seem to reach higher capacities than the ones found by NRPA, with the inlet with wingwalls reaching the highest capacity for all pipe diameters. More tests on the subject could look at the influence on the capacity when increasing the pipe diameter with the same geometries and inlet shape as for the smaller culvert.

Basin length effect

When looking at the results from all three basin lengths, it seems like the basin length of 625 mm gives the lowest capacity. For the cut inlet, this length makes the water flow oscillate and not being stable. This could also be an effect of the inlet shape, which was found to be the worst.

For the other two lengths, the result must be connected to the inlet shapes. The basin length of 876 mm is unstable for both the cut and the projecting inlet, when oscillation occurs. For these inlet shapes, the culvert reaches its capacity at 10 l/s and 14 l/s respectively. The basin length of 315 mm is more stable for both inlets, and the culvert is inlet controlled up to the capacity is reached.

The inlet with wingwalls was established to be the best inlet shape, and therefore the culverts capacity is high for all basin lengths. Both basin length l_b = 876 mm and l_b = 315 mm reach the highest capacity between 14 l/s and 16 l/s. The length of 625 mm gives the lowest capacity.

As a summary, the shortest basin length seems to give the best culvert capacity when comparing all the three inlet shapes. The basin length of 876 mm is better than the length of 625 mm, but one should always compare the lengths in combination with the inlet shape. For the inlet with wingwalls, the error of choosing the wrong basin length is not that prominent as for the other inlets. Additionally, for future studies, more lengths could be examined to find the transition between where the length gives high capacities and where it does not. This can come in hand because the lengths in real life are not as specific as the lengths tested in the laboratory.

Slope effect

The slope of the approach channel should also be seen in connection with the inlet shapes. For all inlets, the slope of 1:5 reaches the same or a higher capacity than the slope of 1:9. Even though the flow is more stable for slope 1:9 when the inlet is cut, the capacity is higher as the culvert reaches a higher discharge before overtopping. From the projecting inlet, it can be seen that reducing the width of the basin has an effect on the capacity for the two slopes. Even though the capacity is reduced when adding walls to the basin with projecting inlet, the situation could be different for other inlets. The results could also be different for other basin lengths, so the changes in the width in combination with changes in the length and inlet should be further studied.

Sediment adding effect

For all inlet shapes, it can be observed that adding sediments affect the culvert capacity. The culvert with cut inlet and wingwalls has an increase in the capacity when sediments are added gradually. When adding sediments all at once, the increase in capacity is noticeable for both the projecting inlet and the wingwalls. Figure 5.21 and 5.22 show that the headwater does in fact decrease when sediments are added gradually and increase when adding them all at once. Even though these Figures represent an inlet with wingwalls and a discharge of 2 l/s, they are representative for other inlets and discharges. Observations during the experiments showed that adding sediments gradually tend to decrease the headwater level, and when adding all sediments at once the headwater can increase.

Typically, sediments deposit as wings on each side of the culvert barrel. When the deposition is formed ass a mass building up in front of the inlet, it is often a result of the velocity in the channel and basin being low. This occurs when the discharge is low, or when the discharge is so high that the basin fills up and overtops. A hydraulic jump then occurs up in the channel and lowers the velocity. The fact that the sediments deposits as wings, can help explain why it seems like the capacity of the culvert increases when adding sediments. If the wings are symmetric on each side of the culvert, they could adjust the flow from the channel and direct it straight towards the inlet, as a jet flow. The culvert will then swallow higher amounts of water and the capacity is increased.

The amount of deposited sediments in the basin shows higher values for deposition when the inlet is cut or projecting. When the inlet has wingwalls, the deposition is lower, which supports that the wingwalls is the best inlet shape.

Sediment size effect

The results show a clear tendency that the sediment size does not affect the culverts capacity at inlet control. For all inlet shapes, the plots coincide almost perfectly. However, differences can be found in the capacity, as a result of the inlet shapes. The cut inlet is still the worst, having the water reach the limit for overtopping at low discharges. Additionally, the culvert goes from inlet to outlet control at 8 l/s. Still, for the highest discharge the sediment size makes the headwater decrease compared to the smaller size, and here the culvert is no longer outlet controlled. The projecting inlet and the inlet with wingwalls reach the same discharge at overtopping, but the headwater values are lower with the wingwalls, and this is still the best inlet shape.

Effect of added mass

From the results, it can be seen that the amount of sediments added to the approach channel influences the capacity differently for the three inlet shapes. The cut inlet has some differences in the headwater, and it can be observed that the culvert reaches a higher capacity when adding 5 kg. For the projecting inlet, the culvert reaches the same capacity for the two amounts. Still, when adding 5 kg sediments the culvert has very high headwater values at 2 l/s and 4 l/s. The flow is more stable when 7 kg sediments are added, which can support that a culvert with projecting inlet has higher capacity with adding 7 kg sediments as opposed to 5 kg. The capacity is high for both amounts added for the inlet with wingwalls. As for the cut inlet, the culvert with wingwalls reaches its highest capacity when 5 kg sediments are added, between 16 l/s and 17 l/s.

Summary

It is clear that the inlet shape has an impact on the culvert capacity, and is the most important effect considered. When comparing all effects, the wingwalls is definitely the best inlet shape giving the highest capacities. The projecting inlet gives the second best capacity with a more stable flow of the water, and reaching higher capacities than the cut inlet. Generally, the cut inlet was found to give a very unstable flow, especially for the basin lengths of 625 mm and 876 mm. The shortest basin length of 315 mm gives the best culvert capacity for all inlets. This indicates a strong influence on the capacity from the basin lengths as well.

Additionally, the slope of the approach channel has a considerable effect on the culvert capacity, where slope 1:5 is better than slope 1:9. Compared to these three effects, adding of sediments has less influence on the capacity, even though the capacity increases. Adding the sediments gradually is better than adding them all at once, which is reasonable considering a landslide versus constant sediment transport. The sediment size has no influence on the capacity, and could be neglected in further studies on the subject. It is clear from the results that the only effect influencing the capacity, when looking at the curves for the two sizes, is the inlet shape. The amount of the sediments added has low influence on the culvert capacity. Also for this effect, the capacity is highly dependent of the inlet shape. The latter experiment was only conducted with one basin length, and further studies with different amounts of sediments could look at the influence of the length in combination with the inlet shape.

For further studies of the inlet, different geometries of the barrel could be tested for the three inlet shapes. In these experiments the culvert was circular, but a rectangular or oval culvert could affect the capacity differently.

6.2 Influence of adding sediments

It may seem like adding of sediments, at least when adding them gradually, increases the culverts capacity. From previous knowledge on the subject, this is a very peculiar observation, since it is known that sediments tend to block the culvert and decrease the capacity. As an answer to this, it could be that the problem often occurs in combination with debris, including everything from small leaves to bigger branches or human deposits. The effect of debris clogging the culvert inlet or barrel has not been taken into account, and should be researched more thoroughly. Still, it is known that also sediments have an impact on the capacity, and more experiments with different geometries should be examined.

Also, it is difficult to verify the influence of the sediments in culverts when the sediments did not deposit in the barrel for any of the measurements that were carried through. However, the positive effect of sediments depositing as wings on each side of the culvert was noticeable. For further studies, it could be interesting to determine the influence of these wings on the water flow, since the water flow seems more stable between the wings.

6.3 Oscillation

Oscillation was a constant problem during the experiments, which especially occurred for the cut inlet. It also occurred for the projecting inlet at some of the geometries, but never for the wingwalls. First, it was assumed that oscillation arose from movements in the laboratory model, since it suddenly appeared for the cut inlet. It was later found that the reason could have something to do with the geometry changes and the culverts capacity. When the geometries around the culvert changed, such that the capacity was reduced, oscillation often appeared. It was decided that oscillation symbolized a geometry that should be avoided, since waves often developed and caused unstable flow patterns that increased the risk of overtopping.

6.4 Duration of measurements

The duration of each measurement was chosen to last for 1 minute without sediments and 16 minutes with sediments. For the clear water experiments, it was found that 60 seconds was enough when the water flow was stable. The experiments with sediments could have been measured for a longer period, but it was found that 16 minutes was more than enough since the measurements in total was time consuming and the number of effects were many. For the cut inlet at 2 l/s, 6 l/s and 8 l/s, the deposited sediments were left in the basin with water running for 15 minutes after the measurements, to see if the sediments were affected of the running water. The result was that the water did not affect the deposited sediments, since the amount deposited was still the same after 15 minutes. For further experiments on this subject, it is recommended that a series of measurements be tested with water flowing for a longer period of time after sediment deposition. It could then be concluded if the sediments are stable when they have deposited, or if the water over time can influence the sediment transport through the culvert.

6.5 Adaption of experiments into real life culvert design

Since there are no detailed guidelines available for culvert design including handling of sediments and debris, these experiments can be a good start in finding solutions for the sedimentation problems. The experiments were conducted in a model with scale 1:10, but the results can still apply for all culvert sizes with similar inlets as the three that were tested. Before construction of a culvert, the site should always be examined. In that way the amount of sediments in the river can be calculated, and the slope of the cannel and size of the basin can be found. The geometry with the most resemblance to the up-scaled model tests can then function as guidance for how the sediments will act around the culvert and influence the capacity. Further, changes in the geometry or inlet shape can be made to better the situation and increase the capacity.

It is also important to have in mind that if the sediment deposition in the basin is high, the basin will eventually fill up and removal of sediments be necessary. Adaption of techniques used at intake structures in removal of sediments can then be of use.

6.6 Uncertainties

When running experiments in a laboratory model, there will always be uncertainties regarding the measurement devices and calibration of these. One should also expect errors when conducting this amount of measurements, considering how accurate the tests were done, especially those that were to be compared.

Measurements errors

The microsonic sensors are especially sensitive, and the wooden blocks used for the calibration had increased slightly during the second calibration, since they were in touch with water. This probably resulted in somewhat higher headwater values, meaning a few millimeters. The scale of the vibrating machine also posed problems, as it would not stabilize and add the given amount of sediments that was intended. This caused the experiment to prolong, and the total amount of sediments added were not always precisely the same. Additionally, the machine had to be turned on manually when the measurements started, and it is not certain that this was fulfilled for all tests. This also applied when sediments were added all at once.

Setup of the model

When constantly changing the inlet shape, basin geometry and slope of the channel, differences can occur for each time. The slope could be angled slightly, such that it was not directed directly towards the inlet, or the geometry of the basin could differ. Also, leakages would appear if the sealing was moved or broken.

Weighing sediments

The sediments that went through the culvert barrel, was collected in a bucked downstream the culvert. For some of the experiments, it was noticed that not all sediments deposited in the bucket, but flowed over and were lost into the pipe system in the laboratory. This affected both the amount of sediments through the culvert and the total amount of sediments added. Also, an old, non-digital weight was used for weighing the sediments. Some inaccuracies should therefore be accounted for during the weighing.

7 Conclusion

Sedimentation and debris attachments in culverts are a prominent problem, especially when necessary literature on the subject to solve these problems is absent. When conducting experiments in the laboratory model to find solutions for handling sediments near and in the culvert, it was expected that the results would clarify this problem. Absolute answers were not found during these experiments, but the work completed points in the right direction in finding answers. It was, however, found good upstream geometries when testing different effects that could help better the problem with overtopping of roads and railways, ergo better the capacity of the culvert. These solutions apply for culverts both with and without sediments.

From the effects that were studied, it was found that some had more influence on the capacity than others. The following list ranks the effects from having most influence at the top to the effect with least influence at the bottom.

- Inlet shape
- Basin length
- Slope of the approach channel
- Way of adding of sediments
- Total weight of added sediments
- Sediment size

The inlet shape turned out to be the most important effect influencing the capacity. It was established that when looking at other effects, the inlet shape has to be considered as well. This is due to the fact that for most of the effect graphs the differences in the capacity was mostly noticeable for each of the inlets, and not necessary the effect it self. A comparison of the capacity for the inlet shapes between the model experiments and NRPAs manual on building of roads, show that the model gives higher capacities than expected from the manual. Additionally, obscurities on which of the inlet shapes giving the best capacity was established. The model experiments found that an inlet with wingwalls give higher capacities for all geometries and pipe diameters. According to NRPAs manual, the inlet with wingwalls is the best up to a diameter of 1 meter; culverts with diameter larger or equal to 1 meter reach a higher capacity with a cut inlet.

The basin length is also of importance for the culvert capacity, where the shortest basin length of l_b = 315 mm was found to be the best. Basin length l_b = 876 mm is generally better than l_b = 625 mm, but one should be careful in stating that this applies for all geometries and culverts. The best way of finding the correct basin length is to compare the length in combination with the inlet shapes. This also applies for the remaining effects; the slope, which gives better capacities at S = 1:5 than for S = 1:9, the way of adding sediments, which gives a slightly increase in the culvert capacity when sediments are added gradually and the size and amount of sediments, which are highly dependent on the inlet shape.

When adding sediments, it was expected that the culvert capacity would decrease. From the experiments conducted in the laboratory model it was found that the sediments do in fact increase the capacity of the culvert, especially when adding them gradually. This is a peculiar observation, considering that field observations show that sediments tend to block the culvert and reduce the capacity. The answer could be that the field observations included not only sediments, but also debris. Attachment of debris and the influence on the capacity were not investigated, so this could be one of the reasons for the deviations. Further studies on how sediments and debris affects the culvert capacity should be conducted, for establishment of both the influence and the correlation between sediments and debris on culvert blockage.

Sedimentation problems can be avoided in some degree by using these results as guidance. It has been observed that sediment deposition in the basin and in front of the inlet increases with reduced culvert capacities. The necessity of a clean culvert and opening in front of the culvert is therefore of same importance as a functioning inlet shape and basin geometry. Consequently, one should tend to choose inlets and geometries that give the highest capacities, and further less deposition in the basin and blockage of the culvert. The performance curves can be up-scaled, such that culvert constructions with similar geometries can be compared with the curves. In that way the capacity of the culvert can be established, and the sedimentation pattern for the given geometry can be found. It will be necessary with further studies on the subject to find more reliable answers in solving problems with sediments around culverts. When these solutions are closer to be found, they can also be adapted for intake structures with similar problems.

8 Further work

As a summary of the discussion and conclusion chapters, a list of further work will be presented. Since the experiments were highly time consuming, there are definitely more tests available for finding solutions to the problems with sediments and debris in culverts. The following parameters should therefore be examined:

- Inlet geometries other than circular
- Comparison of two pipe diameters when all other parameters are constant
- Changing the width of the basin
- More basin lengths in combination with slopes and inlets
- The effect of debris, with and without the influence of sediments
- More geometries in combination with sediments
- Determination of the influence of the sediment deposition pattern
- Longer time frame of the measurements
- Accurately measuring of the water depth in the culvert

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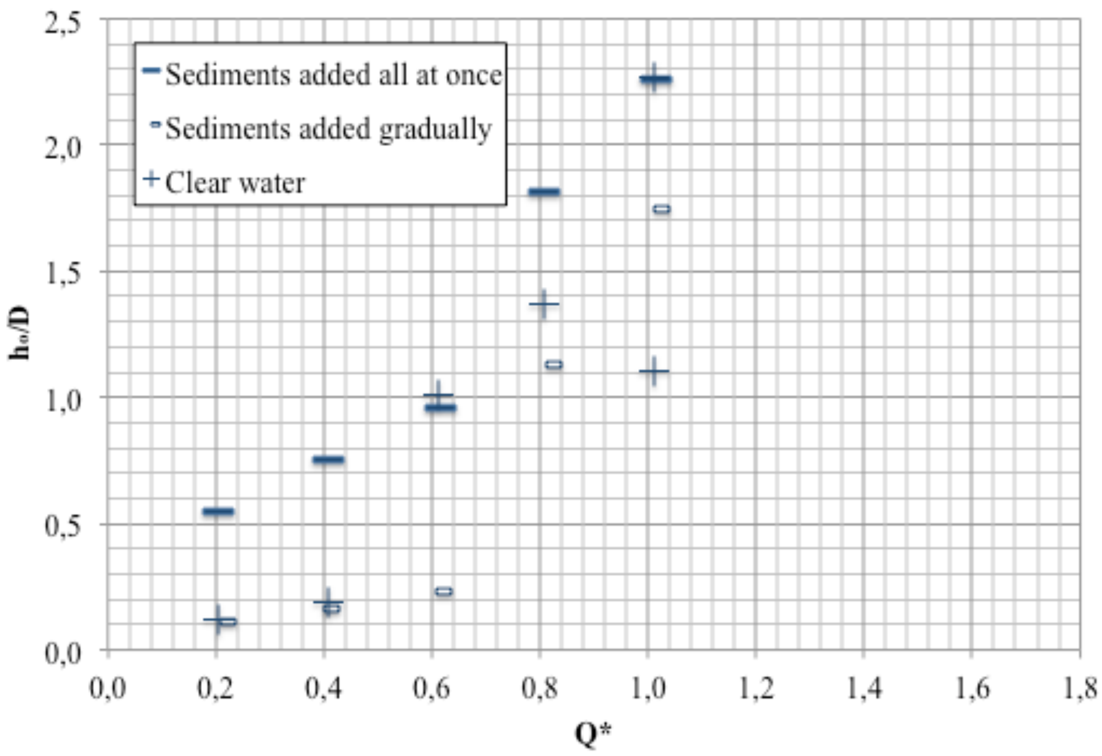
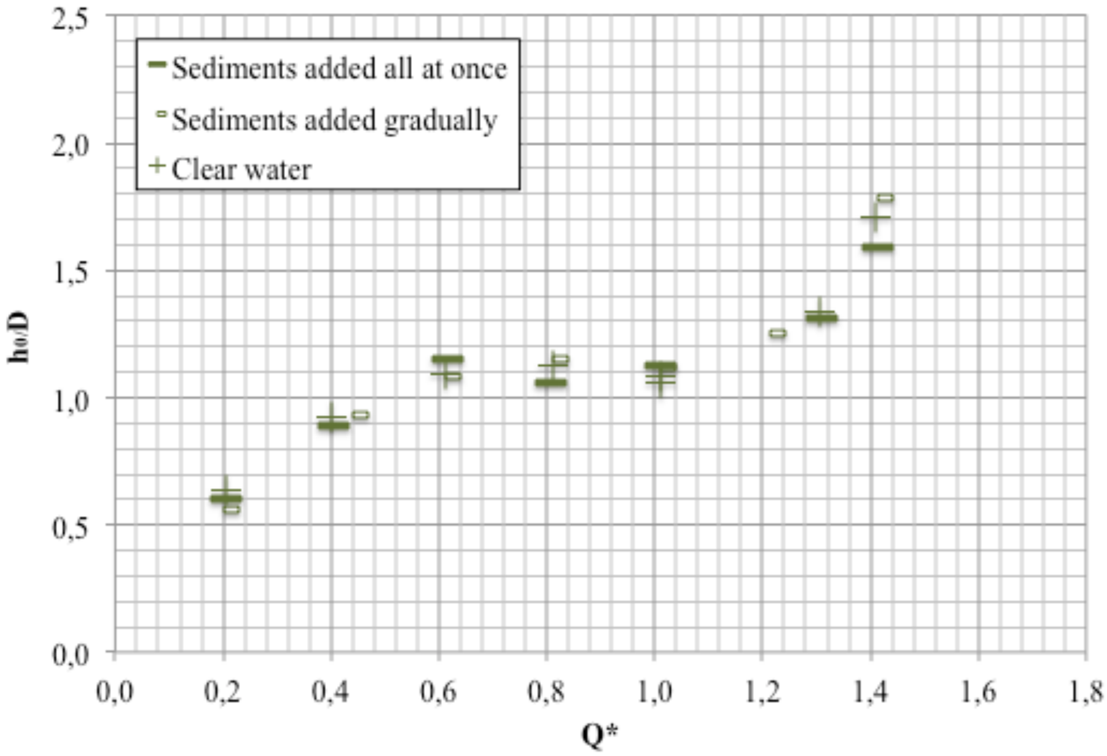
A Sediment adding effect for other basin lengths

This section presents the sediment adding effect graphs for the other basin lengths, l_b = 625 mm and l_b = 315 mm. Also these performance curves are made on the basis of adding 5 kg sediments with size 8 – 16 mm.

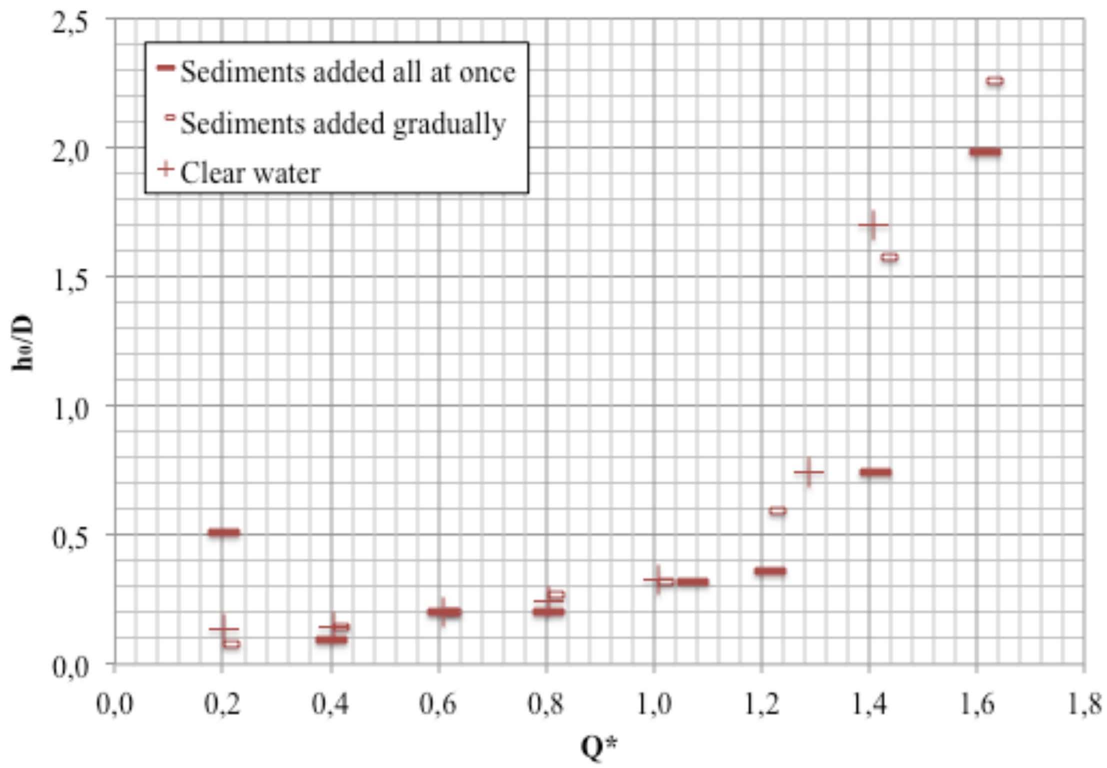
Basin length l_b = 625 mm



A.1 Adding effect for cut inlet with basin length 625 mm



A.2 Adding effect on a projecting inlet with basin length 625 mm

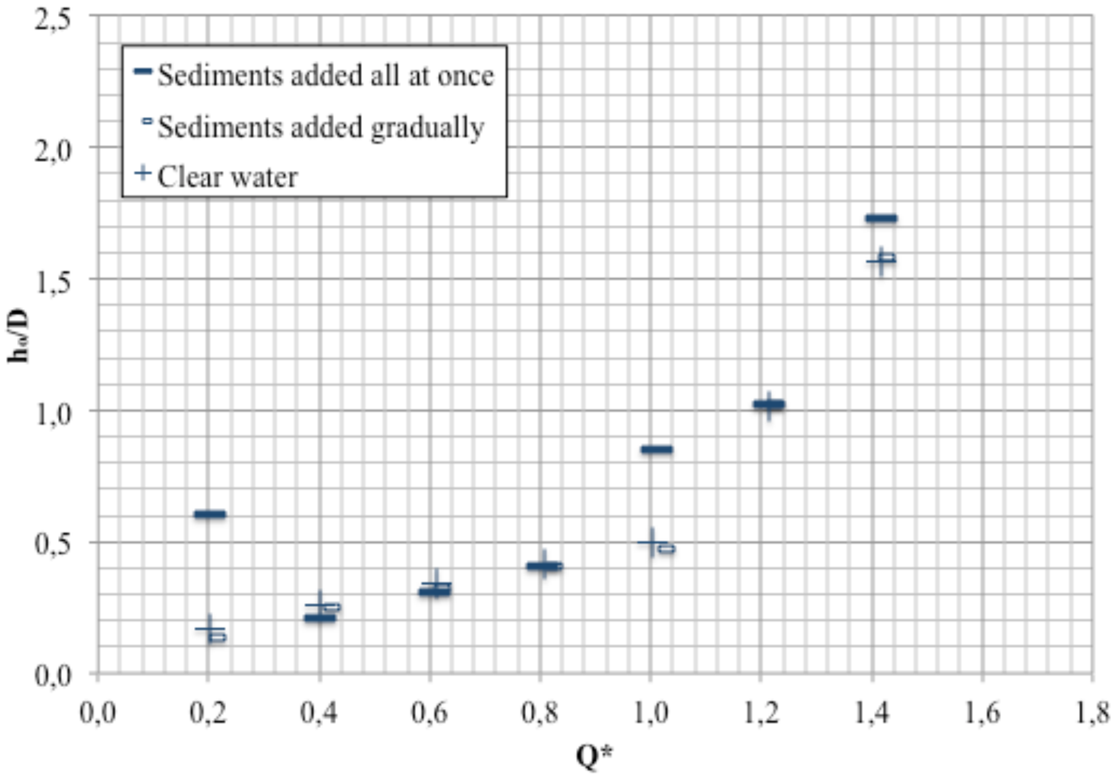


A.3 Adding effect on an inlet with wingwalls and basin length 625 mm

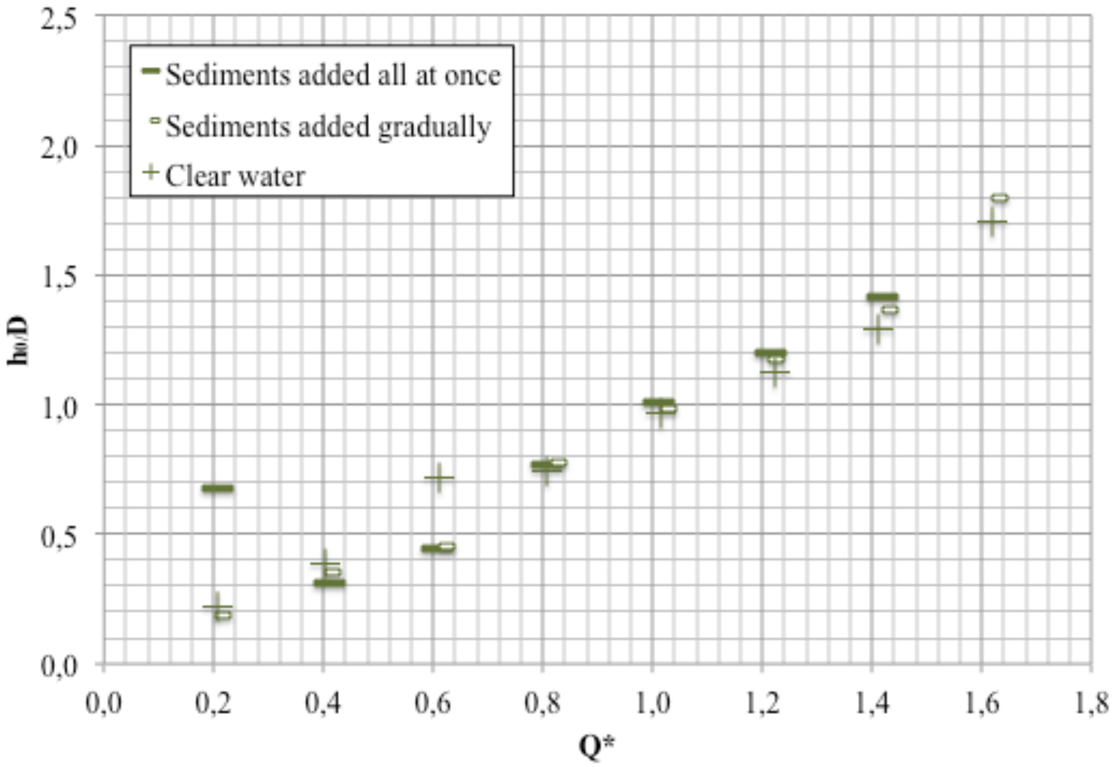
The tendency of the cut inlet giving the lowest capacities can be seen in Figure A.1. As before, the inlet with wingwalls gives the highest capacity. In these graphs, including

Figure A.2 and A.3, the sediments does not seem to affect the capacity as much as the graphs for basin length 876 mm.

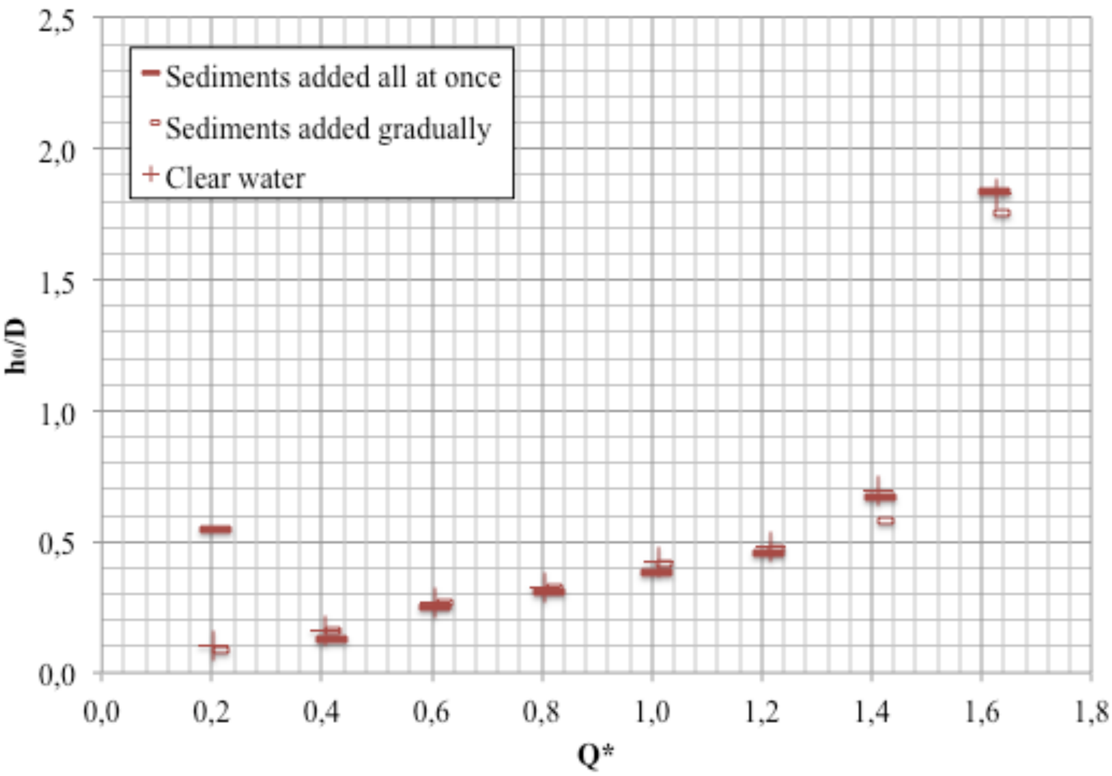
Basin length l_b = 315 mm



A.4 Adding effect on a cut inlet and basin length 315 mm



A.5 Adding effect on a projecting inlet and basin length 315 mm



A.6 Adding effect on an inlet with wingwalls and basin length 315 mm

Figures A.4, A.5 and A.6 indicates no strong relations between adding sediments and changes in the capacity. Only for the projecting inlet, it seems like the capacity is reduced

when sediments are added all at once. The graphs show that the wingwalls is the best inlet design, whilst the projecting inlet is the second best and the cut inlet the worst.
When comparing the basin lengths l_b = 625 mm and l_b = 315 mm, the length effect also becomes clear. It is noticeable that the curves give more stable values when the length is 315 mm compared to 625 mm, so this supports previous assumptions that l_b = 625 mm is the worst length.

B Deposition of sediments

The sediments that deposited in the basin and the ones that went through the culvert were weighed such that the sediment transport could be quantified. It was also interesting to see how much of the total amount of sediments added that deposited in the basin and influenced both the headwater and culvert capacity. The following Tables give a summary of the weight deposited in the basin, weight of the sediments that went through the culvert and the percentage of the deposited sediments of the total amount added, for all effects including sediments. All the measurements with sediments are conducted with a slope of 1:5.

Adding effect

From Table B.1 it can be seen that the cut inlet and projecting inlet has the most sediment deposition in the basin, when the sediments are added all at once. The inlet with wingwalls has significantly less deposition, since most of the sediments went through the culvert. All Tables were based on adding 5 kg of sediments with a size of 8 – 16 mm.

B.1 Amount of sediments deposited in the basin for sediments added all at once, basin length 876 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
All at once	**Cut**	2	0,02	5,11	5,13	99,57
		4	0,00	5,13	5,13	100,00
		6	2,33	2,81	5,15	54,68
		8	2,27	2,88	5,15	55,92
		10	2,59	2,52	5,11	49,32
		12	2,63	2,51	5,13	48,83
		14	0,24	4,90	5,13	95,38
	Projecting	2	0,02	5,05	5,08	99,53
		4	0,58	4,58	5,16	88,74
		6	2,21	2,89	5,11	56,67
		8	2,27	2,78	5,05	55,08
		10	2,10	2,87	4,97	57,80
		12	1,83	3,14	4,97	63,12
		14	2,23	2,71	4,94	54,84
		16	3,95	0,87	4,82	18,06
	Wingwalls	2	0,02	4,98	5,00	99,66
		4	4,16	0,94	5,11	18,47
		6	3,56	1,53	5,09	30,01
		8	3,81	1,28	5,09	25,16
		10	4,25	0,81	5,06	16,08
		12	3,88	1,08	4,96	21,76
		14	3,72	1,23	4,96	24,88
		16	3,59	1,24	4,83	25,61

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

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

Table B.2 shows that when the sediments are added gradually, the projecting inlet has the most deposition of sediments in the basin for all the discharges in total. The lowest amount of sediments deposited in the basin when the inlet was shaped as a wingwall.

B.3 Amount of sediments deposited in the basin for sediments added all at once, basin length 625 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
All at once	**Cut**	2	0,09	4,91	5,00	99,70
		4	2,64	2,36	5,00	47,70
		6	2,98	2,02	5,00	40,80
		8	0,19	4,81	5,00	97,60
		10	2,56	2,44	5,00	49,70
	Projecting	2	-0,07	5,07	5,00	100,00
		4	-0,07	5,07	5,00	100,00
		6	1,65	3,35	5,00	66,07
		8	2,59	2,41	5,00	47,53
		10	3,60	1,40	5,00	27,61
		12	2,63	2,37	5,00	46,75
		14	3,16	1,84	5,00	36,29
	Wingwalls	2	-0,06	5,06	5,00	99,90
		4	3,43	1,57	5,00	30,90
		6	3,30	1,71	5,00	33,60
		8	3,65	1,35	5,00	26,50
		10	3,81	1,19	5,00	23,60
		12	3,65	1,35	5,00	26,90
		14	3,58	1,43	5,00	28,30
		16	3,76	1,24	5,00	25,20

From Table B.3 it can be seen that the values in percentage is somewhat lower when the basin length is 625 mm compared to when the length is 876 mm. It is still the projecting and cut inlet that makes the largest depositions. The inlet with wingwalls still have low amount of sediments depositing in the basin.

B.4 Amount of sediments deposited in the basin for sediments added gradually, basin length 625 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
Gradually	**Cut**	2	5,22	0,29	5,51	5,30
		4	4,54	0,58	5,13	11,39
		6	4,46	0,71	5,17	13,71
		8	2,59	2,61	5,20	50,28
		10	2,98	2,30	5,28	43,52
	Projecting	2	0,01	4,57	4,59	99,76
		4	3,01	2,11	5,13	41,20
		6	1,93	2,90	4,83	60,07
		8	2,18	3,28	5,46	60,11
		10	2,38	2,94	5,32	55,24
		12	2,48	3,03	5,51	54,96
		14	3,12	2,81	5,94	47,38
	Wingwalls	2	5,31	0,24	5,55	4,33
		4	5,66	0,36	6,02	5,98
		6	4,95	0,42	5,37	7,80
		8	5,29	0,52	5,81	8,90
		10	5,10	0,61	5,71	10,66
		12	4,61	0,79	5,40	14,56
		14	4,10	1,53	5,64	27,19
		16	4,57	1,09	5,66	19,22

Table B.4 indicates that the amount of deposited sediments generally increases when the basin length decreases. This especially applies for the projecting inlet. For the cut inlet the values in percentage is higher for the highest discharges, and lower for the lowest discharges. The amount deposited in front of the inlet with wingwalls is slightly higher when the basin length is reduced.

B.5 Amount of sediments deposited in the basin for sediments added all at once, basin length 315 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
All at once	**Cut**	2	0,15	4,88	5,03	96,96
		4	2,79	2,31	5,10	45,30
		6	2,74	2,36	5,10	46,27
		8	3,27	1,84	5,11	36,07
		10	3,96	1,14	5,10	22,41
		12	3,24	1,82	5,06	35,94
		14	2,58	2,49	5,07	49,12
	Projecting	2	0,11	4,98	5,09	97,84
		4	2,49	2,56	5,05	50,74
		6	2,22	2,85	5,07	56,23
		8	2,27	2,80	5,07	55,24
		10	2,24	2,82	5,06	55,72
		12	2,17	2,72	4,89	55,56
		14	2,38	2,49	4,88	51,12
	Wingwalls	2	0,19	4,89	5,09	96,19
		4	4,02	1,11	5,14	21,65
		6	4,73	0,35	5,09	6,90
		8	4,56	0,51	5,07	10,09
		10	4,51	0,55	5,06	10,91
		12	4,23	0,85	5,08	16,64
		14	4,24	0,82	5,06	16,25
		16	4,21	0,89	5,10	17,36

From Table B.5 it can be observed that the amount of deposited sediments has a tendency to decrease in comparison with the other lengths for the cut inlet and wingwalls. The projecting inlet makes more sediments deposit at basin length $l_b = 315$ mm compared to $l_b = 615$ mm, but less than the amount deposited at $l_b = 876$ mm.

B.6 Amount of sediments deposited in the basin for sediments added gradually, basin length 315 mm

Adding	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
-	-	l/s	kg	kg	kg	%
Gradually	**Cut**	2	3,90	0,40	4,31	9,31
		4	3,89	0,82	4,70	17,33
		6	4,07	0,68	4,75	14,35
		8	3,88	0,68	4,56	14,85
		10	3,84	0,82	4,66	17,62
		12	3,56	1,23	4,80	25,69
		14	2,98	1,70	4,69	36,36
	Projecting	2	4,21	0,84	5,05	16,66
		4	3,40	2,57	5,97	43,07
		6	3,19	2,37	5,56	42,61
		8	3,38	2,21	5,59	39,54
		10	2,82	2,80	5,61	49,81
		12	2,36	2,62	4,99	52,63
		14	2,67	2,27	4,94	45,93
		16	2,98	1,86	4,85	38,46
	Wingwalls	2	5,91	0,17	6,08	2,81
		4	5,72	0,40	6,12	6,46
		6	3,86	0,35	4,22	8,35
		8	5,45	0,33	5,79	5,74
		10	4,32	1,12	5,44	20,58
		12	4,54	0,41	4,96	8,31
		14	5,19	0,52	5,72	9,13
		16	4,19	0,96	5,15	18,67

Table B.6 shows that the amount deposited in the basin when the length is 315 mm is generally lower compared to when the length is 625 mm, for all inlets. When comparing the amounts with the one found when the length is 876 mm, it is noticeable that the amount is reduced for the cut inlet. The other two inlets show a tendency of having more sediment deposited in the basin.

Size effect

From Table B.7 is can be seen that when the basin length is reduced, and the sediment size is 8 – 16 mm, the projecting inlet has the most deposition in the basin. Both the cut inlet and the wingwalls have low amounts of sediments deposited for the lowest discharges. When the cut inlet reached its capacity, the amount of sediments increased. The basin length was 625 mm and the amount of 5 kg sediments was added gradually in both experiments shown in the Tables.

B.7 Amount of sediments deposited in the basin for a sediment size of 8 - 16 mm

Size	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
mm	-	l/s	kg	kg	kg	%
8 - 16	**Cut**	2	5,22	0,29	5,51	5,30
		4	4,54	0,58	5,13	11,39
		6	4,46	0,71	5,17	13,71
		8	2,59	2,61	5,20	50,28
		10	2,98	2,30	5,28	43,52
	Projecting	2	0,01	4,57	4,59	99,76
		4	3,01	2,11	5,13	41,20
		6	1,93	2,90	4,83	60,07
		8	2,18	3,28	5,46	60,11
		10	2,38	2,94	5,32	55,24
		12	2,48	3,03	5,51	54,96
		14	3,12	2,81	5,94	47,38
	Wingwalls	2	5,31	0,24	5,55	4,33
		4	5,66	0,36	6,02	5,98
		6	4,95	0,42	5,37	7,80
		8	5,29	0,52	5,81	8,90
		10	5,10	0,61	5,71	10,66
		12	4,61	0,79	5,40	14,56
		14	4,10	1,53	5,64	27,19

B.8 Amount of sediments deposited in the basin for a sediment size of 16 – 32 mm

Size	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
mm	-	l/s	kg	kg	kg	%
16 - 32	**Cut**	2	5,08	0,39	5,48	7,19
		4	4,84	0,66	5,50	11,98
		6	4,26	0,54	4,81	11,32
		8	2,65	1,90	4,56	41,78
		10	3,00	1,99	5,00	39,90
	Projecting	2	0,04	4,21	4,26	98,99
		4	3,34	2,24	5,59	40,16
		6	2,30	2,84	5,14	55,21
		8	3,27	1,78	5,06	35,28
		10	2,81	2,94	5,76	51,14
		12	2,66	2,41	5,08	47,55
		14	2,92	2,24	5,17	43,43
	Wingwalls	2	4,86	0,51	5,37	9,48
		4	3,68	0,25	3,93	6,34
		6	5,06	0,27	5,34	5,13
		8	5,95	0,34	6,29	5,47
		10	5,28	0,36	5,64	6,46
		12	5,47	0,64	6,12	10,53
		14	3,16	1,14	4,31	26,56

Table B.8 shows that when the sediment size is 16 – 32 mm the deposition of the sediments in the basin is more or less the same as for sediment size 8 – 16 mm. The projecting inlet has a slightly higher amount of deposited sediments when the grain size is smaller.

Effect of added mass

Table B.2 from the adding effect is the same Table as the Table for the added mass of 5 kg would be, since the basin length, sediment size and the way of adding the sediments are the same. The Tables in weight effect are based on a basin length of 876 mm, grain size of 8 – 16 mm and sediments added gradually.

From Table B.9 it can be seen that the amount of sediments deposited in the basin when the total amount added is 7 kg, is not that different from when the total amount is 5 kg. The biggest difference is at 2 l/s for the projecting inlet, where the deposition in the basin make 95,36 % of the total amount of the 7 kg added and only 6,32 % of the 5 kg added. This is due to the oscillating pattern to the left when 7 kg were added, as the pattern shown in Figure 5.15. Most sediments went through the culvert, but the once that deposited was placed on the left side of the inlet.

B.9 Amount of sediments deposited in the basin for a total sediment weight of 7 kg

Weight	Inlet shape	Discharge	Weight of sediments through culvert	Weight of sediments left in basin	Total weight of sediments	Percent of total weight left in basin
kg	-	l/s	kg	kg	kg	%
7	**Cut**	2	5,82	0,26	6,08	4,31
		4	1,42	5,10	6,52	78,20
		6	5,13	1,57	6,70	23,45
		8	5,75	1,01	6,76	14,96
		10	4,96	1,49	6,45	23,12
		12	4,20	2,28	6,48	35,19
		14	4,92	1,99	6,91	28,81
	Projecting	2	6,70	0,45	7,15	6,32
		4	4,39	2,75	7,14	38,52
		6	3,90	2,90	6,80	42,65
		8	4,19	2,69	6,88	39,11
		10	3,95	2,91	6,86	42,42
		12	3,56	3,50	7,06	49,58
		14	3,91	3,32	7,23	45,92
	Wingwalls	2	7,24	0,34	7,58	4,45
		4	7,63	0,27	7,91	3,44
		6	7,12	0,35	7,47	4,71
		8	6,58	0,49	7,07	6,99
		10	7,29	0,89	8,18	10,90
		12	6,36	1,39	7,75	17,98
		14	6,67	1,12	7,80	14,38