NTNU – Trondheim
Norwegian University of
Science and Technology

Comparison of the hydraulic capacity of different culvert inlet designs under sediment transport conditions

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Hydropower Development
Submission date: June 2015
Supervisor: Jochen Aberle, IVM
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MŰEGYETEM 1782

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MASTEROPPGAVE

Student: ***Fanni Terlaky***

-

Title: Comparison of the hydraulic capacity of different culvert inlet designs under sediment transport conditions

1 BACKGROUND

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

The hydraulic performance of culverts under sediment transport conditions has been in the focus of a scale model study in the NTNU hydraulic laboratory (Vassdragslaboratoriet) which has been embedded in the research project *Naturfare-infrastruktur, flom og skred* (NIFS) managed by Norges vassdrags- og energidirektorat (NVE), Jernbaneverket and Statens vegvesen. The objective of the study is to contribute to the development of new design guidelines for culverts taking into account the effect of debris and sediments. For this purpose, a range of experiments have been carried out in the framework of MSc-theses and student-project works in order to investigate the effect of different boundary conditions on the culvert capacity. In detail, the experiments have been carried out using different inlet setups, inlet geometries, and varying geometries of the sedimentation basin. All experiments have been carried out with both clear water conditions and using coarse sediment as bed load material and the measurements have been used to establish discharge curves for the different culvert designs with and without effect from accumulated sediments.

2 TASKS

Until today, many experimental data have been acquired in the project, which have been summarized in a total of 5 student-theses. These data have mainly been analyzed with regard to the boundary conditions of the respective experimental study. Therefore, the present study will provide a unifying analysis of the available data in order to identify the favorable culvert inlet design under sediment transport conditions. The thesis should cover the following issues:

1. Literature review of culvert hydraulics and sedimentation transport through culverts with particular focus on steep streams
2. Review of the work carried out in the preceding MSc-theses and student-projects
3. Description of the available data
4. Unifying analyses of the available data
5. Discussion of results and identification of the favorable inlet design
6. Preparation of a report

Discussions with the supervisors will be used to refine details of the individual tasks.

3 SUPERVISION AND DATA

Professor Jochen Aberle from NTNU will be main-supervisor of the thesis. Joakim Sellevold from Statens Vegvesen and Sandor Baranya from Budapest University of Technology and Economics will be co-supervisors. Discussions and input from colleagues and other researchers at NTNU, Statens Vegvesen, SINTEF etc. is recommended. Significant inputs from others shall, however, be referenced in an adequate manner.

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

4 REPORT FORMAT AND REFERENCE STATEMENT

The MSc-thesis shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary of not more than 450 words that is suitable for electronic reporting, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is her own and that significant outside input is identified and referred. The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) as the main target group. The thesis should be submitted in pdf-form in DAIM and in the form of three hardcopies that should be sent to the supervisor/department via the printing shop. The thesis should not be delivered later than Tuesday, June 10, 2015.

Trondheim, 13.01.2015

Jochen Aberle
Professor

Abstract

Culverts are important hydraulic structures whose main purpose is to safely convey water through infrastructures crossing streams (e.g. roads). Several design guidelines exist for clear water conditions, but none of them takes into account the sediments. Therefore, in the framework of the Natural hazards – Infrastructure for floods and landslide (NIFS) project, five student-theses have been prepared in order to bridge this knowledge gap, and contribute to development of new guidelines for culvert design. The theses were based on model tests (1:10) which were designed to specifically study the effect of sediment transport. The culvert's hydraulic capacity was investigated with different boundary conditions, under both clear water condition and sediment load. The present study is the first joint analysis of all the data from these studies, which identifies the favourable culvert inlet design, under sediment transport. The experiments were carried out with three different inlet types (cut, projecting, wingwalls) under inlet control focusing on the effects of the expansion section geometry, the installation of reserve barrel, sediment countermeasures, feeding method, sediment size and sediment amount.

The main findings of the thesis were the followings: under jet dominated flow, the wingwall-inlet provided the highest capacity while in case of milder slope (1:9) and installed energy dissipation, the projecting inlet. The energy dissipator blocks have been installed for generation of a hydraulic jump. Both width and length of the expansion section influenced the culvert's hydraulic capacity. The culvert showed generally the highest performance for the shortest expansion section length (315 mm; model scale), and for the widest expansion section width (876 mm; model scale). Sediment experiments showed that sediment load generally decreased the culvert's hydraulic capacity as the deposited sediment obstructed the flow through the barrel. From the two sediment feeding methods (gradually, all at once) the all at once feeding resulted in higher headwater levels as more sediment deposited in the basin. Although sediment size and amount had only a slight effect on the culvert performance, the water level was generally higher when more sediment (7 kg) was fed to the model. The installation of a reserve barrel, located at a higher level compared to the main culvert, increased the safety of the structure as it was less prone to be blocked by sediments. Experiments with sediment countermeasures showed that both trash racks and debris deflectors are efficient in sediment retention. However, installation of these structures decreased the culvert's hydraulic capacity. Based on these results, an analysis was carried out focusing on hydraulic capacity, embankment safety and costs to find the optimal configuration. The identified configuration is presented and corresponding sketches have been developed.

Összefoglaló

Az átereszek fontos hidraulikai műtárgyak, melyek elősegítik a vízfolyások és vonalas létesítmények (pl. utak) biztonságos kereszteződését. Számos áteresz tervezési útmutató ismert, azonban mindegyik csak tiszta vizes állapotra, azaz hordalék figyelembevétele nélkül javasol műszaki megoldást. A Natural hazards – Infrastructure for floods and landslide (NIFS) project keretein belül 5 diplomamunka készült a Trondheimi NTNU egyetemen, melyek elsődleges célja ennek a tudásbeli hiánynak az áthidalása, illetve egy új, a hordalékterhelést is figyelembevevő tervezési útmutató kifejlesztésének az elősegítése. A diplomamunkák egy a hordalékterhelés hatásait vizsgáló kisminta modell (1:10) alapján készültek. Az áteresz hidraulikai kapacitását különböző peremfeltételek mellett, mind tiszta vízzel, mind hordalék adagolásával vizsgálták. A jelen tanulmány célja a vizsgálati téma bemutatása, a vizsgálati módszerek ismertetése, az említett tanulmányok eredményeinek elemzése és összefoglaló értékelése, majd javaslattétel egy, a hordalék átereszen keresztül való vándorlását is figyelembe vevő optimális áteresz kialakításra. A modellvizsgálatok során három különböző kitorkoló fej kialakítás (rézsűs, függőleges, szárnyas) került tesztelésre, felvíz által szabályozott áramlási viszonyok mellett. Az átereszfej mellett a következő paraméterek hatása került vizsgálatra: felvízi medence geometriája, tartalék áteresz telepítése, hordalékfogók alkalmazása, adagolási módszer, hordalék szemcseméret és mennyiség.

A diplomamunka legfőbb eredményei a következők: a legnagyobb kapacitást vízsugár uralta áramlás esetén a szárnyfalas, míg enyhébb lejtő és energiatörő alkalmazásánál a függőleges átereszfej kialakítás mutatta. Az energiatörő telepítésének, a vízugrás generálása volt a célja. Az áteresz kapacitását a felvízi medence hossza és szélessége egyaránt befolyásolta. A legnagyobb vízátvezető képességet általában a legrövidebb (315 mm; modell méret) és a legszélesebb (876 mm, modell méret) medence alkalmazása eredményezte. Az elvégzett kísérletek alapján általánosságban elmondható, hogy az adagolt hordalék csökkentette az áteresz kapacitását, hiszen a beömlőnyílás előtt lerakódott hordalék akadályozta a víz áramlását az átereszen keresztül. A két vizsgált adagolási módszer (fokozatos, egyszeri) közül az egyszeri adagolás eredményezte a magasabb felvízszinteket, hiszen több hordalék rakódott le a felvízi medencében. Annak ellenére, hogy a hordalék méret és mennyiség csak kis mértékben befolyásolta az áteresz teljesítményét, a vízszintek általában magasabbak voltak, amikor több hordalék (7 kg) került adagolásra. A tartalék áteresz, ami a fő átereszn él magasabb szintre került telepítésre megnövelte a szerkezet biztonságát, hiszen

kevésbé volt hajlamos a hordaléklerakódás okozta eltömődésre. A hordalékfogós vizsgálatok alapján kiderült, hogy mind a gereb, mind az uszadék terelő hatékony eszköz a hordalék visszatartására, jóllehet ezeknek a hordalékfogó szerkezeteknek a telepítése csökkentette az áteresz vízátvezető kapacitását. Az említett eredmények mind hidraulikai kapacitás, mind töltés biztonság, mind költség szempontból elemzésre kerültek az optimális kialakítás megtalálása céljából. Végül a kiválasztott kialakítás bemutatásra és vázlatrajzokkal illusztrálásra került.

Preface

This Master's Thesis, **Comparison of the hydraulic capacity of different culvert inlet designs under sediment transport conditions** was written by *Fanni Terlaky* in spring 2015 under the supervision of *Professor Jochen Aberle*. The main task was to carry out an overarching analysis of five previous experimental studies carried out in the NTNU Hydraulic Laboratory (Vassdragslaboratoriet) and to develop a design of the optimal culvert configuration based on the conclusions from this analysis. I hereby declare the data analysis and culvert design were conducted by me.

This Thesis would have not been possible without the academic support of my main-supervisor, *Professor Jochen Aberle*. Therefore, I use this opportunity to present my gratitude for his great help during the completion of this work. I wish to thank my two co-supervisors: *Joakim Sellevold* from Statens Vegvesen for providing necessary knowledge on culverts from real life experiments and *Sándor Baranya* from Budapest University of Technology and Economics for his both academic and English support.

At last, I wish to thank my sister, *Krisztina Terlaky* and my cousin, *Viktor Terlaky* for proof reading of the thesis.

Fanni Terlaky

Trondheim, June 2015

Abbreviations- and Notations list

Abbreviations

NIFS	Natural hazards – Infrastructure for floods and landslide / Naturfare – infrastruktur, flom og skred
NNRA	Norwegian National Rail Administration / Jernbaneverket
NRPA	Norwegian Public Roads Administration / Statens vegvesen
NTNU	Norwegian University of Science and Technology / Norges teknisk-naturvitenskapelige universitet
NVE	Norwegian Water Resources and Energy Directorate / Norges vassdrags- og energidirektorat

Notations

D	Culvert barrel diameter [m]
d	Grain diameter [m]
D_r	Reserve culvert diameter [m]
Fr	Froude number [-]
ft	Foot
ft^3/s	Cubic foot/second(s)
g	Gravitational acceleration [m/s^2]
h	Water depth [m]
h_0	Headwater depth [m]
h_a	Height of approach channel [m]
h_b	Height of expansion section (basin) [m]
h_{cr}	Height of upstream (collecting) reservoir [m]
h_D	Water depth in pipe (free surface flow) [m]
h_t	Tailwater depth [m]
HW	Headwater depth [m]
k_a	Roughness of approach channel [$m^{1/3}/s$]
k_b	Roughness of basin [$m^{1/3}/s$]
k_c	Roughness of barrel [$m^{1/3}/s$]
kg	Kilogram(s)

L	Length dimension
l/s	Litre/second(s)
l_a	Length of approach channel [m]
l_b	Length of expansion section (basin) [m]
l_c	Barrel length [m]
l_{cr}	Length of upstream (collecting) reservoir [m]
m	Metre(s)
M	Mass dimension
m/s	Metre/second(s)
m/s^2	Metre/square second(s)
m^3/s	Cubic metre/second(s)
m_f	Weight of fed sediments [kg]
mm	Millimetre(s)
m_t	Weight of transported sediments [kg]
Q	Discharge [m^3/s]
Q*	Dimensionless discharge [-]
Q*	Dimensionless discharge [-]
Re	Reynolds number [-]
S	Slope of approach channel [-]
S_b	Slope of expansion section (basin) [-]
S_c	Slope of culvert [-]
S_{rc}	Slope of reserve culvert [-]
t	Time span of feeding [s]
T	Time dimension
TW	Tailwater depth [m]
v	Flow velocity [m/s]
w_a	Width of approach channel [m]
w_b	Width of expansion section (basin) [m]
w_{cr}	Width of upstream (collecting) reservoir [m]
μ	Dynamic viscosity [kg/m/s]
μ*	Dimensionless dynamic viscosity [-]
ρ	Fluid density [kg/m3]
ρ_s	Sediment density [kg/m^3]

Table of Contents

List of Tables

List of Figures

1 Introduction

Culverts are important hydraulic control structures, whose main purpose is to convey the required volume of water effectively and safely through infrastructure, such as roads and railroads. The hydraulic capacity of culverts depends on hydraulic flow conditions, transported sediment and debris. During flood events, the amount of transported sediment and debris increases, which increases the risk of reduced capacity and complete blockage of the culvert. Furthermore, hydrological conditions are expected to change in Norway as a result of climate change, so increased precipitation and more intense storm events are predicted. Consequently, the existing culverts will have to convey more water than what they were designed for, and there is a need to upgrade their capacity. However, solely improving the discharge capacity is not sufficient. Catchment wide transport processes also have an effect on culvert performance, thus both sediment load and debris accumulation have to be taken into account (Aberle, 2015). Therefore, the proper understanding of both water flow and sediment transport through culverts are necessary to assess and upgrade their performance, in order to ensure safe roads and future infrastructure installations.

Unfortunately, the existing knowledge of culvert design in steep mountainous areas with consideration of sediment transport is insufficient. In order to bridge this knowledge gap, a scale model study in the NTNU hydraulic laboratory (Vassdragslaboratoriet) was initiated by the Norwegian Public Roads Administration (NRPA – Statens vegvesen), the Norwegian National Rail Administration (NNRA – Jernbaneverket), and the Norwegian Water Resources and Energy Directorate (NVE – Norges vassdrags- og energidirektorat) within the research programme Natural hazards – Infrastructure for floods and landslides. The main purpose of the study is to contribute to the development of new guidelines for culvert design in steep streams, under inlet control, taking into account the effect of transported debris and sediment. In order to investigate the effect of different boundary conditions a range of experiments have been carried out in the framework of MSc-theses and student-projects. In addition to the effectivity of different inlet shapes, the effect of the sedimentation basin geometry and the sediment feeding process (size-, amount-, feeding method of sediment) were investigated. All experiments were carried out with both clear water conditions and coarse sediment as bed load material. The experimental data were used to establish discharge curves for the different culvert geometries and sediment load conditions. In the framework of these theses the ecological aspect of the culverts was not examined, only the hydraulic capacity of the culvert and the sedimentation pattern at the different initial conditions.

To date a total of five student-theses have been prepared in the framework of the project. All of them considered different boundary conditions and analysed their effect on culvert performance. The main aim of the present study is to provide an overarching and unifying analysis of the available data from the five studies, in order to identify the favourable culvert inlet design under sediment transport conditions. The thesis is structured as follows: in Chapter 2 a general overview is presented related to the culverts, culvert hydraulics and culvert design. Furthermore, existing knowledge about the sedimentation and debris accumulation at the culvert areas is discussed. After the literature review the applied scale model and its attributes are presented in Chapter 3.1. In Chapter 3.2 the results of the previous studies are analysed and the effects of the different initial conditions are summarized. As a result of the unifying analysis which is presented in Chapter 4, an optimal culvert configuration is chosen and presented in Chapter 5. In Chapter 7 proposals are presented for the further work.

2 Culverts

2.1 Background

Culverts are hydraulically short structures buried under high-level embankments to convey stream flow safely under them (Novak, et al., 2007; Norman, et al., 2001). In Norway, free openings under transportation lines which have a width less than 2.5 metres are called culverts (Statens Vegvesen, 2011). A wide range of culvert configuration exists including different construction materials, shape and inlet design. To select the appropriate culvert attributes, the following factors are necessary to be taken into consideration: roadway profiles, channel characteristics, flood damage evaluations, construction and maintenance costs, and estimates of service life (Norman, et al., 2001).

Culverts are closed conduits or open-bottom culverts. Both types are available with various cross-sectional shapes. The most commonly used closed conduit shapes, depicted in Figure 2.1, include circular, box (rectangular), elliptical, and pipe-arch. All closed conduits are constructed such that the entire perimeter consists of the same material. Open bottom culverts, on the other hand, use the natural stream bed as the bottom section and only the upper part is manufactured from artificial materials. Figure 2.2 shows the common arch and box configurations (Schall, et al., 2012).

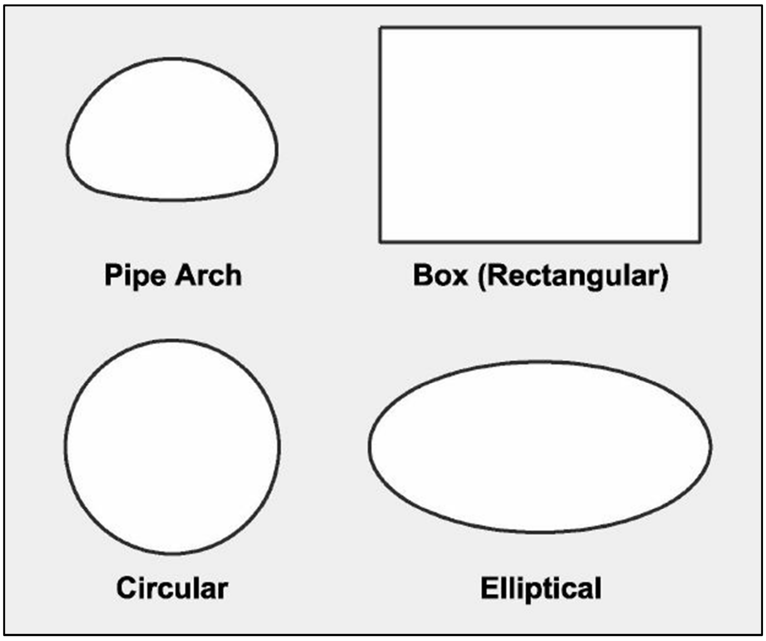

Figure 2.1 Commonly used closed conduit shapes (Schall, et al., 2012)

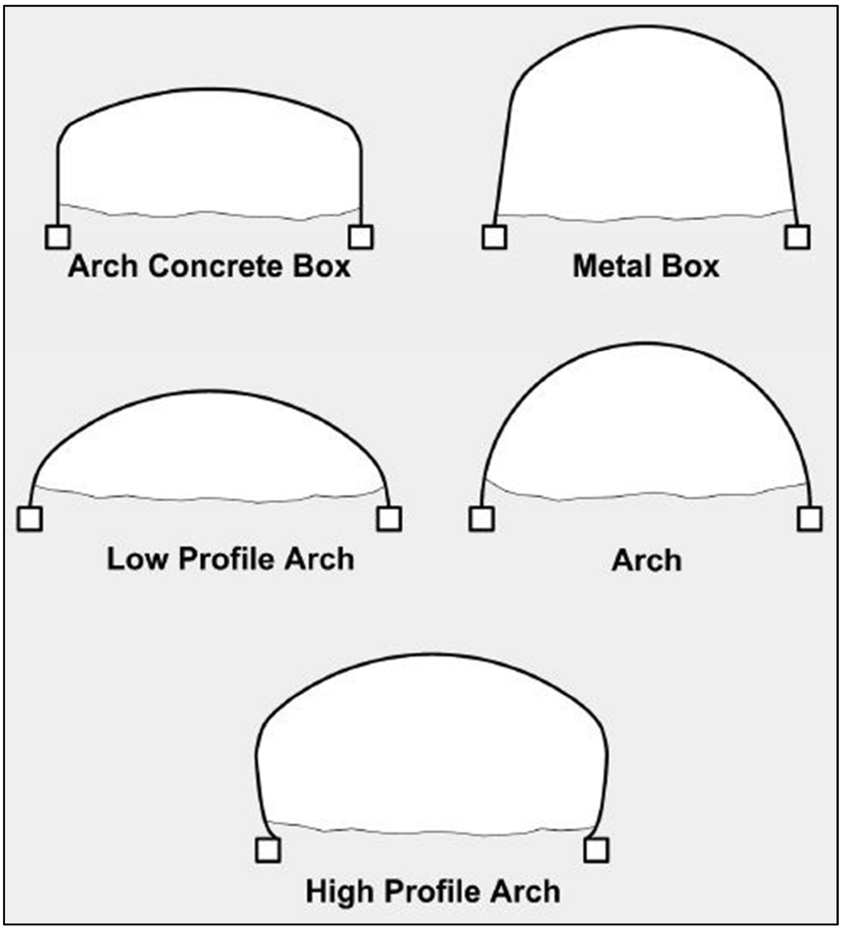

Figure 2.2 Commonly used open bottom culvert shapes (Schall, et al., 2012)

Additionally, a multi-barrel system might be necessary to convey water through low fills or on wide, shallow streams. This solution is more economical than the use of a single wide span. Nevertheless sedimentation and debris accumulation are significant problems related to multi-barrel systems. To reduce this problem, the culverts in these systems are installed on two levels thus only the lower ones are susceptible to clogging by debris and sediment (Schall, et al., 2012).

Nowadays culverts are typically constructed from concrete (both reinforced and non-reinforced), corrugated metal (aluminium or steel) and plastic (high-density polyethylene (HDPE) or polyvinyl chloride (PVC)). The selection of construction material depends on the required structural strength, hydraulic roughness, durability (corrosion and abrasion resistance), and constructability. In some cases the lining of a culvert with another material may be necessary to inhibit corrosion and abrasion, or to reduce hydraulic resistance (Schall, et al., 2012).

Numerous different inlet configurations are used for culvert barrels. They are either prefabricated or constructed in-place. Four standard inlet types are depicted in Figure 2.3, and include projecting, wingwalls, precast end sections, and culvert ends mitred to conform to the fill slope (Schall, et al., 2012). “Properly designed entrance structures prevent bank erosion and improve the hydraulic characteristics of the culvert” (Novak, et al., 2007). For example wingwalls provide structural stability to the culvert as they retain the embankment slopes and improve the hydraulic capacity by funnelling flow into the culverts (Creamer, 2007).

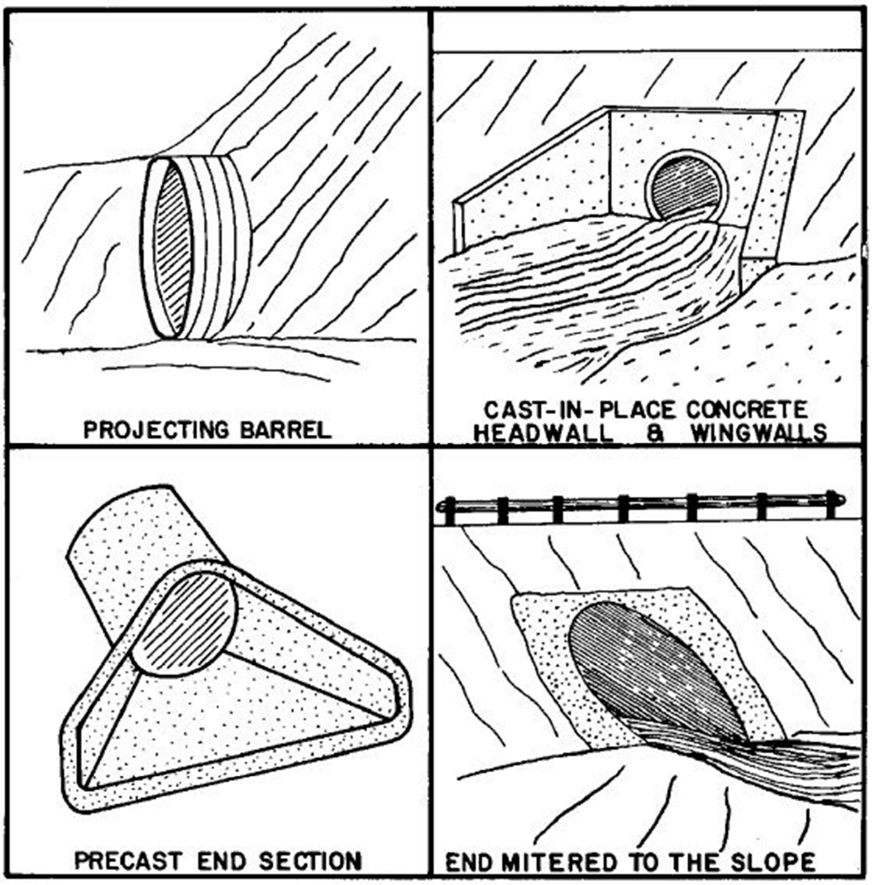

Figure 2.3 Four standard inlet types (Norman, et al., 2001)

Sedimentation and debris accumulation are widespread problems for culverts. To avoid or reduce the risk of culvert blockage structural and non-structural measures have been used. The structural measures include debris deflectors, -racks, -risers, -cribs, -fins, dams and basins, and non-structural measures include the management of the upstream watershed and continuous maintenance (Bradley, et al., 2005).

2.2 Culvert hydraulics

The openings of culverts are usually smaller than the cross-section of natural channels. Culvert barrels, therefore act like an obstruction on streams and cause reduction of their hydraulic capacity. As a result the water depth upstream of the structure, termed headwater, increases (Creamer, 2007). This larger water depth provides the gravitational (potential) energy required to force the flow through the culvert. The inlet edge of the culvert causes flow contraction, which in turn results in flow energy loss at the entrance of the barrel. This energy loss can be decreased and the hydraulic performance of the culvert can be increased by creating a more gradual flow transition at the entrance area by using curved edges (Figure 2.4) (Schall, et al., 2012).

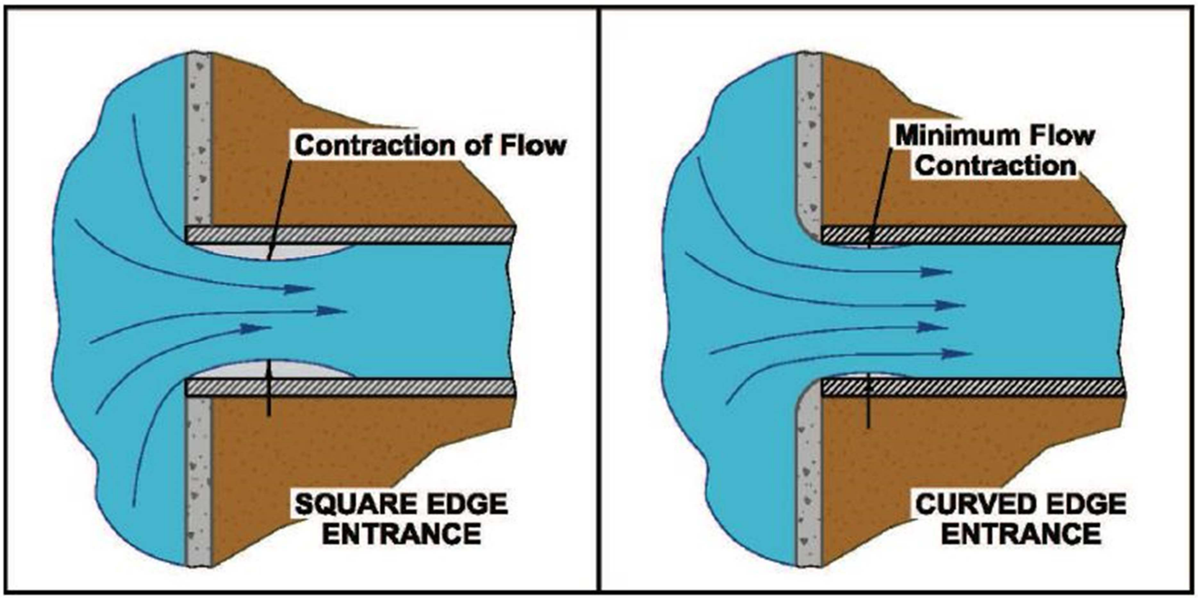

Figure 2.4 Entrance contraction (Schall, et al., 2012)

Culverts not only increase headwater depth, but typically also increase flow velocity in the barrels, as a result of flow constriction. Higher flow velocities can result in streambed scour or bank erosion around the culvert outlet. To avoid these problems, increased barrel roughness or use of energy dissipators could be necessary (Schall, et al., 2012).

Flow in the culvert is usually non-uniform, with regions of both gradually varying and rapidly varying flows, and an exact theoretical analysis of flow conditions would be extraordinarily complex. Eighteen different culvert flow types have been defined by the U.S. Geological Survey based on inlet and outlet submergence, flow regime in the barrel, and downstream brink depth. Change in flow rate and tailwater depth can cause change of the flow type (Norman, et al., 2001). The tailwater is defined as the downstream water depth, which is measured from the outlet invert (Schall, et al., 2012).

The flow through the entrance at low flows behaves like weir flow, while at much higher flows acts like orifice flow. In the case of weir flow the entrance is unsubmerged and there are some predictable relationships between the discharge and the depth, whereas in the case of orifice flow the entrance is submerged and the discharge through the opening increases as the headwater depth above the opening increases (Creamer, 2007).

2.2.1 Flow conditions

Two types of flow conditions occur in culverts: pressurised or free surface flow. The flow type depends on upstream and downstream conditions, barrel characteristics, and inlet geometry (Schall, et al., 2012).

Pressurized flow occurs when the culvert's entrance or exit is submerged and water is under pressure as a result of backpressure due to high tailwater elevation, or high headwater depth. Regardless of the cause, the upstream and downstream conditions and the hydraulic characteristics of the culvert affect the capacity of a culvert that operates under pressure flow (Schall, et al., 2012).

Free surface flow occurs in a culvert when the flow in the barrel does not fill the culvert's cross-sectional area. Three different flow regimes are defined: subcritical, critical and supercritical flow. These flow regimes are defined based on the evaluated dimensionless number termed Froude number (Fr):

$$Fr = \frac{v}{\sqrt{gh}} \tag{2.1}$$

where v is the average flow velocity, g is the gravitational acceleration and h is the representative depth (typically the equivalent depth or the hydraulic depth). Flow is subcritical when $Fr < 1.0$, supercritical when $Fr > 1.0$ and critical when $Fr = 1.0$. The critical flow condition gives the lowest specific energy for flow (Chanson, 2004). The three flow regimes are illustrated in the flow conditions over a small dam in Figure 2.5. Upstream of the dam crest, high water depth and low flow velocity results in subcritical flow, while downstream of the dam crest, supercritical flow occurs due to low water depth and high velocity. The dividing point between the sub- and supercritical flow at the dam crest is where the critical flow occurs (Schall, et al., 2012).

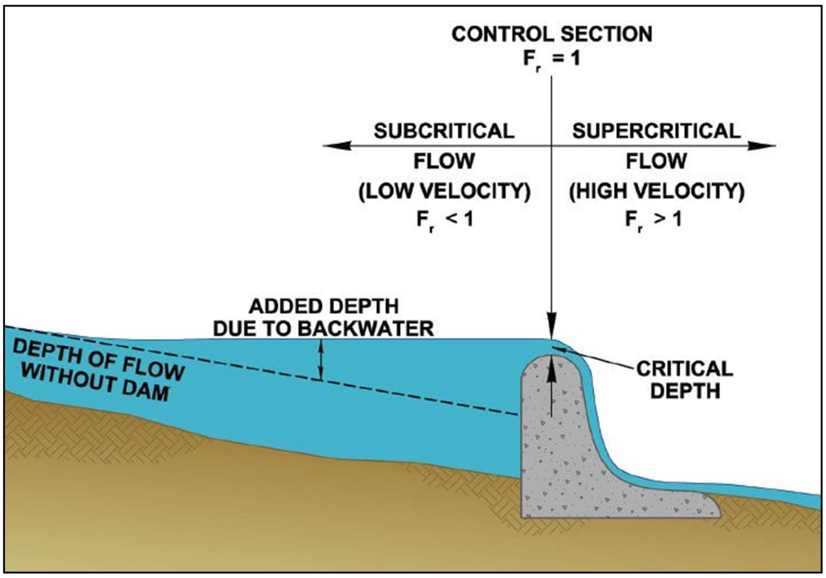

Figure 2.5 Flow conditions over a small dam (Schall, et al., 2012)

This type of flow distribution may occur in a steep culvert that is partly full (Figure 2.6). In this case subcritical flow exists in the upstream channel, critical flow occurs at the culvert inlet and due to flow acceleration supercritical flow exist in the culvert barrel (Schall, et al., 2012).

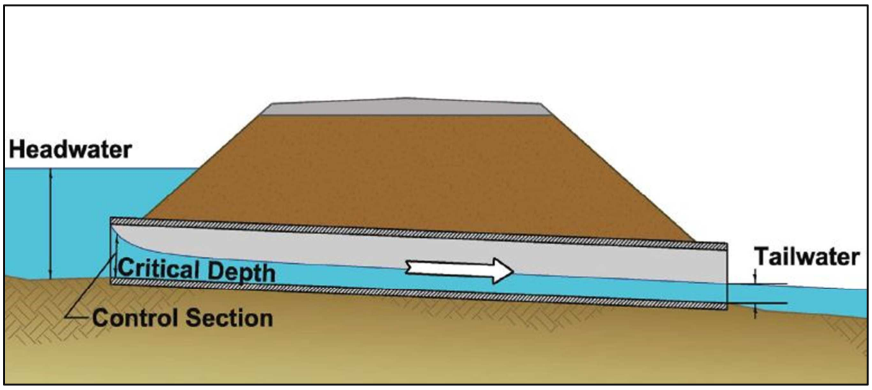

Figure 2.6 Typical inlet control flow section (Schall, et al., 2012)

2.2.2 Types of flow control

Depending on the location of the control section two flow control types exist: inlet and outlet control. At the control section a unique relationship is discernible between the flow rate and the elevation of the upstream water surface (Norman, et al., 2001). The ideal location of the control section depends on the pressure characteristics and the subcritical and supercritical flow regimes in the barrel (Schall, et al., 2012). Generally, culverts that are operating on mild slopes, the control section is located around the outlet. Conversely, on steep slopes the inlet control is used more commonly (Iowa Department of Natural Resources, 2009).

In case of inlet control, the control section is located close to the inlet and more water can be conveyed through than entering the barrel. As a result, the headwater level depends on the culvert entrance characteristics (Iowa Department of Natural Resources, 2009).

Outlet control is when flow is controlled by downstream conditions. In this case the predominant factors in determination of the headwater level are the head losses caused by tailwater conditions and barrel friction (Iowa Department of Natural Resources, 2009).

The influencing factors on the hydraulic capacity for both cases are shown in detail in Table 2.1.

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

There are different examples for both inlet and outlet controlled flows depending on the submergence of the inlet and the outlet. The following table (Table 2.2) and the sketches in Figure 2.7 show the specifications of the different flow types.

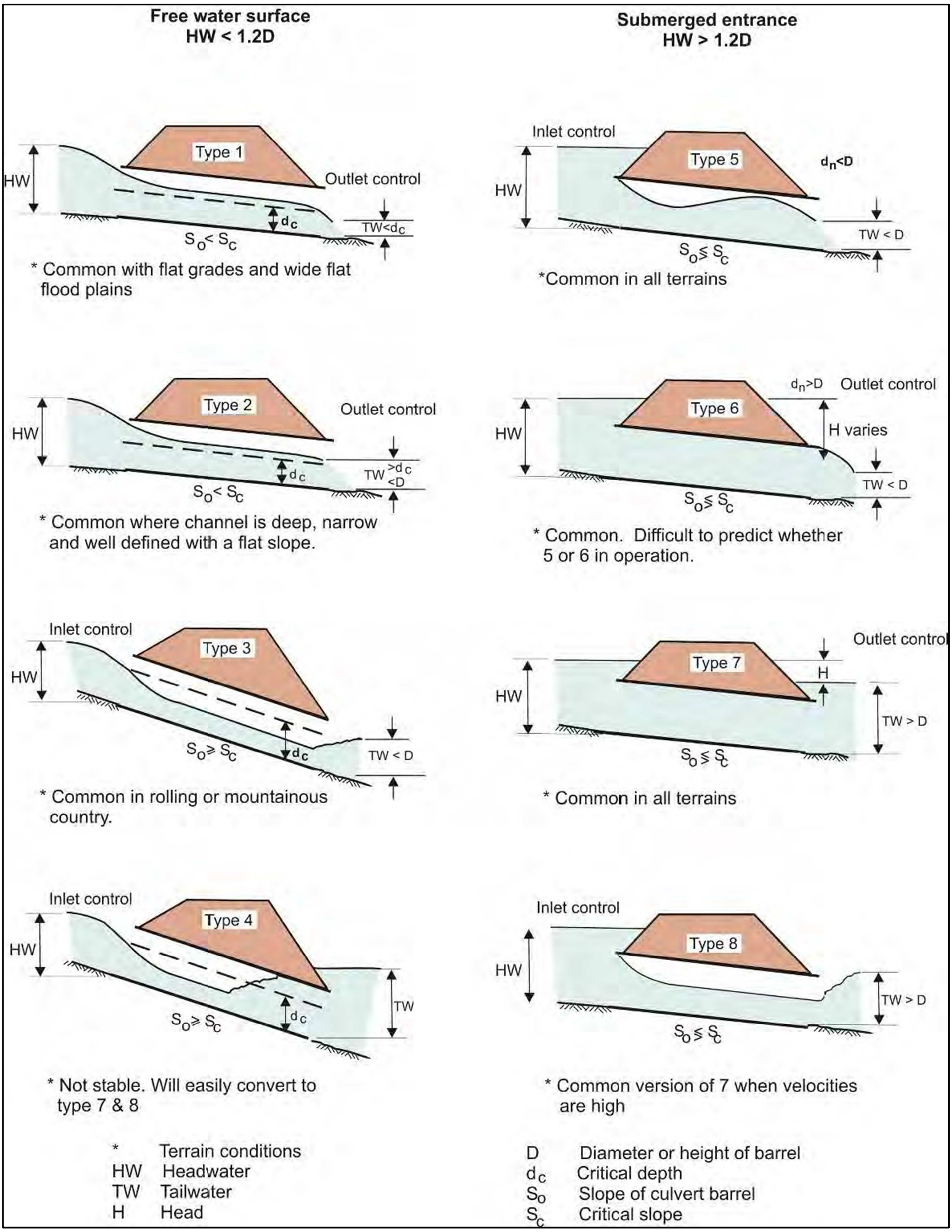

Figure 2.7 Examples for inlet and outlet control (Queensland Government, 2013)

Flow type	Flow Control	Submerged Inlet: HW>1.2D	Submerged Outlet: TW>D	Length Full
Type 1	Outlet control	No	No	None
Type 2	Outlet control	No	No	None
Type 3	Inlet control	No	No	None
Type 4	Inlet control	No	Yes	Part
Type 5	Inlet control	Yes	No	Most
Type 6	Outlet control	Yes	No	All
Type 7	Outlet control	Yes	Yes	All
Type 8	Inlet control	Yes	No	None

Table 2.2 Flow types in culvert

Type 1 flow is a condition where both the inlet and the outlet are unsubmerged, the barrel flows partly full over its length and the critical depth occurs just downstream of the culvert entrance hence the flow in the barrel is subcritical. Type 2 flow is similar to the previously described condition, with the difference that the tailwater depth is higher than the critical depth. Type 3 flow is when both the inlet and the outlet are unsubmerged and the control section is close to the inlet, In this case the hydraulic jump occurs at the outlet thus the flow is supercritical in the barrel. Type 4 flow occurs with inlet control and a submerged outlet, but in this case a hydraulic jump occurs within the culvert barrel. In case of Type 5 flow the entrance is submerged, the control section is located right after the entrance and a wave occurs in the barrel, which is then followed by the unsubmerged outlet. Type 8 flow is similar to this, but here the flow is supercritical within the barrel and the hydraulic jump occurs right after the outlet section. Type 6 and 7 flows show two outlet controlled situations. Type 6 flow occurs with a submerged inlet and an unsubmerged outlet: the barrel flows fully over its length, but the water level decreases right after the barrel. Type 7 flow occurs when both ends of the culvert are submerged.

2.2.3 Performance curves

A performance curve is a plot that shows the relation between the headwater depth and the flow rate. This graphical depiction of the culvert operation is a good representation of the hydraulic capacity of the culvert for different headwaters. The dominant control at a given headwater is difficult to predict, hence a plot of both the inlet and the outlet curves is necessary (Schall, et al., 2012). On the left side of the Figure 2.8 a typical performance diagram is shown with both inlet and outlet controlled curves.

All the experiments that are presented in this thesis were carried out under inlet control. Therefore, only the performance curves with inlet control are presented in more details. The performance curve of a culvert under inlet control has three different regions. At low headwater, the entrance of the culvert is unsubmerged and operates as a weir. In this case the upstream elevation can be predicted for a given discharge. At higher headwater the entrance is submerged and operates as an orifice. The transition zone between weir and orifice control is poorly defined. This zone then is approached by depicting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves (Norman, et al., 2001). A typical inlet control performance curve is depicted on the right side of the Figure 2.8.

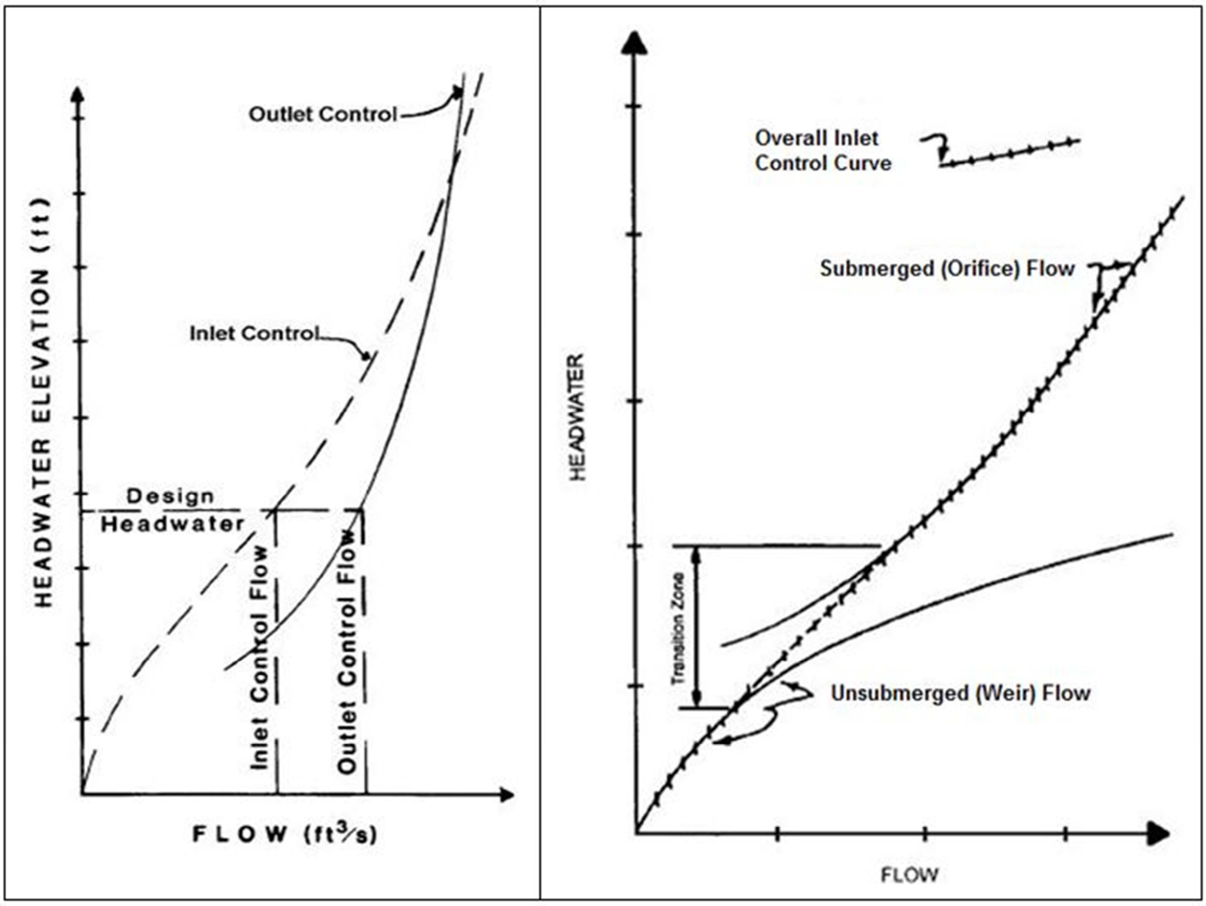

Figure 2.8 Performance curves (Norman, et al., 2001)

2.3 Culvert design

In Norway the regulations for culvert design are published by the NRPA in a manual called Håndbok 018 Vegbygging. This book is a guideline for road building and contains the most important information for the planning, design and construction process.

Table 2.3 shows data from this handbook describing how culvert diameter and the type of the inlet influence the hydraulic capacity of the culvert. The table describes inlet controlled flow situations where the ratio between the headwater depth (h) and the inside culvert diameter (D) equals unity. The three inlet types are presented in Table 2.3 and are illustrated in Figure 2.9.

Table 2.3 shows that when the culvert diameter does not exceed the one metre, the wingwalls inlet has the best hydraulic performance; the cut inlet has the highest hydraulic capacity for the diameters greater than one metre. The projecting inlet shows the lowest capacity for all culvert diameters.

Inlet design	**Diameter [mm]**								
	300	**400**	**500**	**600**	**800**	**1000**	**1200**	**1400**	**1600**
Wingwall [l/s]	67	135	232	361	726	1247	1940	2818	3895
Cut [l/s]	65	132	228	357	723	1250	1954	2851	3956
Projecting [l/s]	57	117	204	320	652	1133	1780	2607	3628

Table 2.3 Hydraulic capacity of culverts with inlet control, h/D = 1.0 (Statens Vegvesen, 2011)

Figure 2.9 Inlet types: A – Wingwalls; B – Cut; C – Projecting (Statens Vegvesen, 2011)

The manual also prescribes, that straight culverts with a length less than 15-20 metres should be designed with inlet control for the required discharge, hence further the design process for circular culverts with inlet control is presented briefly based on the guideline from the Federal Highway Administration.

Nomographs are used to determine the headwater depth (HW) under inlet control for the designed discharge (Q) and a selected culvert configuration (see Figure 2.10 for an example). If the headwater is larger than the allowable level or overtopping limit the configuration should be changed (Schall, et al., 2012). The overtopping limit in Norway is defined as double the culvert diameter from the upstream invert of the culvert (Statens Vegvesen, 2011)

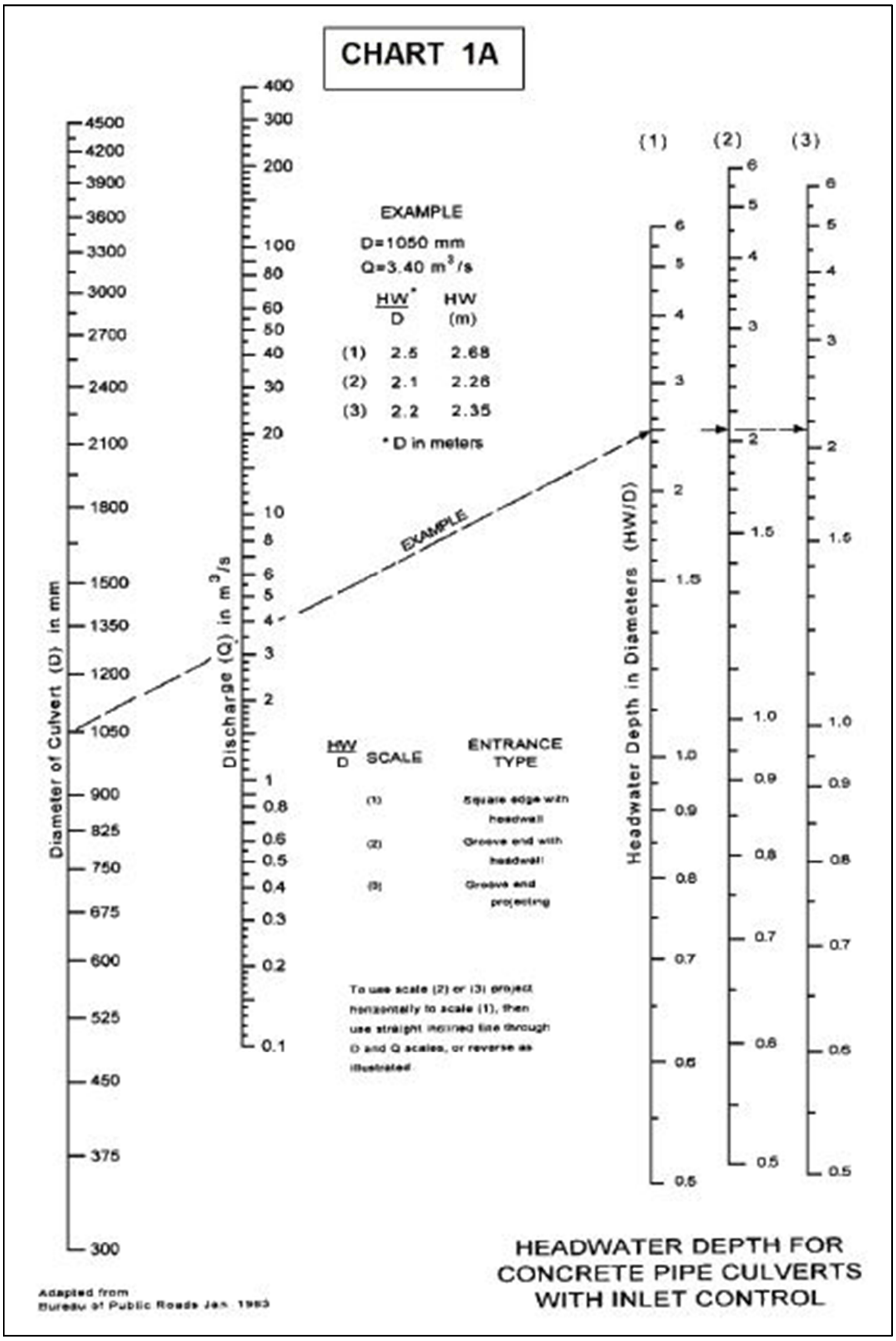

Figure 2.10 Nomograph for culvert design (Schall, et al., 2012)

2.4 Sedimentation in culverts

Sedimentation in culverts is a common and costly problem (Flanagan, et al., 1998; Rigby, et al., 2002; Ho, 2010; Queensland Government, 2013; Ho, et al., 2013). Culverts are typically constructed on relatively mild slopes to avoid supercritical flow upstream of the entrance of the barrel, even though culverts on mild slopes tend to have larger problems with sediment deposition (Ho, 2010). Similarly Flanagan et al. (1998) describe the ratio of the culvert slope to the channel slope as an index value for the sediment plugging hazard. On a steep stream a relatively flat culvert is more prone to sediment deposition than steeper culverts (Flanagan, et al., 1998).

Accumulation of sediment commonly causes partial blockage at the culvert entrance, thereby reducing the hydraulic capacity of the culvert. Vegetation, which usually colonizes and strengthens the accumulated sedimentary deposits, makes it also harder to erode, further exacerbating the problem. In Iowa, for example the excavation of the deposited sediment from the culvert is necessary usually every two years (Ho, et al., 2013).

The blockage of culvert barrels has four main consequences (Rigby, et al., 2002):

- Flood levels increase upstream of the culvert.
- Downstream of the culvert flood peak discharge may change, due to the attenuation effect of the stored water upstream of the structure.
- Floodwater may reach other parts of the catchment due to the increased headwater level.
- Overtopping flow scours the road or rail embankment, thus increasing the possibility of collapse. Failure of the embankment, then releases a surge of water towards the downstream channel.

Most of the currently existing guidelines provide design prescriptions for clear water conditions only. The investigation of culvert performance is complicated when the effect of sedimentation is taken into account. Sediment accumulation around the culvert is influenced by many factors, such as the size and characteristics of the stream‘s bed and bank material, the hydraulic characteristics of different hydrology events, culvert geometry and transition design, and the vegetation present around the channel (Ho, 2010). Consequently, flow conditions around the culvert are complex and difficult to predict. Creation of design guidelines for sedimentation-free culverts, or the building of sedimentation preventing control measures is, therefore complex. For a better understanding of flow patterns and sedimentation characteristics at culverts, experiences with existing culverts, the currently available methods and results from laboratory and field measurements and simulation models are used (Ho, et al., 2013).

2.5 Debris accumulation at culverts

In addition to sedimentation, debris accumulation is also a major problem at culverts. During flood events, streams commonly carry floating and submerged debris which can plug the culvert entrance or accumulate in the barrel (Schall, et al., 2012). Generally the culvert diameter is less than the width of the stream bed which increases the probability of debris accumulation. Therefore, small culverts in relatively wide channels are more prone to blockage by woody debris. An increase of the culvert diameter reduces the risk of blockage, as longer pieces of woody debris are required to initiate culvert plugging. As a result, “the ratio of culvert diameter to stream bed width provides one indication of plugging potential in woodland settings” (Flanagan, et al., 1997).

Widening of the stream channel immediately upstream of the culvert increases the probability of culvert blockage. In the widening section floating debris starts to rotate due to turbulent eddies and then accumulate at the culvert entrance, which initiates plugging (Figure 2.11). Straight, narrow channel approaches are, therefore recommended (Flanagan, et al., 1997).

Typically the accumulation of woody debris is the initiating factor of culvert plugging as it forms an obstruction at the culvert entrance, which traps sediment. Figure 2.12 depicts the process of the culvert plugging by debris and sediment (Flanagan, et al., 1998).

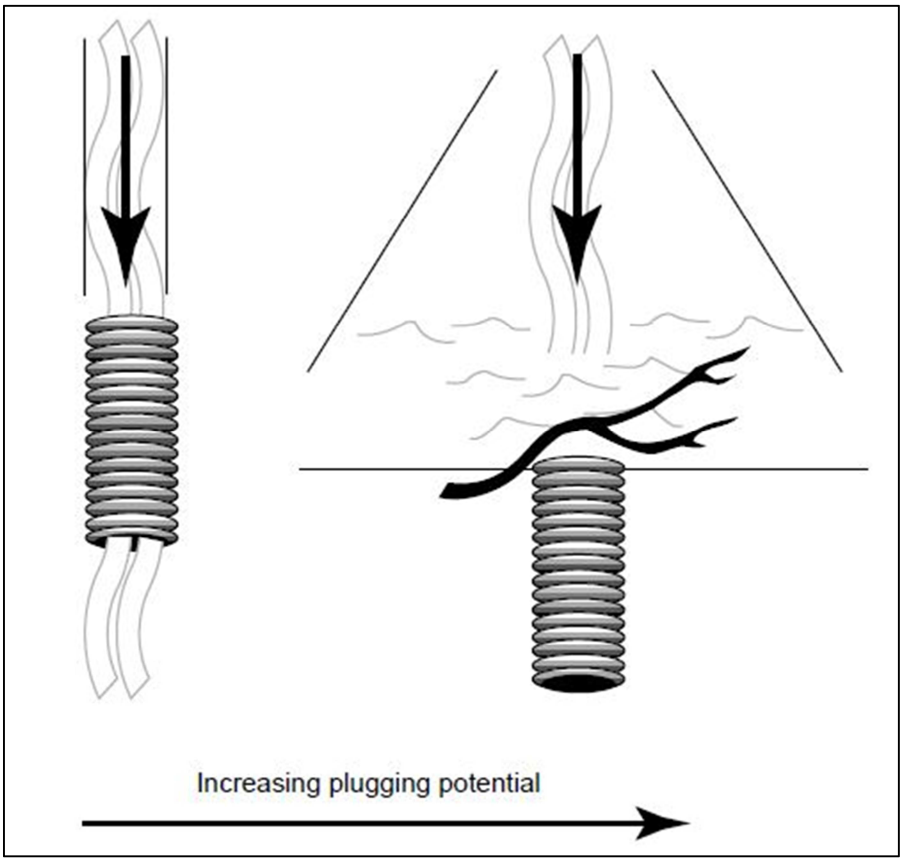

Figure 2.11 Plugging potential of culverts (Flanagan, et al., 1997)

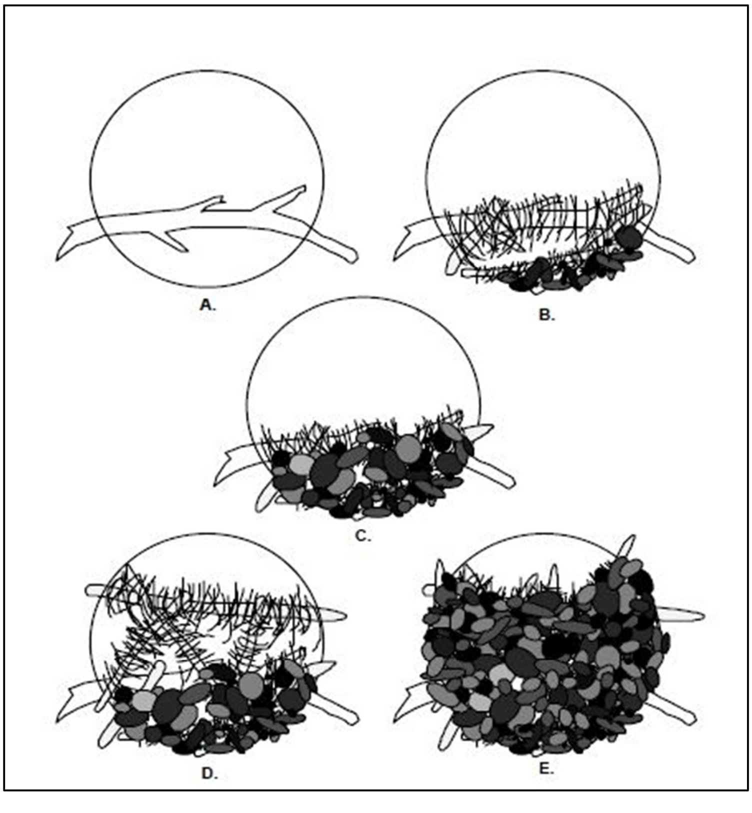

Figure 2.12 Plugging process of culverts (Cafferata, et al., 2004)

The following techniques facilitate the passage of woody debris and sediments (Cafferata, et al., 2004):

- Significantly smaller headwater depth to culvert diameter ratio than 1.0 (i.e. at maximum flow, the culvert flows one-half or two-third full)
- As wide, or nearly as wide culvert diameter as the width of the active stream channel (particularly for small streams)
- Installation of the culvert at the same gradient as the natural steam channel
- Parallel aligned culvert to the natural channel (i.e. avoiding angular deviation)
- Application of a single large culvert than several small ones as it is better for wood passage

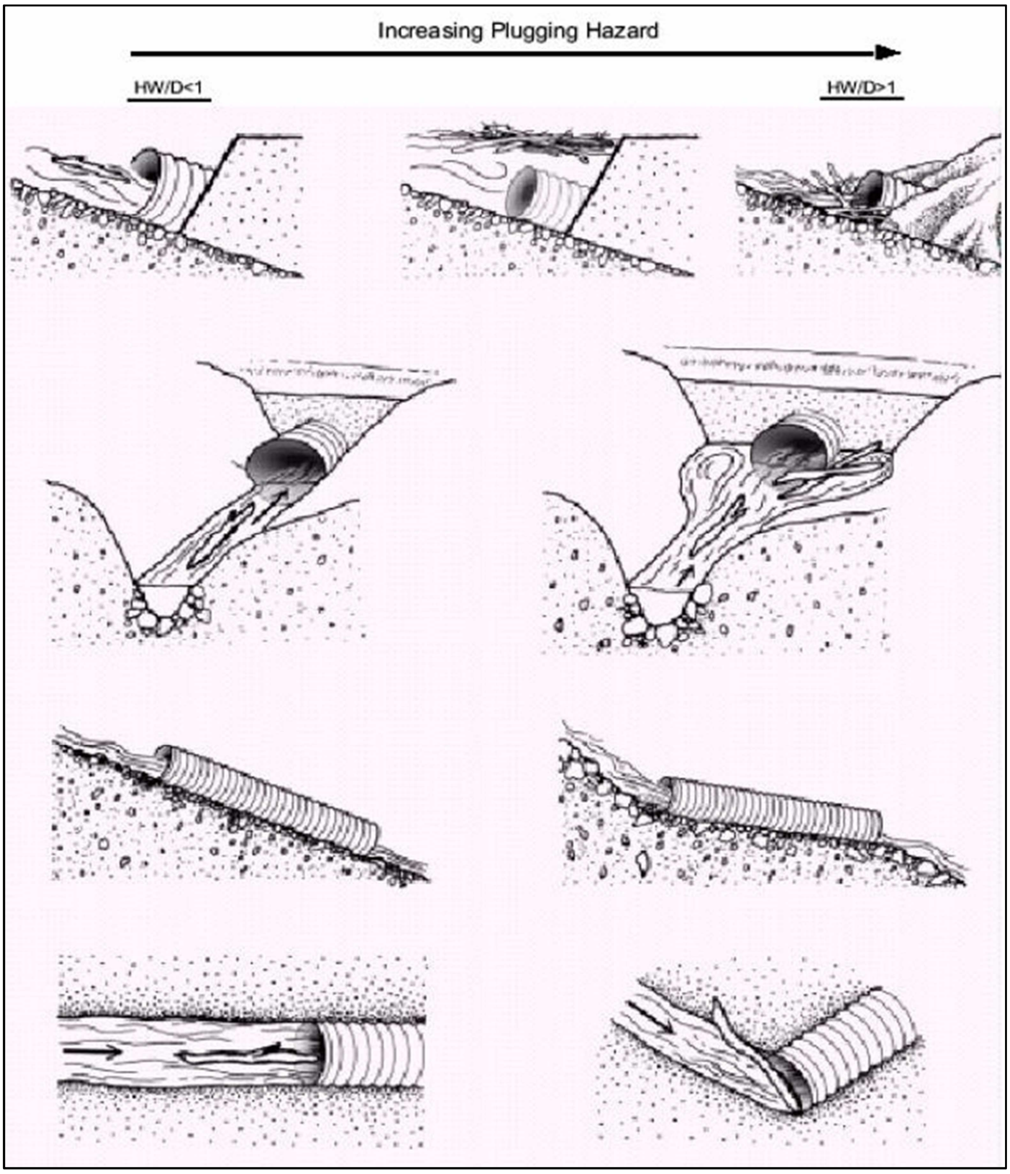

Figure 2.13 Influencing factors of culvert plugging (Cafferata, et al., 2004)

3 Experimental setup and data

This chapter presents the general experimental setup used in the studies related to culvert sedimentation carried out at NTNU hydraulic laboratory in framework of the NIFS-project. In addition, a brief overview on the main results of the 5 theses which have been prepared so far will be given.

3.1 Experimental setup

The culvert scale model that was used in the five previous student-theses was set up in the NTNU hydraulic laboratory (Vassdragslaboratoriet). The model was based on the Froude-similarity with a scale 1:10 and mimics a culvert in a steep stream. The main components of the model were the upstream (collecting) reservoir, approach channel, expansion section (basin) and the single culvert barrel with the culvert inlet (Figure 3.1).

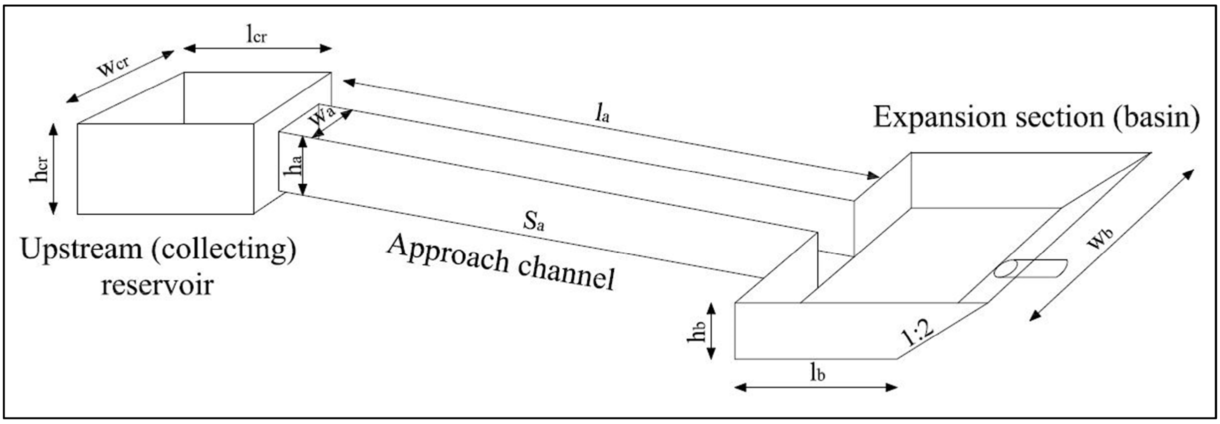

Figure 3.1 Basic configuration of the model (modified from a figure of Dirks (2014))

The slope of the approach channel, the width and the length of the expansion section and the culvert inlet were variable. The three different inlet configurations which were examined in the theses are wingwalls with an angle of 45°, the cut inlet and the projecting inlet. The inlet configurations are shown in Figure 3.2. Furthermore, other additional structures were added to the model in the different projects such as energy dissipator blocks (Hendler, 2014), reserve culvert barrel (Faqiri, 2014), debris deflector or trash racks (Dirks, 2014). Figure 3.1 depicts the basic configuration of the scale model and Table 3.1 gives the technical specifications of the models in the individual theses.

Figure 3.2 Culvert inlet shapes: A) Wingwalls, B) Cut inlet, C) Projecting inlet (Gotvassli, 2013)

		Gotvassli, 2013	Hendler, 2014	Putri, 2014	Faqiri, 2014	Dirks, 2014
Upstream reservoir						
~ length [mm]	l_{cr}	785	785	785	785	785
~ width [mm]	w_{cr}	535	535	535	535	535
~ height [mm]	h_{cr}	420	420	420	420	420
Approach channel						
~ length [mm]	l_a	2400	2400	2400	2400	2400
~ width [mm]	w_a	230	230	230	230	230
~ height [mm]	h_a	300	300	300	300	300
~ slope	S	1:5 1:9	1:5 1:9 1:50	1:9	1:9	1:9
Expansion section						
~ length [mm]	l_b	876 625 315	876	876	876	876
~ width [mm]	w_b	1100	1100	876 657 555 438 292	1100	1100
~ height [mm]	h_b	300	300	300	300	300
~ slope	S_b	2%	2%	2%	2%	2%
Embankment slope		1:2	1:2	1:2	1:2	1:2
Culvert						
~ diameter [mm]	D	100	100	100	100	100
~ slope	S_c	2%	2%	2%	2%	2%
Energy dissipatior blocks (3 pcs)			20x20x20 mm	20x20x20 mm	20x20x20 mm	20x20x20 mm
Reserve culvert						
~ diameter [mm]	D_r				60	
~ slope	S_{rc}				2%	
Debris deflector						✓
Trach racks						✓

Table 3.1 Technical specifications of the model

The basic construction material of the model was plywood. The culvert was made of a plastic barrel with a diameter of D=100 mm, which, according to the model scale represents a culvert with a diameter of D=1 m. The debris deflector and trash racks were milled from an aluminium plate.

The scale model was designed to examine the performance of a culvert on steep stream under inlet control; therefore, the measurements were stopped when the culvert started to work under outlet control. Furthermore, the flow under inlet control was only influenced by the inlet and the upstream conditions (Table 2.1) thus instead of the whole culvert, only the culvert entrance was built in the model. In addition, the water in the model falls freely from the outlet, so the downstream water level never induces outlet control. Outlet control can be assumed when the barrel runs full.

During the experiments discharge and water levels were measured under steady flow conditions. Flow discharge was controlled by a valve and measured with a magnetic-inductive flow meter (Siemens Sitran FM Magflo MAG500) while the water levels were measured with ultrasonic sensors (Microsonic mic+ Ultrasonic Sensors). The experiments were carried out with both clear water and with sediment load. Sediment was fed using a vibration machine and depending on the setup it simulated a landslide (all at once feeding) or a steady sediment transport (gradual feeding), which are common in natural streams. After the experiments the accumulated sediment in the expansion section as well as the transported sediment downstream of the barrel were collected and weighed separately. The measuring system is depicted on Figure 3.3: a) depicts the flow meter, b) shows the vibration machine and c) illustrates the ultrasonic sensors.

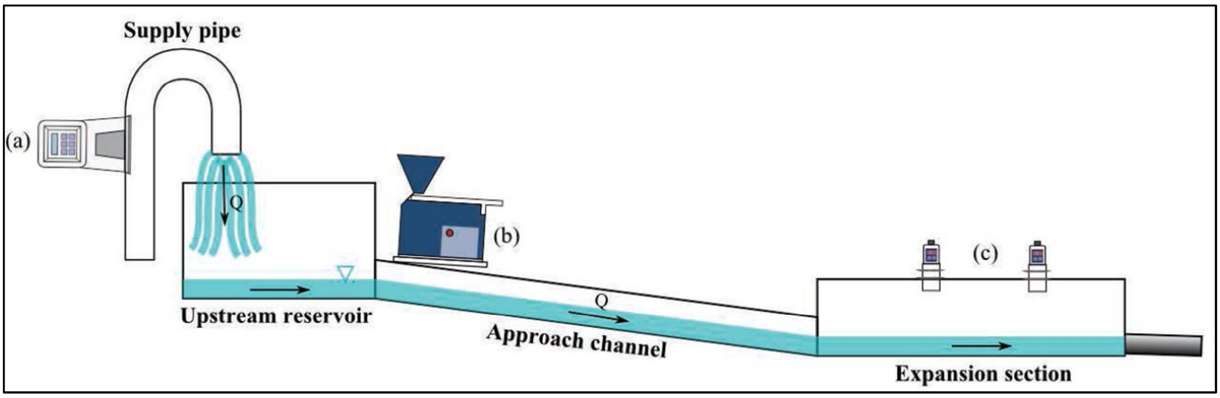

Figure 3.3 Measuring system: a) flow meter, b) vibration machine c) ultrasonic sensors (Dirks, 2014)

3.2 Data

Data collection from the experiments, comprise discharge measurements [l/s], water levels [mm] and sediment weights [kg]. From the discharges and water levels performance curves were obtained. In this subchapter the focus and main results of the five previous projects are presented.

3.2.1 Length effect under jet dominated flow

Gotvassli (2013) examined the effect of inlet shape (wingwalls, cut inlet, projecting inlet), the basin length (876, 625, 315 mm), the slope of the approach channel (1:5, 1:9), the sediment feeding method (gradually, all at once), and the size (8-16 mm, 16-32 mm) and amount (5 kg, 7 kg) of the sediments. The applied technical specifications of the model are shown in Table 3.1. After the experiments, performance curves were established to compare the influence of the different factors on the culvert's hydraulic capacity. Based on the results of the experiments, the inlet shape was found to be the most influencing factor on culvert performance. The inlet with wingwalls was the most reliable shape as high amount of water was conveyed through the culvert under stable flow conditions. The application of the cut inlet, in contrast, turned had the lowest capacity due to the often unstable and oscillating flow conditions. The basin length also influenced the capacity. The capacity was higher with the shortest length, because the jet, which occurred due to the steep approaching channel, was directed towards the barrel. Additionally, the steeper approach channel (1:5) had a higher capacity, although the flow was more stable with the milder slope (1:9). The results of the experiments under sediment load showed a tendency of an increased capacity with both gradually and all at once feeding. This is not in accordance with the existing knowledge on the subject, as the decrease of the capacity was assumed under sediment load. In the experiments, the flow pattern strongly influenced the sediment deposition. The resulting altered inlet shape and basin geometry are important factors in sedimentation. The sediment preferentially accumulated in front of the culvert when the inlet shape and the basin geometry resulted in a lower capacity. These experiments were carried out under jet regime, as flows were supercritical in the steep approach channel. This boundary condition was not intentional, and strongly influenced the results, as the flow often became unstable and the jet often oscillated. It is important to take this effect into account when we would like to compare results from Gotvassli (2013) with the results from the other theses.

3.2.2 Effect of energy dissipation structure

Hendler (2014) focused on the effect of the slope and to avoid the jet regime which was specific to Gotvassli (2013). The experiments were carried out with the variation of the following parameters: inlet shape (wingwalls, cut inlet, projecting inlet), slope of the approaching channel (1:5, 1:9, 1:50), position of the culvert (centred, moved to the right), energy dissipator blocks (with, without them), sediment feeding method (gradually, all at once), and size (8-16 mm, 16-32 mm, sand: 0.4-0.8 mm) of the sediments. As a result of the application of the energy dissipator blocks the headwater levels increased in the experiments, so the hydraulic capacity was reduced. With the blocks the projecting inlet showed the best performance, while the wingwalls showed the worst. The experiments resulted in higher headwater depths, so lower hydraulic capacity with the application of the milder slope (1:50) than with the steeper slope (1:5). However, in case of steep slopes the flow energy is high which is undesirable due to embankment stability reasons. Therefore, additional energy dissipation structures should be used to decrease the flow energy (i.e. flow velocity) upstream of the culvert. The sediment experiments without cubes showed that the capacity is lower with the all at once feeding than with the gradually feeding and when the energy dissipation was installed more sediment stayed in the expansion section and in the approaching channel. The displacement of the culvert influenced both the hydraulic capacity and the sediment pattern a little. As a result more sediment stayed in the expansion section and the capacity was also decreased slightly. The experiments with sand were carried out to investigate the sediment deposition pattern in case of fine sediment for all three inlet types.

3.2.3 Effect of varying expansion section width

The main focus of Putri (2014) was to examine the influence of the different basin width (876, 657, 555, 438, 292 mm) on the culvert capacity. Additionally, similarly to the previous studies, the effect of the inlet shape (wingwalls, cut inlet, projecting inlet), the sediment feeding method (gradually, all at once), and the size (8-16 mm, 16-32 mm) and amount (5 kg, 7 kg) of the sediments were investigated. The technical specifications of the model are presented in Table 3.1. In Putri (2014) three energy dissipator blocks were used in the model, which were developed in Hendler (2014) to avoid the unstable, oscillating flow regime and induce a hydraulic jump before the culvert entrance. The results of the experiments showed that the most influencing factor is the inlet shape as it was also found in the previous studies also and for the same discharge, the hydraulic capacity decreased with decreasing width. The experiments with sediments generally showed lower hydraulic capacity and the narrower expansion section turned out to transport less sediment through the culvert. Furthermore, the sedimentation pattern was strongly influenced by the location of the hydraulic jump as the sediments tended to deposit right after the emergence of the hydraulic jump. Nevertheless, the feeding method, size and amount of the sediment had insignificant effect on the culvert performance.

3.2.4 Effect of reserve barrel

Faqiri (2014) focused on the use of multi-barrel culvert system. The experiments were carried out with different inlet shapes (wingwalls, cut inlet, projecting inlet), sediment feeding methods (gradually, all at once) and with different size (8-16 mm, 16-32 mm) and amount (5 kg, 7 kg) of sediments. To avoid the jet regime and induce the hydraulic jump before the culvert, energy dissipator blocks were used. The technical specifications are shown in Table 3.1. In accordance with the previous studies the inlet shape turned out the most influential parameter on the culvert capacity. The wingwalls and the cut inlet gave similar capacity results, however the flow conditions were more stable with the wingwalls inlet. In contrast, the projecting inlet had lower performance, while in the sediment transport it turned out to be more efficient than the two other inlet shapes. The application of the reserve barrel increased the total barrel cross-section thus increased the hydraulic capacity for all tested inlet configurations. As this second barrel was installed on a higher elevation than the main barrel it was less prone to be blocked by sediments thus gave extra safety to the culvert system. The reserve barrel basically did not influence the sediment pattern, only decreased the headwater level.

3.2.5 Effect of sediment countermeasures

The focus of Dirks (2014) was to investigate the effect of trash racks and debris deflectors on the hydraulic capacity and also on the sedimentation. The experiments were carried out with the three different inlet shapes (wingwalls, cut inlet, projecting inlet) under clear water conditions and under sediment load. During the sediment experiments the feeding method (gradually, all at once) and the size (8-16 mm, 16-32 mm) of the sediment were varied. The technical specifications are presented in Table 3.1. The results from the tests showed that both the trash racks and the debris deflectors reduce the sediment transport through the barrel. Furthermore, the installation of these structures obstructed the flow through the culvert, thus negatively influenced the hydraulic capacity of the culvert. The debris deflectors kept back more sediment, but the hydraulic performance with them were more reduced than with trash racks. In conclusion, these structures increased the headwater depth, so the embankment was overtopped at lower discharges than without them.

4 Data analysis and results

This chapter provides a unifying analysis of the available data in order to identify the favourable culvert inlet design under clear water and sediment transport conditions. The results will also be presented in a dimensionless framework and for this purpose; a dimensional analysis is carried out first.

4.1 Dimensional analysis

"Dimensional analysis is a rational procedure for combining physical variables into dimensionless products, thereby reducing the number of variables that need to be considered" (Hughes, 1993).

The first step of the dimensional analysis is to find the physical variables which have an effect on the studied phenomenon. In case of this studied scale-model under clear water conditions Table 4.1 summarises the relevant physical variables for inlet control conditions. Taking these parameters into account and applying the Buckingham Pi-theorem (Buckingham, 1914), dimensionless pi parameters can be formed. The Pi-theorem says that: "In a dimensionally homogeneous equation involving "n" variables, the number of dimensionless products that can be formed from "n" variables is "n-r" where "r" is the number of fundamental dimensions encompassed by the variables" (Hughes, 1993). As it is shown in Table 4.1 in case of the present model there are 19 variables and 3 base dimensions (mass (M) – length (L) – time (T)) which means 16 dimensionless products can be formed.

Section	Parameter	Unit	Dimension	Description
Governing parameter	Q	m^3/s	L^3/T	Discharge
Approach channel	S	-	-	Approach channel slope
	l_a	m	L	Approach channel length
	w_a	m	L	Approach channel width
	h_a	m	L	Approach channel height
	k_a	$m^{1/3}/s$	$L^{1/3}/T$	Roughness of approach channel
Culvert basin	h_0	m	L	Headwater depth
	S_b	-	-	Basin slope
	l_b	m	L	Basin length
	w_b	m	L	Basin width
	h_b	m	L	Basin height
	k_b	$m^{1/3}/s$	$L^{1/3}/T$	Roughness of basin
Culvert	D	m	L	Barrel diameter
	k_c	$m^{1/3}/s$	$L^{1/3}/T$	Roughness of barrel
	Inlet shape	-	-	Inlet shape
	Barrel position	-	-	Position of culvert barrel
Fluid	ρ	kg/m^3	M/L^3	Fluid density
	μ	kg/m/s	M/L/T	Dynamic viscosity
Gravitation	g	m/s^2	L/T^2	Gravitational acceleration
	19 variables		3 base dimensions	

Table 4.1 Physical variables in case of clear water conditions

The dimensionally homogeneous equation of the system is the following:

$$Q = f(S, l_a, w_a, h_a, k_a, h_0, S_b, l_b, w_b, h_b, k_b, D, k_c, Inlet\ shape,\ Barrel\ position,\ \rho, \mu, g) \qquad (4.1)$$

The main purpose of the steep approach channel configuration was to mimic flood flow situations in mountain streams thereby acknowledging that the setup was rather generalised as detailed features of mountain streams were not simulated. However, the steep channel setup resulted in supercritical approach flow conditions that may indeed occur in mountain streams. In the dimensional analysis the attributes of the channel were considered as fixed boundary conditions so they were not taken into account. It is worth mentioning that the slope was varied during the experiments. For all slopes supercritical flow prevailed in the approach channel. Furthermore, basin roughness and slope were not varied. Therefore, these parameters and the height of the basin, as it had no effect on the capacity, were not taken into account in the dimensional analysis. The position of the culvert barrel was also neglected in the dimensional analysis either as it was investigated only in one thesis.

In conclusion, the Equation 4.1 after the simplification has the following form:

$$Q = f(h_0, l_b, w_b, D, Inlet\ shape, \rho, \mu, g) \tag{4.2}$$

To eliminate the 3 base dimensions, mass-length-time fluid density, barrel diameter and the gravitational acceleration were used respectively.

Firstly the discharge (Q) was made to dimensionless by dividing it with the square root of the gravitational acceleration (g) in order to eliminate the time dimension then the length dimension was also eliminated by using the barrel diameter (D). The result is the dimensionless discharge (Equation 4.3) which was used to create dimensionless performance curves (Equation 4.3 exemplarily shows dimensions of the individual parameters). This expression has the form of the Froude number (see Equation 2.1).

$$Q^* = \frac{Q}{\sqrt{g} D^{5/2}} \quad \rightarrow \quad \left[\frac{\frac{L^3}{T}}{\sqrt{\frac{L}{T^2}} L^{5/2}} \right] = \left[\frac{\frac{L^3}{T}}{\frac{L^3}{T}} \right] \tag{4.3}$$

Secondly the water depth (h_0), the basin length (l_b) and the basin width (w_b) were made to dimensionless by dividing them with the barrel diameter (D).

At last the dimensions of the dynamic viscosity (μ) were eliminated as well. For this purpose the viscosity μ was divided by the fluid density (ρ) to eliminate the mass dimension then by the square root of the gravitational acceleration (g) to eliminate the time dimension. Last the length dimension was eliminated as well with using the barrel diameter (D). The result is shown in the Equation 4.4. The reciprocal of this expression has the form of a Reynolds number.

$$\mu^* = \frac{\mu}{\rho \sqrt{g} D^{3/2}} \quad \rightarrow \quad \frac{\frac{M}{LT}}{\frac{M}{L^3} \sqrt{\frac{L}{T^2}} L^{3/2}} = \frac{\frac{M}{LT}}{\frac{M}{LT}} \tag{4.4}$$

In conclusion, the Equation 4.2 has the following form after rearranging it into a new equation expressed in terms of dimensionless products:

$$\frac{Q}{\sqrt{g} D^{5/2}} = f\left(\frac{h_0}{D}, \frac{l_b}{D}, \frac{w_b}{D}, Inlet\ shape, \frac{\mu}{\rho \sqrt{g} D^{3/2}} \right) \tag{4.5}$$

For illustration purposes, only clear water has been looked at but if the effect of the sediments is also taken into account the dimensional analysis becomes more difficult as the number of the influencing factors would increase significantly. For the present study Table 4.1 is supplemented with the grain diameter, sediment density, weight of fed and transported sediments, and with the time span of feeding, in case of sediment transport (Table 4.2).

Section	Parameter	Unit	Dimension	Description
Sediments	d	m	L	Grain diameter
	ρ_s	kg/m^3	M/L^3	Sediment density
Sediment transport	m_f	kg	M	Weight of fed sediments
	m_d	kg	M	Weight of deposited sediments
	t	s	T	Time span of feeding

Table 4.2 Physical variables related to sediments

Due to the previously mentioned difficulties in the present study only the sediment deposition (η_d) is investigated related to the sedimentation which is the weight ratio of the deposited (m_d) and fed (m_f) sediments (Equation 4.6).

$$\eta_d = \frac{m_d}{m_f} \quad \rightarrow \quad \frac{M}{M} \tag{4.6}$$

4.2 Clear water experiments

At first clear water experiments were carried out with the different configurations in all previous studies. This subchapter gives a summary of the effects of the different factors on the hydraulic capacity of the culvert.

4.2.1 Effect of the slope and the energy dissipation

The effect of the slope was investigated in Gotvassli (2013) and Hendler (2014). First, the different slopes were tested without and then with energy dissipator blocks. Without energy dissipation and with a slope of 1:5, jet regime dominated in the expansion section and the flow was always supercritical in the approach channel. The jet, as it flowed directly through the barrel, and increased the hydraulic capacity compared to the existing guidelines (e.g. (Statens Vegvesen, 2011)). Besides the high kinetic energy which was caused by the previously mentioned flow condition, the oscillation of the jet was a constant problem, especially at the application of the cut inlet. This oscillating jet strongly influenced the capacity as it was moving from side to side and induced waves which often overtopped the embankment. The oscillation was reduced with wingwalls and with slope of 1:9. Hydraulic jump only seldom occurred at the slope transition for lower discharges while at higher discharges it was more prone to develop. The energy dissipator blocks in Hendler (2014) were installed to trigger the hydraulic jump on the approach channel and let subcritical flow through the culvert. Consequently the kinetic energy of the flow was reduced and the water surface became calmer which is favourable due to embankment safety reasons.

In general for all inlet types the installation of the energy dissipator blocks increased the headwater depth in the expansion section but the flow conditions were much calmer. However, a small jet was still visible with the projecting inlet. Without energy dissipation the wingwalls setup showed the best performance while with the installation of the blocks the projecting inlet turned out to have the highest capacity. In conclusion, the blocks had the least influence in case of projecting inlet while in case of the other two inlet types the changing was bigger. Figure 4.1 summarizes the effect of the blocks on the hydraulic capacity for the three inlet types with a slope of 1:9. A similar effect diagram in case of 1:5 slope with wingwalls is shown in Figure A.1.

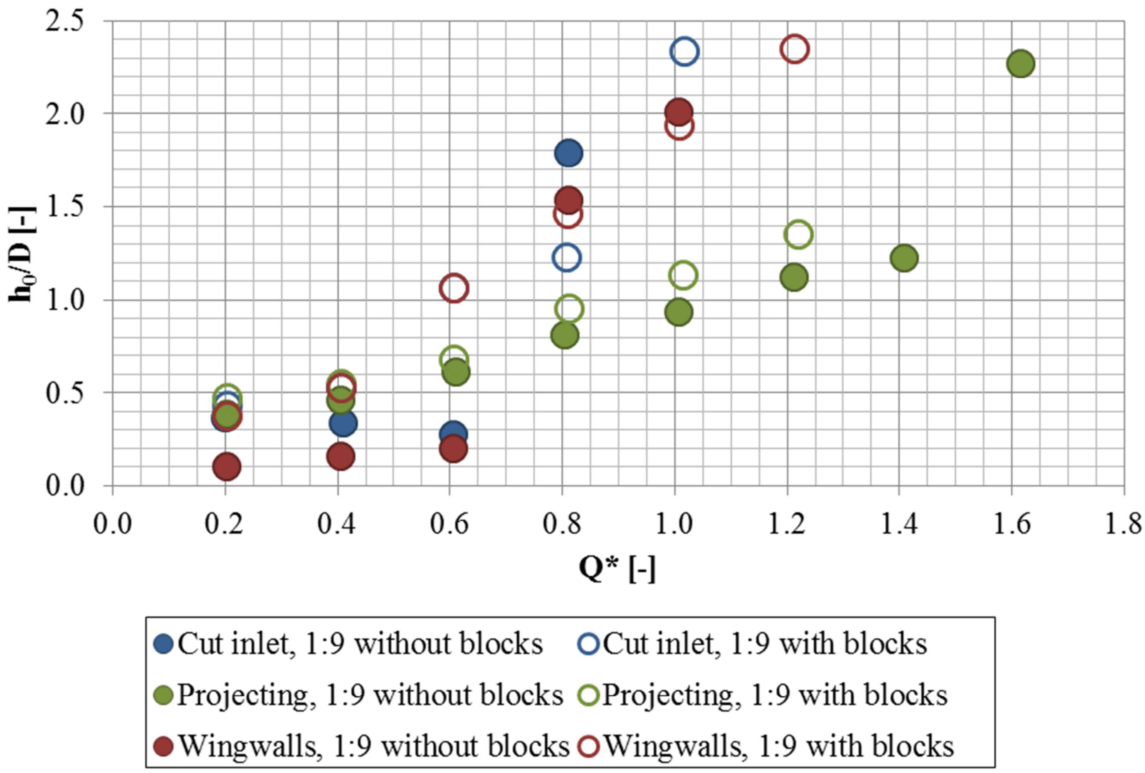

Figure 4.1 Effect of the energy dissipation with slope 1:9 (based on the results of Gotvassli (2013) and Hendler (2014))

The different slopes also influenced the performance of the culvert. In general the hydraulic capacity was higher or the same with the steeper slopes. However, the inlet shape had bigger influence on the culvert performance. The summary diagrams are shown in Appendix A. for all three inlet types (Figure A.1, Figure A.2, Figure A.3, Figure A.4).

In addition to the previously mentioned investigations, experiments with culverts which were moved 10 cm to right from the centreline of the model in Hendler (2014). The experiments were carried out with projecting and cut inlet, with slope 1:9 and 1:50. In general the displacement of the culvert caused an increase in the headwater level. This increase was negligible in case of cut inlet with slope 1:50 while in case of projecting inlet with slope 1:9 the difference between the two curves was bigger especially at higher discharges. Summary diagrams are in Appendix A. (Figure A.5, Figure A.6).

4.2.2 Effect of the expansion section geometry

The effect of the expansion section geometry was investigated in two M.Sc. theses (Gotvassli, 2013; Putri, 2014). In Gotvassli (2013) the focus was on the effect of the basin length while in Putri (2014) it was on the effect of the basin width. The length effect was examined with a slope of 1:5, without energy dissipation while the width with a slope of 1:9 and with the application of energy dissipator blocks.

In the experiments of Gotvassli, (2013) a jet regime dominated which oscillated in the expansion section especially in case of cut inlet. The oscillating pattern (Figure 4.2) sometimes also appeared when projecting inlet was used but with wingwalls it was rarer. This phenomenon strongly influenced the capacity of the culvert as the flow became unstable and waves occurred in the basin. The results showed that the setup with the shortest length gave the best performance for the cut and the projecting inlet as the travel distance was shorter and the jet was directed towards the culvert. In these cases the performance curves were smoother than the one with the longer basin lengths (Figure 4.3). With the wingwalls setup the performance curves were similar for all lengths (Figure 4.3 red marks) consequently the capacity did not depend on the basin length as the wingwalls directed the flow through the barrel. All in all the wingwalls turned out to have the highest capacity with a stable flow condition while the projecting inlet showed the lowest capacity. However, with the cut inlet setup the flow conditions were more unstable than the one with the projecting inlet and the oscillating pattern was more likely to appear which is undesirable and should be avoided due to embankment safety reasons. Basin length effect diagrams for the different inlet configurations are shown in Appendix A. (Figure A.7, Figure A.8, Figure A.9).

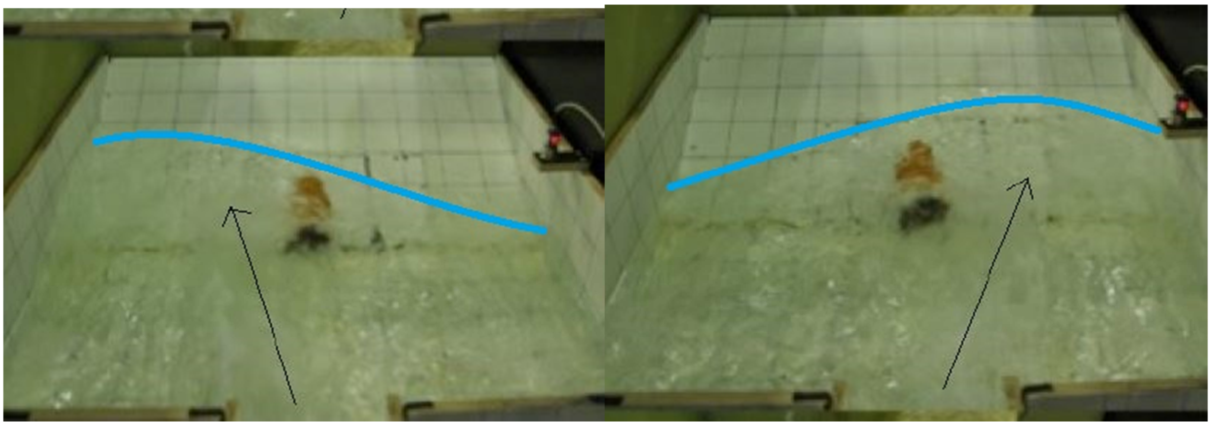

Figure 4.2 Oscillating jet with projecting inlet (Gotvassli, 2013)

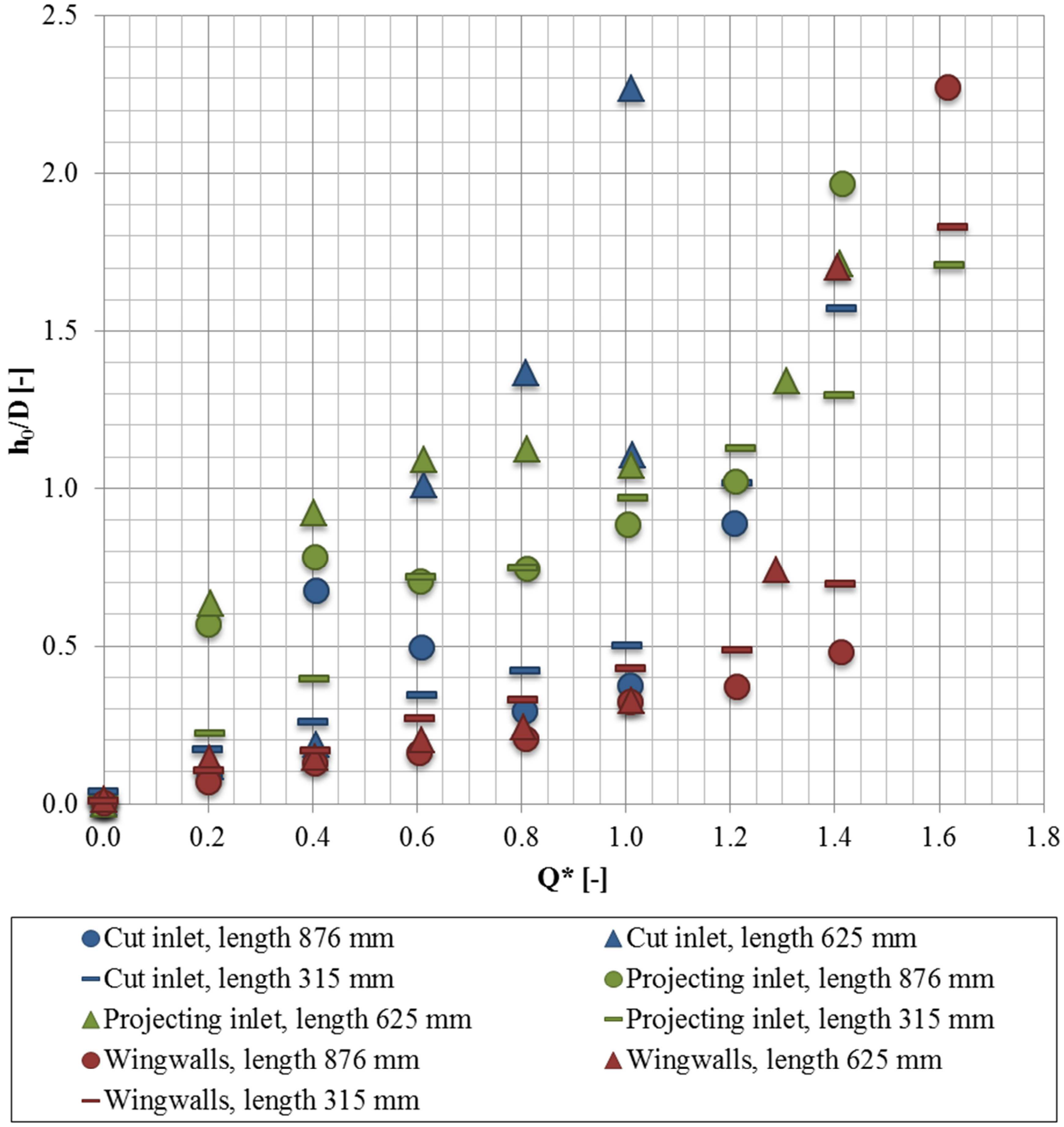

Figure 4.3 Basin length effect with slope 1:5 (based on the results of Gotvassli (2013))

The test series in Putri (2014) were carried out with application of energy dissipator blocks. This improvement induced a hydraulic jump on the approach channel consequently the flow was supercritical on the approach channel and subcritical in the expansion section. Furthermore, the jet regime which was specific to experiments in Gotvassli (2013) was avoided as the energy excess was reduced with the installation of the blocks. The location of the hydraulic jump was influenced by the water depth in the basin as the back water effect which occurred at higher water depths, shifted the hydraulic jump further up from the slope transition. With the projecting inlet setup sidewise oscillation (Figure 4.4) was visible for low discharges so when the culvert was unsubmerged. As the water depth increased, the culvert started to be submerged this oscillation gradually changed into wave movements. The cause of this phenomenon was presumably the larger width of the flow compared to the culvert barrel diameter. This oscillation was also visible with the cut inlet but not with the wingwalls because the wingwalls directed the flow through the culvert and prevent the oscillation.

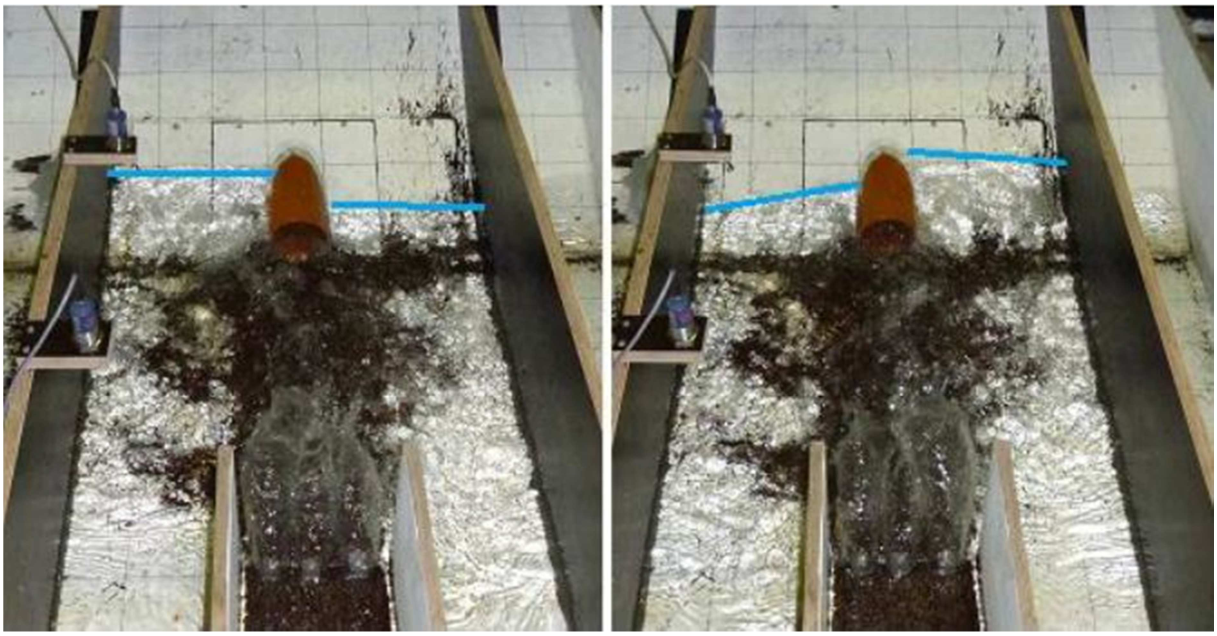

Figure 4.4 Sidewise oscillation with projecting inlet (Putri, 2014)

The results showed that the performance of the projecting inlet was influenced the most by the basin width compared to the two other inlet types. The wingwalls showed almost the same performance for all the investigated basin width while the one with the cut inlet only small deviations were visible between the curves. The projecting inlet performed the highest capacity with the widest basin (876 mm) and the lowest with the narrowest (292 mm) as the narrow width caused a water depth increase due to the backwater effect. The performance curves with the projecting inlet setup are shown in Figure 4.5. The effect diagrams for the two other inlet types are shown in Appendix A. Summarizing, with the 876 mm width the projecting inlet showed the best performance compared to the other inlet configurations. With the other widths the performance curves were similar for all inlet types. Summary effect diagrams are in Appendix A. (Figure A.10, Figure A.11, Figure A.12).

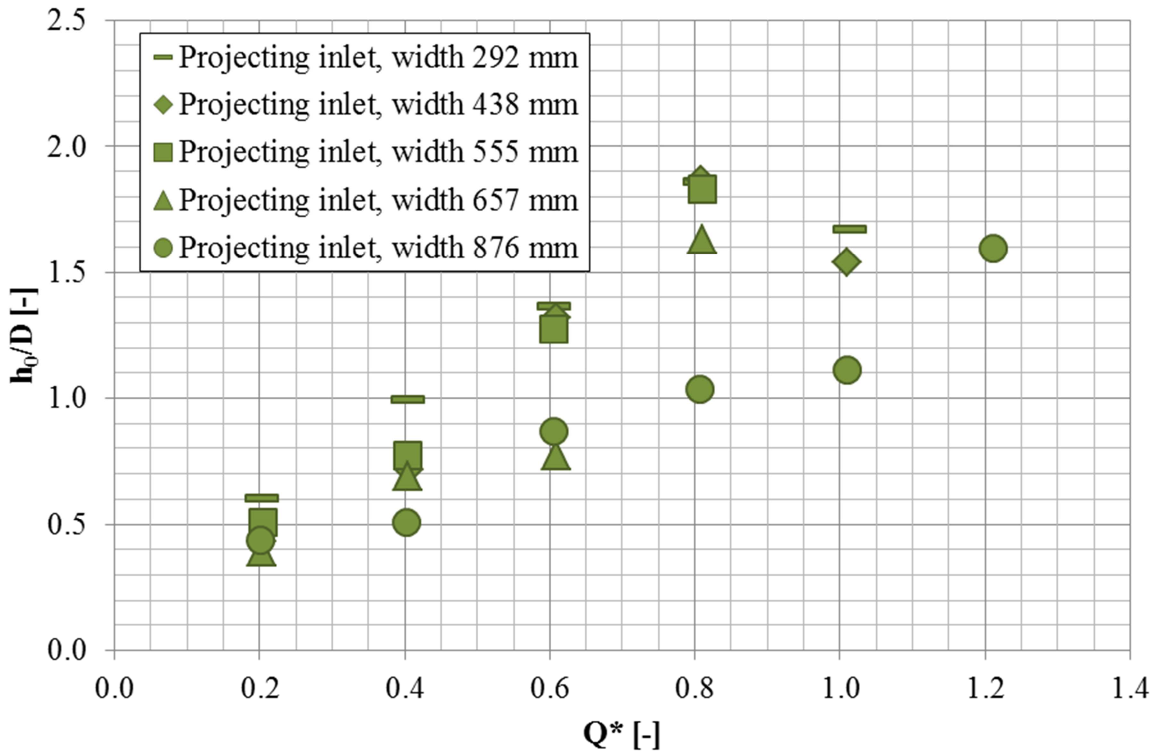

Figure 4.5 Basin width effect with projecting inlet, slope 1:9 (based on the results of Putri (2014))

4.2.3 Effect of a reserve barrel

The effect of a reserve barrel was investigated in Faqiri (2014) A smaller (d=60 mm), additional barrel was developed into the existing model. The reserve barrel was built a centre-to-centre distance of 420 mm from the main culvert and an elevation of 40 mm from the embankment toe (Figure 4.6). The approach channel slope was 1:9 and the energy dissipator blocks were installed at the entrance of the expansion section. The expansion section was 876 mm long and 1100 mm wide. The experiments were carried out with single barrels and with multi-barrel systems. The different tested configurations are shown in Table 4.3. The measurement of the discharge in the individual culverts in the multi-barrel system was not possible. Therefore, the results were analysed in the model scale.

Barrel combinations	Inlet type		
	Cut	Projecting	Wingwalls
Only main culvert	X	X	X
Reserve barrel		main culvert: closed	
Main culvert + Reserve barrel	X	X	X

Table 4.3 Clear water experiments in Faqiri's thesis

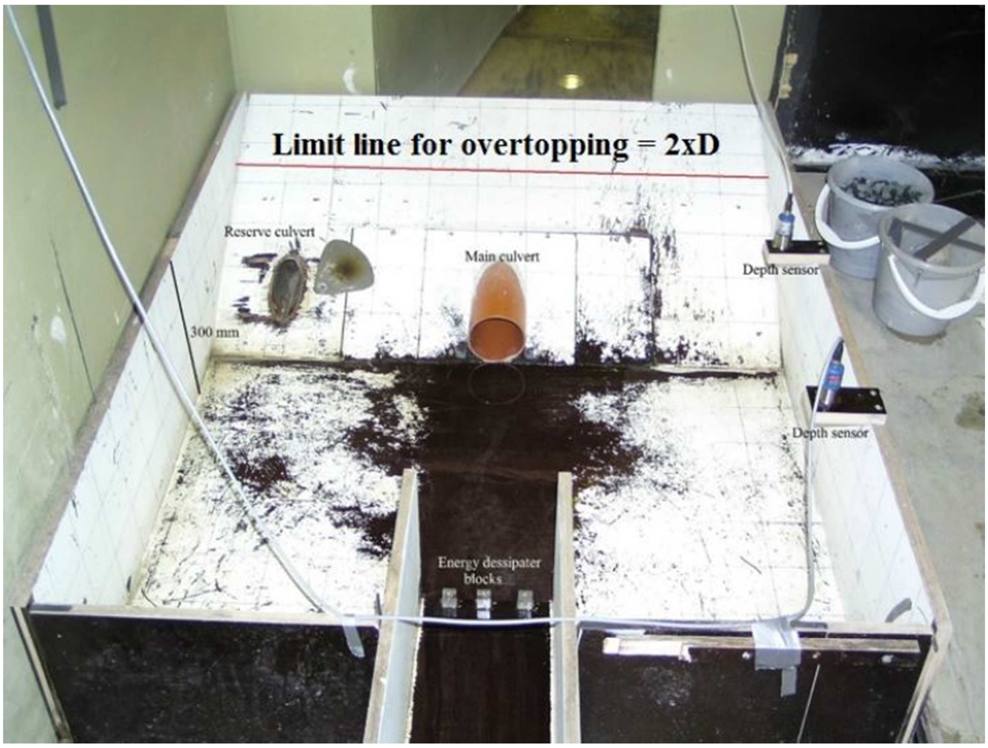

Figure 4.6 Model configuration with reserve barrel (Faqiri, 2014)

The energy dissipator blocks induced a hydraulic jump on the approach channel and increased the water depth in the expansion section as energy and the velocity of the flow were reduced. However, in the experiments a jet flow was still visible but not as strong as in the test series of Gotvassli (2013). The hydraulic conditions were different with the 3 inlet configurations when the culvert was unsubmerged. In case of projecting inlet sidewise oscillation, water circulations and surface waves were visible while in case of cut inlet higher water level was measured above the culvert (Figure 4.7). The wingwalls setup gave the most stable flow conditions as only small circulations were visible during the measurements. On the other hand as the water depth increased and the culvert became submerged the jet flow and the circulations disappeared and only surface waves were visible for all inlet types.

Figure 4.8 shows how the inlet shapes influence the performance of the multi-barrel systems. The results with wingwalls and cut inlet are close to each other except at discharge of 6 l/s where the cut inlet gave higher hydraulic capacity. The projecting inlet shows better performance from 6 l/s but the assessment of the outlet conditions presented that the culvert operated under outlet control from 8 l/s so the pressure flow resulted in lower headwater depths for this inlet type. The two other inlet types operated under inlet control for all examined discharges.

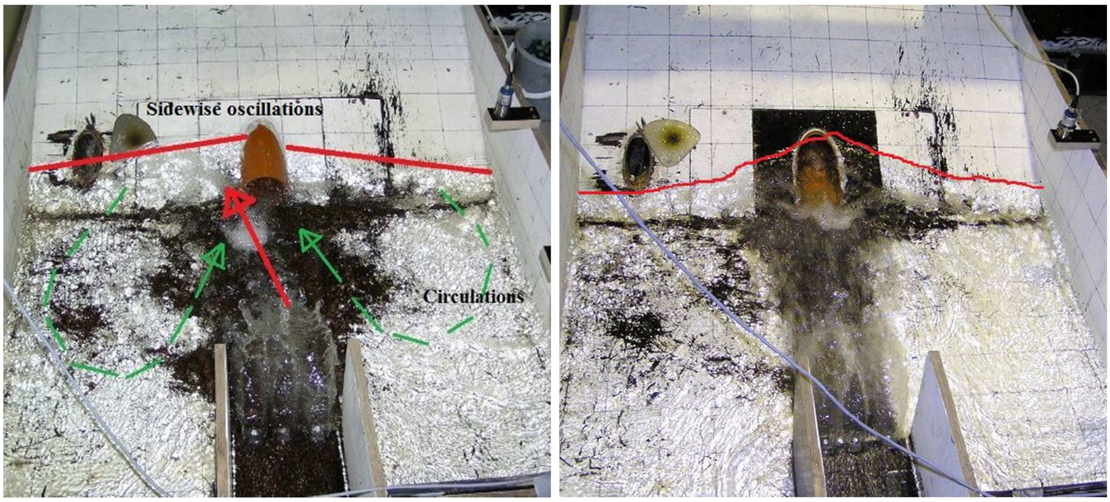

Figure 4.7 Hydraulic conditions with projecting (left) and cut inlet (right) (Faqiri, 2014)

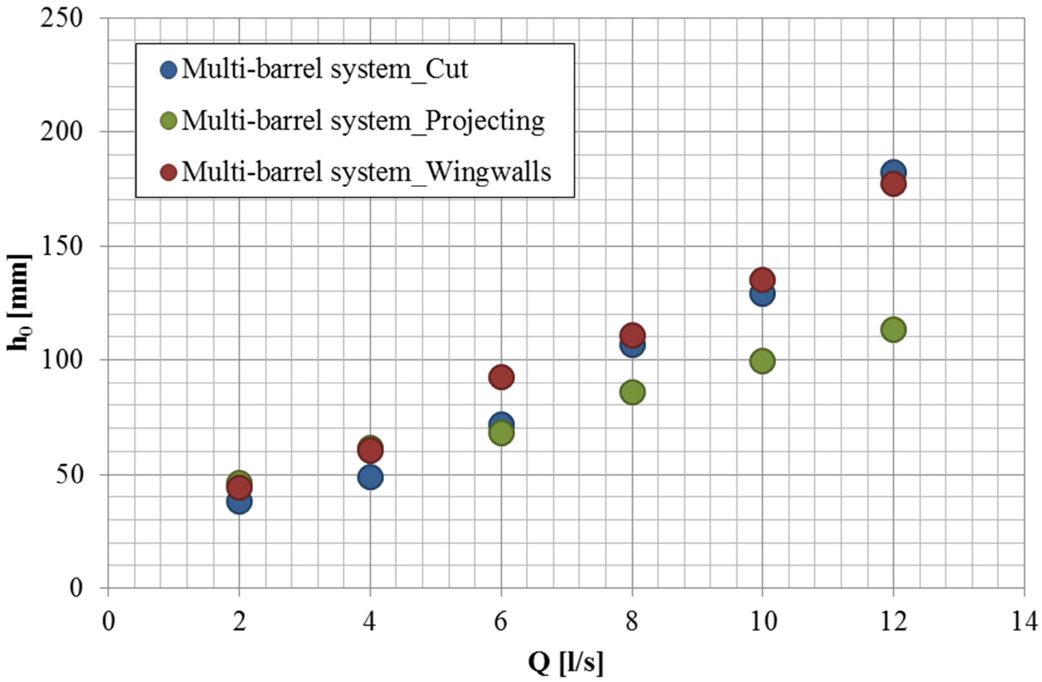

Figure 4.8 Effect of the inlet shape on the performance of the multi-barrel system (based on the results of Faqiri (2014))[1]

The hydraulic conditions with single barrel setup were similar to the multi-barrel systems'. The only difference was the decreased headwater depth with the multi-barrel system. In the multi-barrel systems the total cross sectional area was bigger. Furthermore, the velocity was also higher due to the higher discharge for the same headwater depth. These reasons caused the decrease of the headwater level. Figure 4.9 depicts this water depth decline in case of the

[1] For the performance curve of the multi-barrel system with wingwalls the data from the experiments which were carried out in February 2014 were used instead of the ones from May 2014(which were presented in Faqiri's thesis) because in case of the two other inlet shapes also the data from February 2014 were used.

wingwalls. Performance curves for the cut and the projecting inlet are in Appendix A. (Figure A.13, Figure A.14). The head differences for 4 l/s and 6 l/s in case of projecting inlet and for 2 l/s and 4 l/s in case of cut inlet were negative due to uncertainties in the measurements. Theoretically the headwater level cannot be higher when the cross sectional area is bigger for the same discharge. Therefore instead of the negative values zero differences were taken into account.

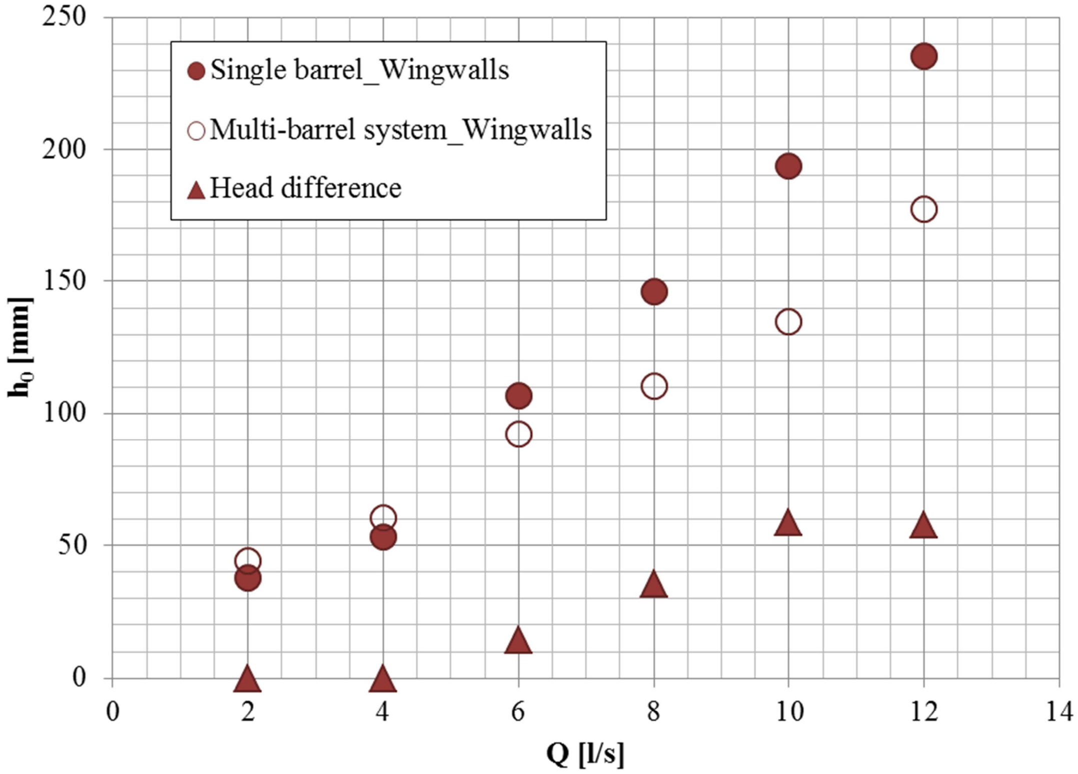

Figure 4.9 Effect of the reserve barrel with wingwalls (based on the results of Faqiri (2014))[2]

The capacity of the reserve barrel was measured individually as a simulation of the case when the main culvert is clogged by sediments and debris. The hydraulic conditions in this case were more stable and tranquil compared to the multi-barrel and the other single barrel experiments. Performance curve for this case is shown in Figure 4.10.

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[2] For the performance curve of the multi-barrel system with wingwalls the data from the experiments which were carried out in February 2014 were used instead of the ones from May 2014(which were presented in Faqiri's thesis) because in case of the two other inlet shapes also the data from February 2014 were used.

In conclusion, the installation of the reserve barrel increases the hydraulic capacity for all inlet types. Furthermore, the safety of the structure is also increased as the reserve culvert is less prone to be blocked by sediments and debris.

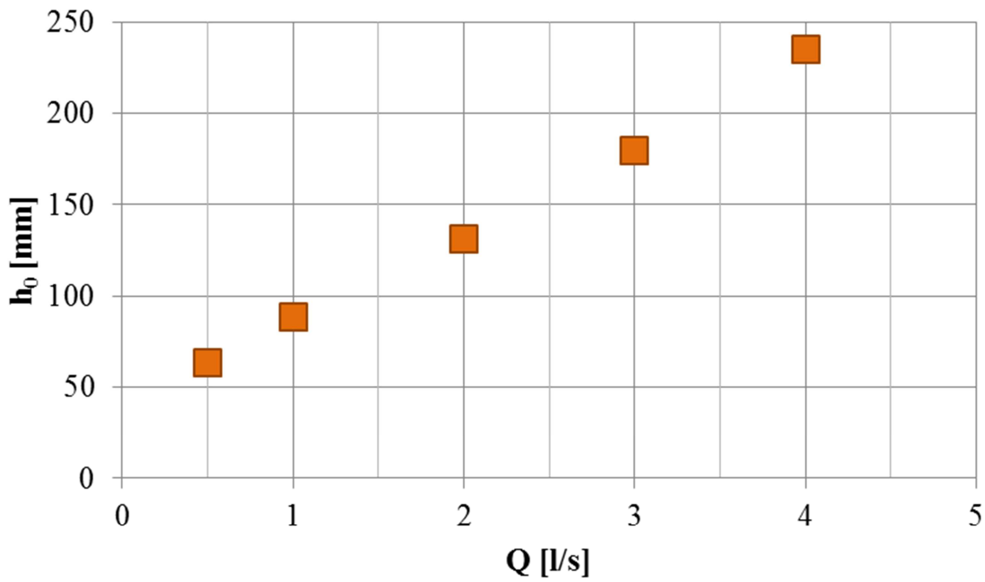

Figure 4.10 Hydraulic capacity of the reserve barrel (based on the results of Faqiri (2014))

4.2.4 Effect of trash racks and debris deflector

The effect of trash racks and debris deflector was examined in Dirks (2014). The model setup was the same as in Faqiri (2014) but during test series in Dirks (2014) the additional culvert was closed. The applied sediment countermeasures are shown in Appendix A. (Figure A.15, Figure A.16, Figure A.17, Figure A.18). Both the trash racks and the debris deflectors were milled from an aluminium plate and for the cut and projecting inlet the same debris deflector was used.

In general the results showed that both the trash racks and the debris deflectors increased the headwater depth in the expansion section as they represented a local energy loss in the flow and regarding to the Bernoulli-equation, it resulted the increase of the headwater level. This increase was bigger at the application of debris deflector. Furthermore, with debris deflector the flow was turbulent and sometimes also vortices arose around the culvert inlet.

Without the trash racks and debris deflector the projecting inlet showed the best performance for the clear water experiments (Figure A.21). Nevertheless the biggest increase in the water depth occurred with the projecting inlet when the sediment countermeasures were installed in the model. The lowest hydraulic capacity occurred with the application of the debris deflector. The performance curves with projecting inlet for the different cases are shown in Figure 4.11.

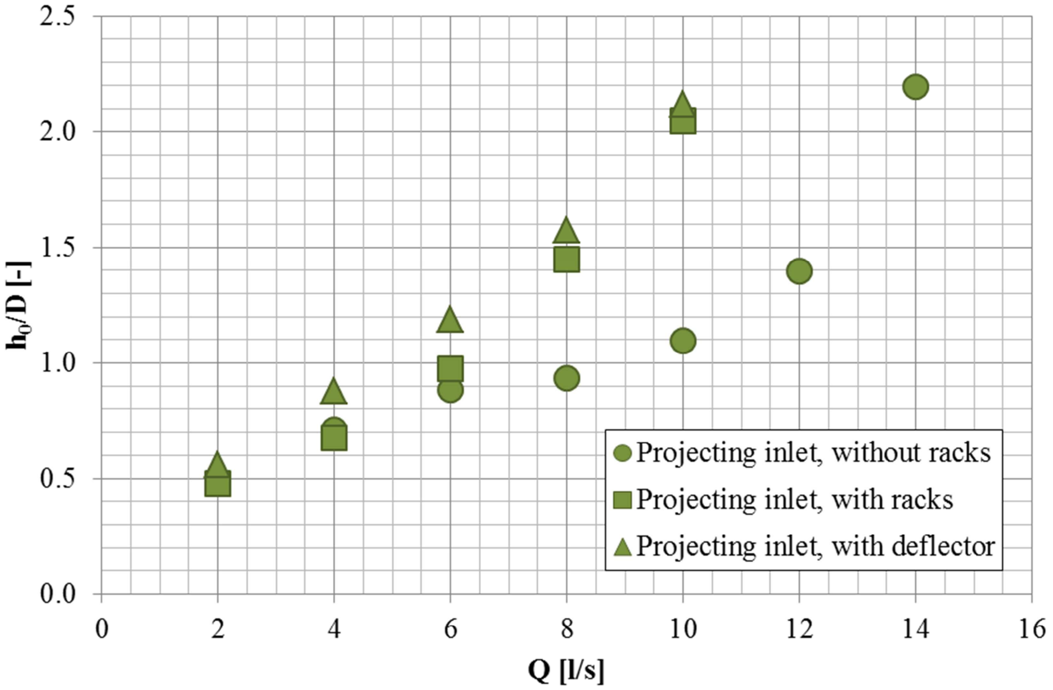

Figure 4.11 Effect of sediment countermeasures at projecting inlet (based on the results of Dirks (2014))

The cut inlet showed similar hydraulic capacities for all three cases. However, a small increase was visible with the debris deflector in the headwater depths for lower discharges compared to the other two cases (Figure A.19). With wingwalls the hydraulic capacity was more reduced with the application of the sediment countermeasures than without them. In fact the measured values with both trash racks and debris deflectors were similar (Figure A.20).

In conclusion, the examined sediment countermeasures decreased the hydraulic capacity of the culvert for all three inlet types. The highest headwater levels occurred with debris deflectors. The worst performances were shown with these structures by the cut inlet. With trash racks the hydraulic capacity was similar for the wingwalls and for the projecting inlet while with debris deflector the wingwalls performed the highest capacity (Figure A.22, Figure A.23).

4.2.5 Effect of inlet shape

The results which are presented in the previous chapters show that the configuration of the culvert inlet has a significant effect on the hydraulic capacity. In addition, the effect of the inlet is also highly influenced by the flow conditions. For example the wingwalls turned out as the best inlet configuration under the jet regime which was specific to experiments in Gotvassli (2013) where the slope of the approach channel was 1:5 and there was no energy dissipation. In these tests the wingwalls directed the jet towards the culvert so it could easily flow through the culvert (Figure 4.3). In the case of slope 1:9 the projecting inlet also gave interesting results. For low discharges (Q*=0.2-0.6) the wingwalls showed the best performance but for higher discharges the projecting inlet gave the higher capacity values (Figure 4.1). The application of the energy dissipator blocks resulted in calmer flow conditions in the expansion section. Due to the energy dissipation the headwater level increased especially in case of the cut inlet and wingwalls while in case of the projecting inlet the increase was much smaller (Figure 4.1). Consequently with slope 1:9 and energy dissipation the projecting inlet turned out to be the best configuration. The tests with multi-barrel systems showed similar results as the projecting inlet gave the lowest headwater levels while the performance curves of the two other inlet shapes coincided almost perfectly (Figure 4.8). The application of trash racks and debris deflectors equaled the performance curves of the 3 inlet configurations thus the inlet shape did not have significant effect on the hydraulic capacity of the culvert with debris control measures installed (Figure A.22, Figure A.23).

In conclusion, based on the experiment results the projecting inlet turned out to be the best configuration while the wingwalls showed the lowest performance. However, under jet regime which should be avoided due to embankment safety reasons, the wingwalls had higher capacity. The results with cut inlet in most cases gave the capacities between the two other inlet types.

4.3 Experiments with sediments

During the experiments beyond the basic flow patterns the sediment transport patterns were examined. This subchapter gives a summary about the effect of the different geometries, configurations and sediment features on the flow and sedimentation.

4.3.1 Effect of sediment size and amount

The effect of the fed sediment size was examined in all the previous five theses (Gotvassli, 2013; Hendler, 2014; Putri, 2014; Faqiri, 2014; Dirks, 2014) while the effect of sediment amount was examined only in three theses (Gotvassli, 2013; Putri, 2014; Faqiri, 2014). The applied sizes and amounts were 8-16 mm, 16-32 mm and 5kg, 7kg respectively. There was also one test series with sand (0.4-0.8 mm) in Hendler (2014).

In Gotvassli (2013) the sediment size effect with an approach channel slope 1:5, with 5 kg gradually fed sediments was investigated. The results showed that the sediment size has an insignificant effect on the culvert capacity. A slight difference was noticeable for higher discharges in case of cut inlet but it only occurred when the flow changed to outlet controlled. In Putri (2014) only the projecting inlet was examined for the sediment size effect. The approach channel slope was 1:9 and energy dissipator blocks were applied in the tests. The experiments were carried out with a sediment amount of 7 kg which was fed first gradually then all at once. The obtained performance curves showed that the sediment size does not have a significant effect on the hydraulic capacity of the culvert (Figure 4.12). In Faqiri (2014) the same basic model setup was applied as in Putri (2014) with a 1:9 approach channel slope with energy dissipation but in Faqiri (2014) all the three inlet types were examined with the application of 5 kg gradually fed sediment. For cut inlet and wingwalls the two curves from the two different test series with the two sediment sizes coincided well. Nevertheless in case of projecting inlet the experiments with 16-32 mm sediments gave lower headwater levels as in that case the sediments were transported continuously through the barrel. In contrast the smaller grains were first deposited in front of the culvert, and then, when there was enough energy in the flow they were washed through the barrel. The sediment size effect in Hendler (2014) was investigated with approach channel slope 1:50 in the case of wingwalls at 6 l/s. As the result of the mild slope all the sediments with both grain diameters were settled down in the approach channel and stayed there until the end of the experiments. Tests were also carried out with sand (0.4-0.8 mm) Hendler (2014). The sand in all experiments (centrelined wingwalls, cut inlet to the right, projecting inlet to the right) first settled in the approach channel, then started to move to the expansion section. A passage was created through the sediments by the flow, but when the barrel was displaced to the right, a sediment heap formed in front of the culvert, and obstructs the flow through it. The sediment size effect was also investigated with trash racks and debris deflectors installed in Dirks (2014). With debris deflector the grain diameter had no effect on the culvert performance but with trash racks slight differences were noticeable in case of cut and projecting inlet. In both cases the headwater levels were slightly higher when the bigger sediments were applied. The possible reason for this is that the smaller particles were more prone to get through the racks and as a result they meant smaller obstruction for the flow.

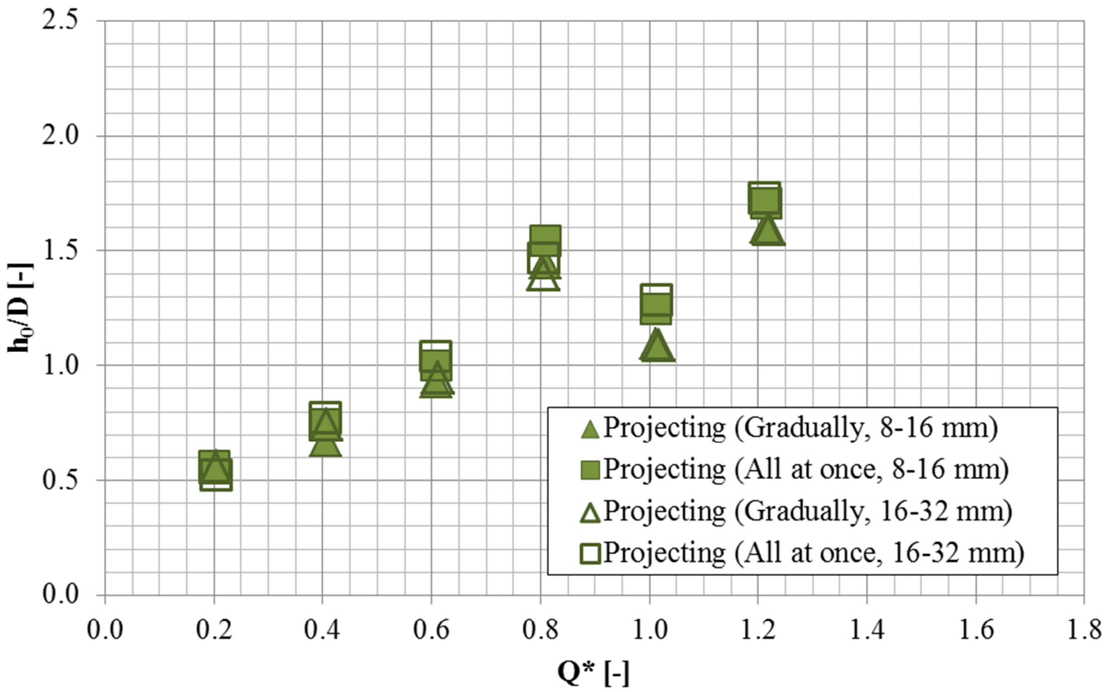

Figure 4.12 Sediment size effect on the culvert capacity – Slope 1:9 with energy dissipation, Projectig inlet with 7 kg fed sediment (based on the results of Putri (2014))

In Gotvassli (2013) the same model setup was used for the sediment amount effect examinations as for the size effect tests. In case of wingwalls the sediment amount had no influence on the capacity while in case of cut inlet the influence was slightly bigger. For most of the discharges the deposited sediment amounts were bigger when 5 kg sediment was fed. In case of projecting inlet the differences in the headwater levels were bigger especially for low discharges. These differences decreased with the increase of the discharge until they disappeared completely. The higher water levels in case of 5 kg sediment were the result of the sediment deposition in the expansion section which occurred right after the hydraulic jump. In the test with the 7 kg sediment this hydraulic jump did not occur thus the sediments went straight through the barrel. Consequently, the water levels were lower than in the experiments with 5 kg sediment. The experiments in Putri (2014) with energy dissipation and slope 1:9 showed similar results with regards to the effect of sediment amount. The performance curves with both sediment amounts coincided well, as only small differences were noticeable (Figure 4.13). In contrast, in case of projecting inlet the water levels at Q*=0.6 and 0.8 were higher when 7 kg sediment was fed because when 5 kg sediment was fed to the model, more sediment was transported through the culvert. At the other discharges the sediment amount had only a slight influence on the capacity.

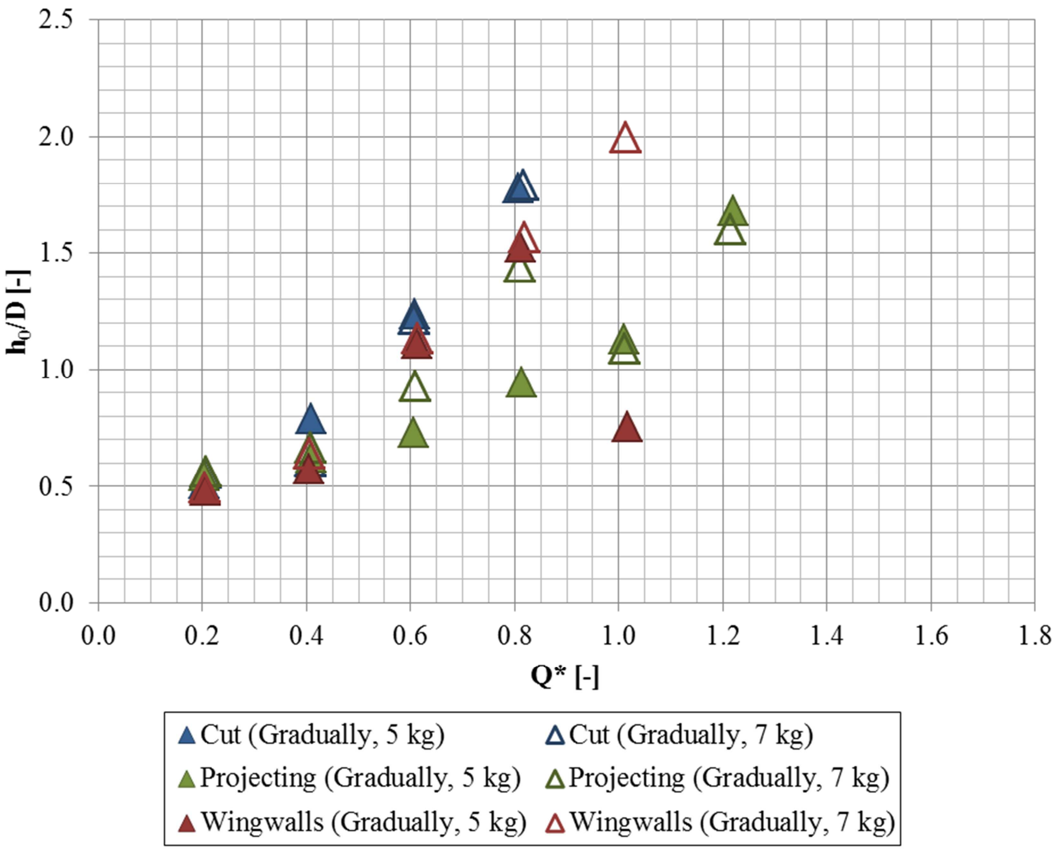

Figure 4.13 Sediment amount effect on the culvert capacity – Slope 1:9 with energy dissipation, 8-16 mm sized sediment (based on the results of Putri (2014))

Experiments in Faqiri (2014) with the multi-barrel systems also confirmed that in case of cut and wingwalls inlet the sediment amount has little effect on the culvert capacity. In case of cut inlet, the smaller while in case on wingwalls, the bigger amount of sediments resulted in slightly lower headwater levels. In case of projecting inlet, the two performance curves (5kg and 7kg fed sediment) coincided well. However, a bigger difference in the headwater level occurred at 6 l/s as more sediment deposited when 7 kg sediment was fed to the model.

In conclusion, the sediment size had little or no effect on the headwater level in the expansion section. In case of the multi-barrel system with projecting inlet the application of the smaller grains resulted in higher water levels while in case of applied trash racks with cut and projecting inlet, the application of the bigger sediments resulted in higher water elevations. The experiments with focus on the sediment amount effect showed that in case of cut inlet and wingwalls the fed amount had little or no effect on the culvert capacity. In case of the projecting inlet the differences were bigger. In general the water levels were higher when more sediment was fed to the model as more sediment accumulated in the expansion section. However, the main influencing factors were the inlet shape and the hydraulic conditions such as the presence and location of the hydraulic jump. For example the experiments in Gotvassli (2013) with projecting inlet showed that as a result of the occurred hydraulic jump more sediment deposited in the expansion section than without it. This held true even if the fed amount of sediment was smaller. Figures with performance curves and with deposited sediment amounts related to this chapter are presented in Appendix B. (Figure B.1 to Figure B.18and Figure B.71 to Figure B.85).

4.3.2 Effect of the slope and the energy dissipation

Gotvassli (2013) and Hendler (2014) formed the base for the determination of the slope and the energy dissipation effect on the culvert performance under sediment load (Gotvassli, 2013; Hendler, 2014). In Gotvassli (2013) experiments were made with a slope 1:5 without energy dissipation while in Hendler (2014) tests were carried out with and without energy dissipation in case of slope 1:9. In both studies two sediment feeding method were used (gradually and all at once) and the applied sediment amount was 5 kg while the sediment size was 8-16 mm in Gotvassli (2013) and 16-32 mm in Hendler (2014). As the sediment size had little or no effect as has already been mentioned in the previous chapter, the results were comparable.

In general the sediment transport and the sedimentation pattern were related to the flow pattern in the expansion section. In case of cut inlet an oscillating jet was visible when the slope was 1:5. Due to this jet which directed the flow to the left at Q*=0.4 a local peak is visible in the performance curve for all cases (clear water, gradually and all at once feeding) (Figure 4.14). This local peak disappeared when the milder slope was used in Hendler (2014). The water levels were even lower with clear water and gradually feeding experiments as the oscillating pattern disappeared. However, the capacity with all at once feeding decreased as most of the sediments deposited in the expansion section in front of the culvert entrance and created an obstruction for the flow. The installation of the energy dissipator blocks increased the headwater levels in both the clear water and the sediment experiments as the decreased energy and velocity resulted in the deposition of more sediment. In case of projecting inlet the oscillation was not noticeable thus the jet in case of the slope 1:5 was directed towards the culvert. Consequently the results of the three experiments (clear water, gradually and all at once feeding) were similar. The sediment feeding had a little effect on the capacity. In case of the milder slope similarly to the case of cut inlet the capacity decreased with all at once feeding due to the lower energy. The installation of the blocks also increased the headwater levels in case of gradually feeding as the sediments deposited right after the hydraulic jump which was triggered by the blocks. The experiments with wingwalls showed that the sediment did not have a significant effect on the capacity. The only effect was observed at the lowest discharge, where the flow did not have enough energy to transport the all at once fed sediments. The application of the milder slope increased the water levels with all at once feeding similarly to the other inlet types. In turn the usage of the energy dissipation equalized the three performance curves.

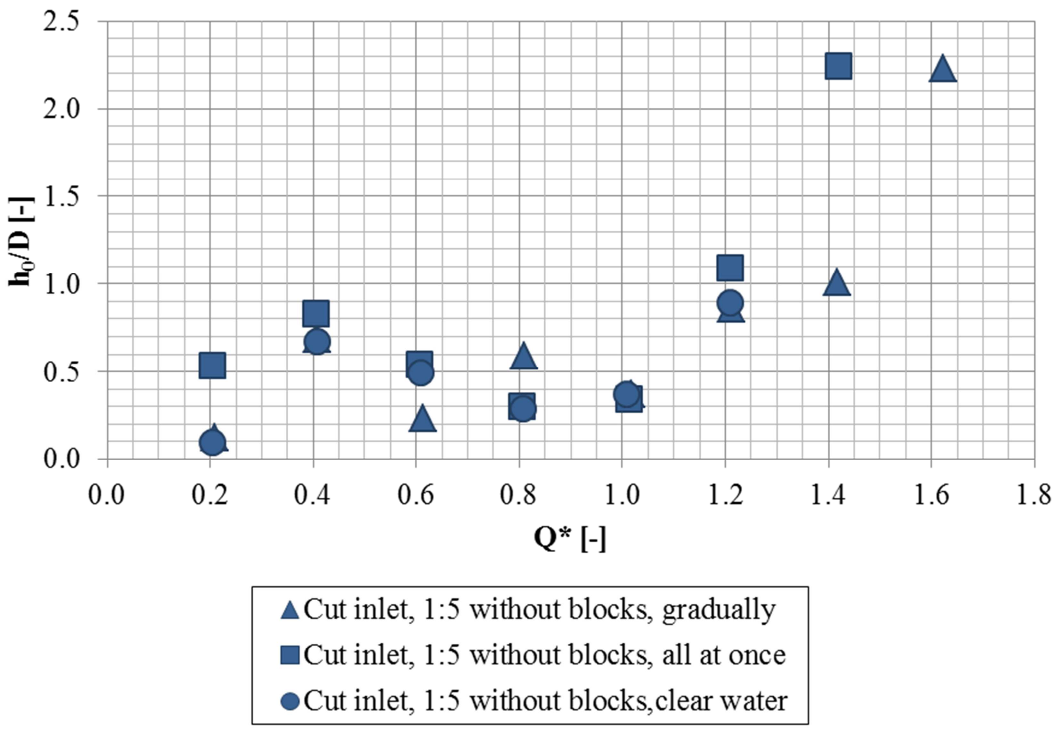

Figure 4.14 Culvert capacity with cut inlet under sediment transport – slope 1:5 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

The amount of the deposited sediment was influenced by the slope, the application of the energy dissipation, the inlet shape and the feeding method. The transported amount decreased with the usage of the milder slope and the energy dissipation (Figure 4.15). The blocks had bigger effect on the sediment deposition as they triggered a hydraulic jump. Consequently the sediments deposited right after that. The examination of the accumulated sediment amount showed that the wingwalls inlet was the most efficient in the sediment transport followed by the cut and then the projecting inlet when energy dissipator blocks were not used. However, with the application of the blocks the projecting inlet turned out to be the most efficient in sediment transport. Furthermore, most of the all at once fed sediments accumulated in the expansion section because at low discharges the flow did not have enough energy to transport the sediments through the barrel. At higher discharges the backwater effect prevents the sediment transport.

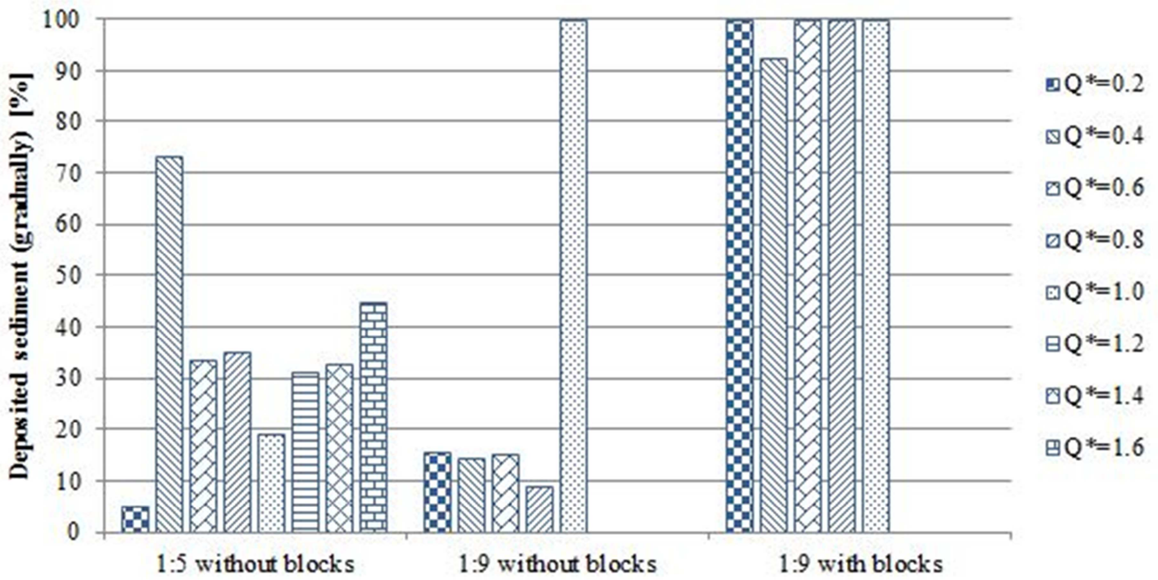

Figure 4.15 Deposited sediment amount in case of cut inlet with gradually feeding – slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

In conclusion, the fed sediment increased the water level in the expansion section especially when the sediments were fed all at once. The reason of the water level increase was the accumulated sediment in the basin. In case of slope 1:5 without energy dissipation there were no big differences between the clear water and sediment experiments as the sediments did not affect the flow significantly. In case of the milder slope the clear water and the gradually feeding tests gave similar results but the all at once feeding results showed lower capacities as more sediment accumulated in front of the culvert and built an obstruction on the way of the flow. The application of the blocks further decreased the culvert capacities as even with gradually feeding nearly all the sediments accumulated in the expansion section. Figures with the performance curves and with the deposited sediment amounts related to this chapter are presented in Appendix B. (from Figure B.19 to Figure B.31).

4.3.3 Effect of the expansion section geometry

The effect of the expansion section geometry was examined in Gotvassli (2013) and Putri (2014). The experiments with focus on the effect of the basin length were carried out with slope 1:5 without energy dissipation and with the application of 5 kg 8-16 mm sized sediments (Gotvassli, 2013). Furthermore, the experiments with the different basin widths were accomplished with slope 1:9 with energy dissipation and the application of 7 kg 8-16 mm sized sediments (Putri, 2014).

The experiments with the cut and projecting inlet showed that the application of the 625 mm basin length resulted in the lowest capacity while with the other two examined lengths, the capacity values were higher and close to each other (Figure 4.16). The high capacities with the application of the shortest basin length were caused by the jet which due to the short distance could flow directly through the barrel. In case of the wingwalls all the three performance curves with the three different basin lengths coincided well which means the length had no influence on the culvert performance. The clear water experiments showed that the flow with wingwalls was more stable than with the other two inlets as in those cases an oscillating patterns were visible and the flow was unstable especially with cut inlet. The headwater levels in case of cut inlet with all at once feeding were higher than the ones with gradually feeding or clear water experiment especially in case of the 625 mm length. The feeding method in case of wingwalls and projecting inlet had only a slight effect on the headwater levels. Nevertheless the deposited sediment amount was influenced by the feeding method and the basin length as well. The deposited amount was bigger with all at once feeding and smaller with the shortest basin length. Of the tested inlet types, the wingwalls turned out to be the most efficient in the sediment transport and also gave the best hydraulic capacity. The projecting inlet gave the lowest capacity and was least efficient with regards to flushing through sediments.

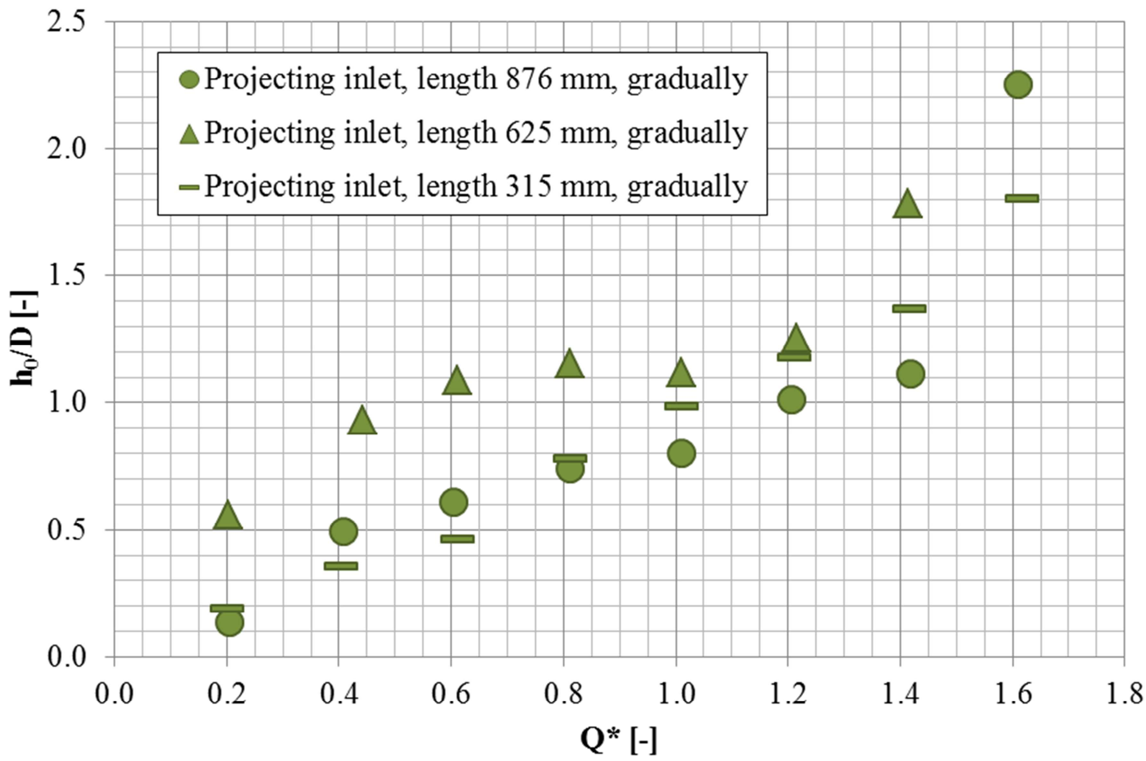

Figure 4.16 Culvert capacity with projecting inlet under sediment transport – length effect with gradually feeding (based on the results of Gotvassli (2013))

The results from the width effect experiments showed that the sediment feeding had little or no influence on the headwater levels. In case of projecting and cut inlet the all at once feeding caused a small headwater increase when the basin was 876 mm wide. In case of wingwalls, the three performance curves coincide well. The basin width had only a slight effect on the hydraulic capacity in case of wingwalls and cut inlet. With the projecting inlet the two narrower setups resulted in lower capacities compared to the wider basin, where more sediment was flushed through the barrel. The most sediment was transported through the culvert with the 4 l/s discharge for all inlet types because the hydraulic jump was closer to the barrel, and thus the sediments could easier pass through. Under sediment transport conditions, the projecting inlet turned out to be the most efficient while with the other two inlets nearly no sediment went through the barrel. However, in case of cut inlet at 4 l/s with gradually feeding 40% of the sediments was transported but in the other cases nothing. The effect of the feeding method on the deposited amount was only noticeable in case of the projecting inlet as more sediment was transported with the gradually feeding method (Figure 4.17, Figure 4.18).

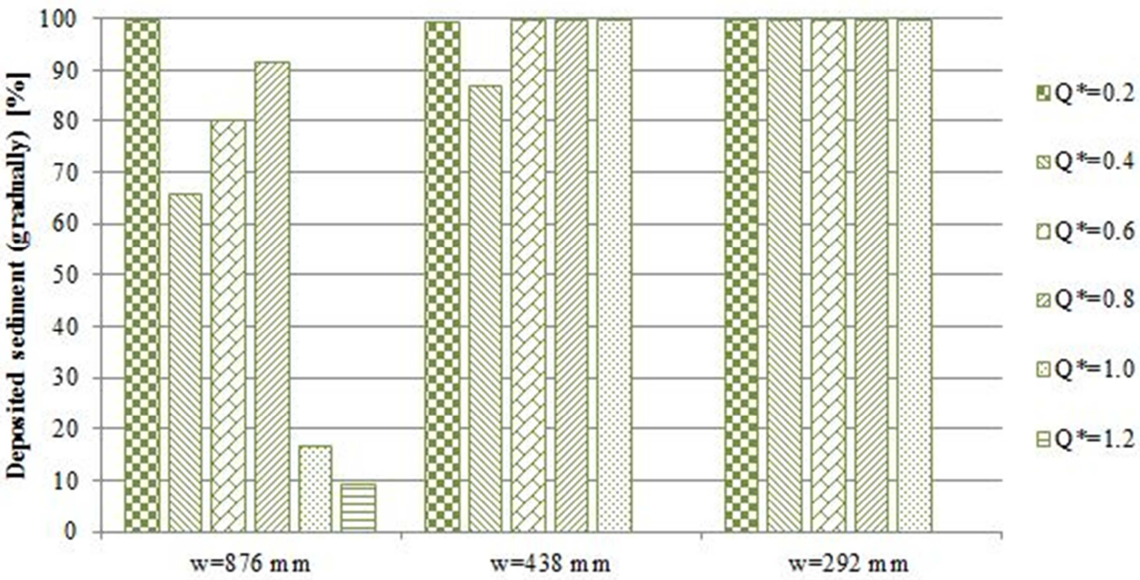

Figure 4.17 Deposited sediment amount in case of projecting inlet with gradually feeding – width effect (based on the results of Putri (2014))

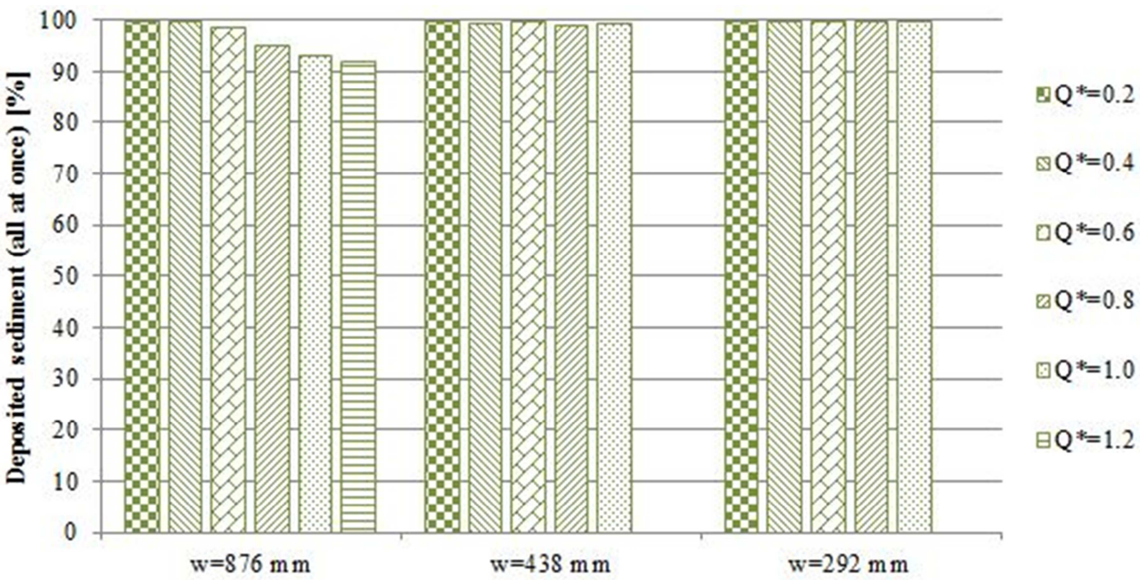

Figure 4.18 Deposited sediment amount in case of projecting inlet with gradually feeding – width effect (based on the results of Putri (2014))

In conclusion, the application of the 625 mm basin length turned out to have the lowest hydraulic capacities for cut and projecting inlet. The results with the other two basin length were similar to each other. In case of the wingwalls, the basin length did not have an effect on the culvert performance so the three curves coincide well. The sediment transport was slightly influenced by the basin length. The feeding method had more influence on it. The gradually feeding resulted in higher sediment transport capacity than the all at once feeding. Consequently the headwater levels especially in case of cut inlet with 625 mm long basin were higher with all at once feeding. The basin width effect experiments showed that the headwater levels were lower with the widest basin as more sediment was transported with it. Furthermore, the sediment feeding method also had an effect on the hydraulic capacity and on the deposited sediment. With all at once feeding the headwater levels were slightly higher especially in case of the 876 mm basin width where nearly no sediment was transported through the barrel. However, in case of the two narrower widths even with gradually feeding no sediment was transported except with projecting inlet with 438 mm width. Figures with the performance curves and with the deposited sediment amounts related to this chapter are presented in Appendix B. (from Figure B.32 to Figure B.70).

4.3.4 Effect of a reserve barrel

Sediment experiments with the multi-barrel systems were carried out with the application of 5 kg sediment with 8-16 mm grain diameter (Faqiri, 2014). The experiments with the wingwalls and with the cut inlet showed that the sediment feeding increased the water level for all discharges with both feeding methods except of the case when the sediments were fed all at once and the discharge was 6 l/s. In that case the water level was lower than in the clear water experiment especially in case of the wingwalls (Figure 4.19). The sediments which deposited right after the energy dissipation made a smooth transition between the approach channel and the expansion section and helped to direct the flow straight through the culvert. In case of the wingwalls the gradually fed sediments started to deposit in the approach channel, and were then deposited in the centreline of the expansion section. No sediment was deposited in the barrel. Furthermore, in case of the cut inlet, the sediments first deposited close to the culvert entrance then with the increase of the discharge they moved towards the approach channel. At 12 l/s due to the backwater effect all the sediments deposited right after the energy dissipator blocks. For both inlet types, the all at once fed sediments deposited right after the blocks for all discharges. Consequently, more sediment was transported when the sediment was fed gradually and more sediment deposited in the expansion section when the all at once feeding method was applied. In case of the projecting inlet, the headwater elevations for most of the discharges were higher with both gradually and all at once fed sediments than without them, with insignificant differences between the two cases. The transport of the sediment similarly to the other two inlet types was more efficient when the sediments were fed gradually as the delivery of the particles was continuous during the experiments. The percentage of the deposited sediments showed that the sediment transport in that case increased almost linearly with the discharge while with all at once feeding until 8 l/s more than 90% of the fed sediments accumulated in the expansion section.

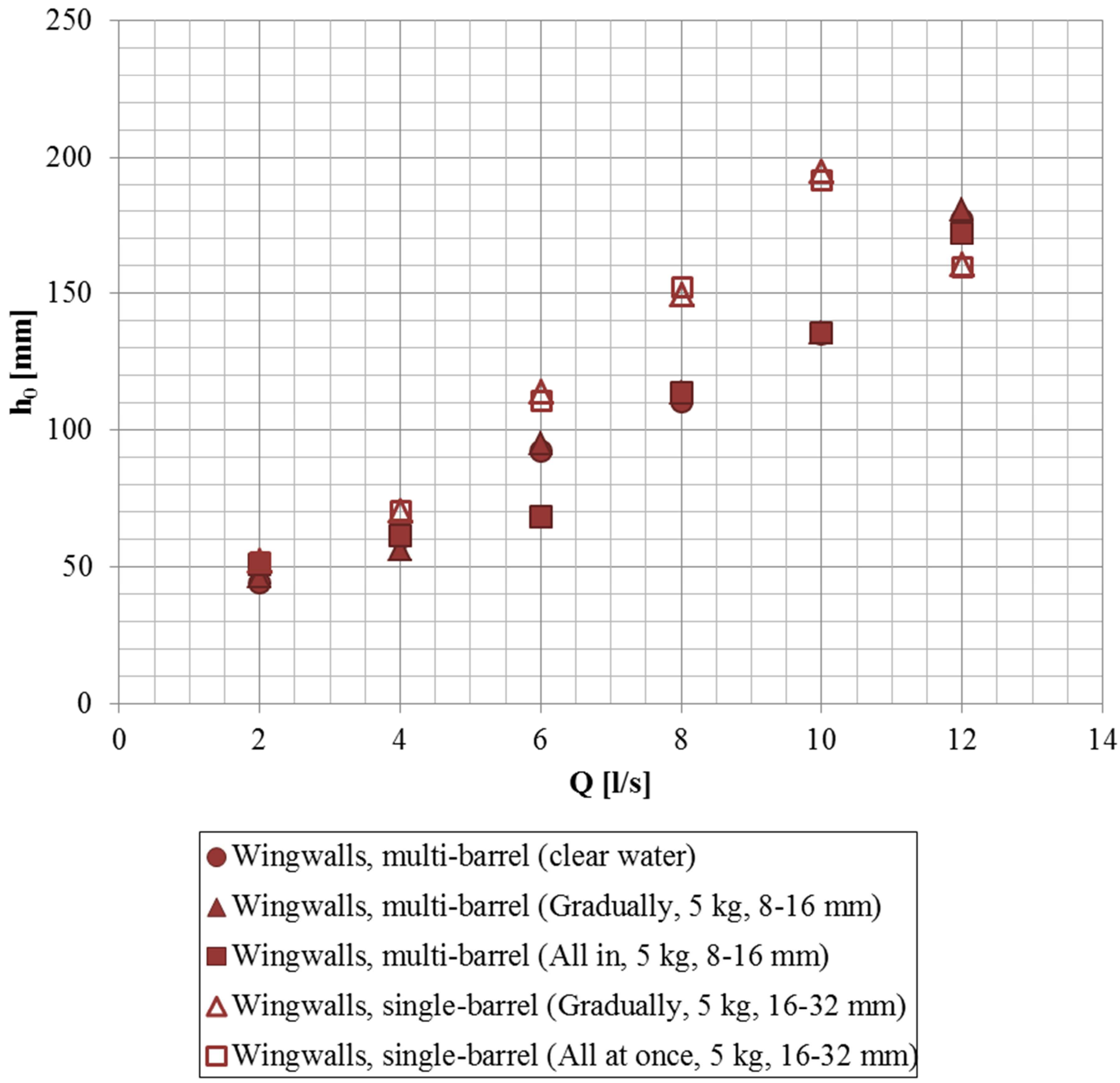

Figure 4.19 Sediment effect in multi- and single barrel system with wingwalls(based on the results of Faqiri (2014) and Hendler (2014))[3]

The results of the multi-barrel experiments were also compared to the ones from the single-barrel tests (Hendler, 2014). The headwater levels were lower so the hydraulic capacity was higher with the application of the multi-barrel system due to the headwater reduction, which was the result of the increased total barrel cross-sectional area (Figure 4.19). Consequently, at

[3] For the performance curve of the multi-barrel system with wingwalls I used the date from the experiments which were carried out in February 2014 instead of the ones from May 2014(which were presented in Faqiri's thesis) because in case of the two other inlet shapes also the data from February 2014 were used.

the same water level the discharge and the velocity were higher in case of multi-barrel system hence the sediment transport was also more efficient (Figure 4.20).

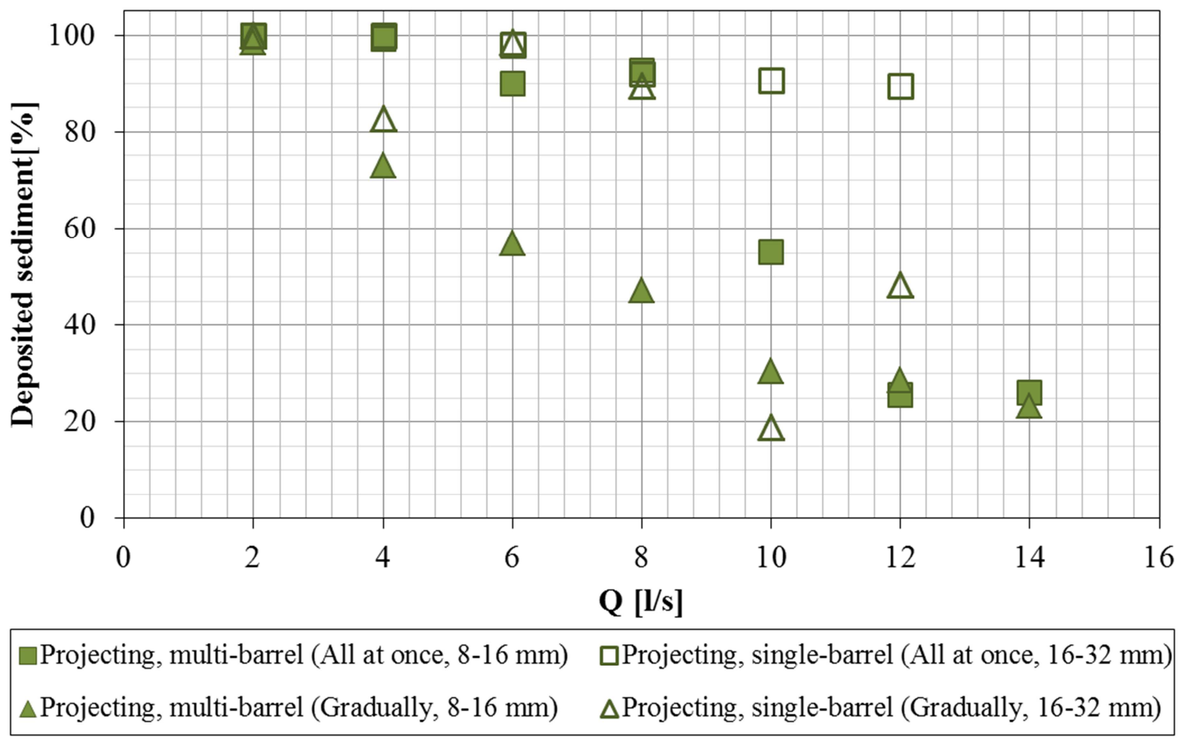

Figure 4.20 Sediment deposition with multi- and single-barrel system in case of projecting inlet (based on the results of Faqiri (2014) and Hendler (2014))

In conclusion, feeding of sediment increased the headwater levels for all inlet types with both feeding methods due to the accumulated sediments. The effect was greater when the accumulation occurred around the culvert entrance. When the maximum capacities were reached, the discharges were similar for both sediment transport and clear water experiments. The sediments which were fed all at once were more prone to accumulate in the expansion section thus less sediment was able to get through the culvert. For the three examined inlet types, the projecting inlet turned out to be the most efficient under sediment transport conditions, as the ratio of the transported sediments increased with the discharge. The comparison of the multi and single-barrel systems showed that the application of the reserve barrel increased the total barrel cross-section, thus the conveyed amount of water was higher for the same headwater levels. Consequently, the sediment transport was more efficient and additionally the safety of the structure also increased due to the reserve barrel which was located on a higher elevation and less prone to be blocked by sediments. Figures with the performance curves and with the deposited sediment amounts related to this chapter are presented in Appendix B. (Figure B.71 to Figure B.74).

4.3.5 Effect of trash racks

The effect of trash racks and debris deflectors on the culvert performance under sediment load was investigated in Dirks (2014). The setup was the same as in the clear water experiments (S=1:9, l_b=876 mm, w_b=1100 mm). The experiments for both sediment countermeasures were carried out with the three inlet shapes (Cut inlet, Projecting inlet, Wingwalls), with two feeding methods (Gradually, All at once) and with two sediment sizes (8-16 mm and 16-32 mm) and amounts (5 kg and 7 kg).

Fundamentally the main purpose of these structures is to prevent the blockage of the culvert and the failure of the structure by sediments and debris (Dirks, 2014). The results from Dirks (2014) show that both sediment countermeasures are efficient in sediment retention. With debris deflector 100% of the added sediments was deposited in the expansion section. Only with the projecting inlet when the 8-16mm sized grains were fed all at once, at 4 l/s around 1% of the sediments left the basin and went through the barrel. In case of trash racks more sediment went through the barrel but the percentage of the deposited sediment was still above 94% for all cases. In case of wingwalls regardless of the feeding method and sediment size, all the sediments were deposited in the expansion section. In case of cut inlet at 4 l/s when the 8-16 mm sized grains were fed gradually 96% deposited. Furthermore, at 6 l/s with both all at once and gradually feeding less than 1% of the 8-16 mm grains went through the barrel. With regards to sediment retention, the projecting inlet turned out to be the least efficient design in case of applied trash racks, as when the sediments were fed gradually with 8-16 mm grain size at 4, 6 and 8 l/s around 5% of the fed sediments were flushed through the culvert (Figure 4.21). The bigger sediment particles were less prone to get through the racks.

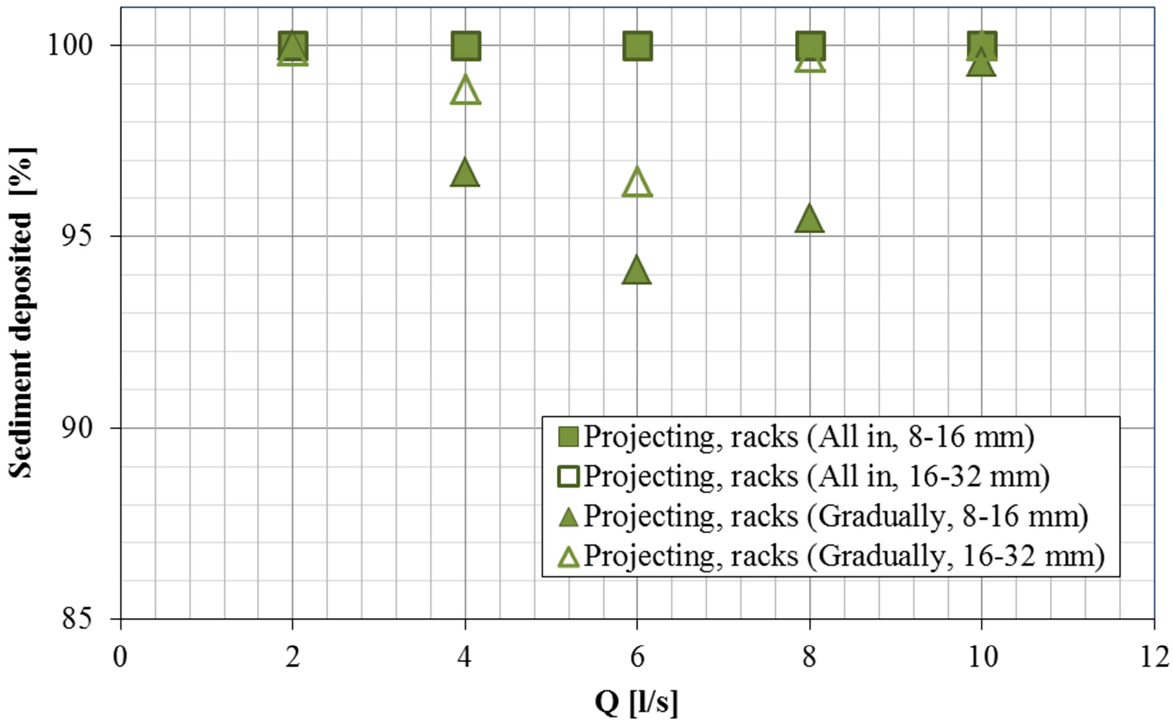

Figure 4.21 Projecting inlet with trash racks – sediment deposition (based on the results of Dirks (2014))

Beside the sediment deposition, the headwater levels were also examined during the experiments. As already mentioned in the discussion of the clear water experiments (Chapter 4.2.4) the application of the sediment countermeasures increased the water levels in the basin due to induced the energy loss. Under the different sediment conditions in case of debris deflectors, similar headwater levels were measured for each discharge regardless of the feeding method and grain size. The same can be said about the wingwalls with trash racks while in case of cut and projecting inlet the headwater levels were slightly higher when sediments were fed to the system. The larger sediment grains increased the water levels more for both inlet types. With the application of cut inlet, the all at once feeding method resulted in higher water levels (Figure 4.22). In case of projecting inlet, the gradually feeding resulted in the highest water elevations.

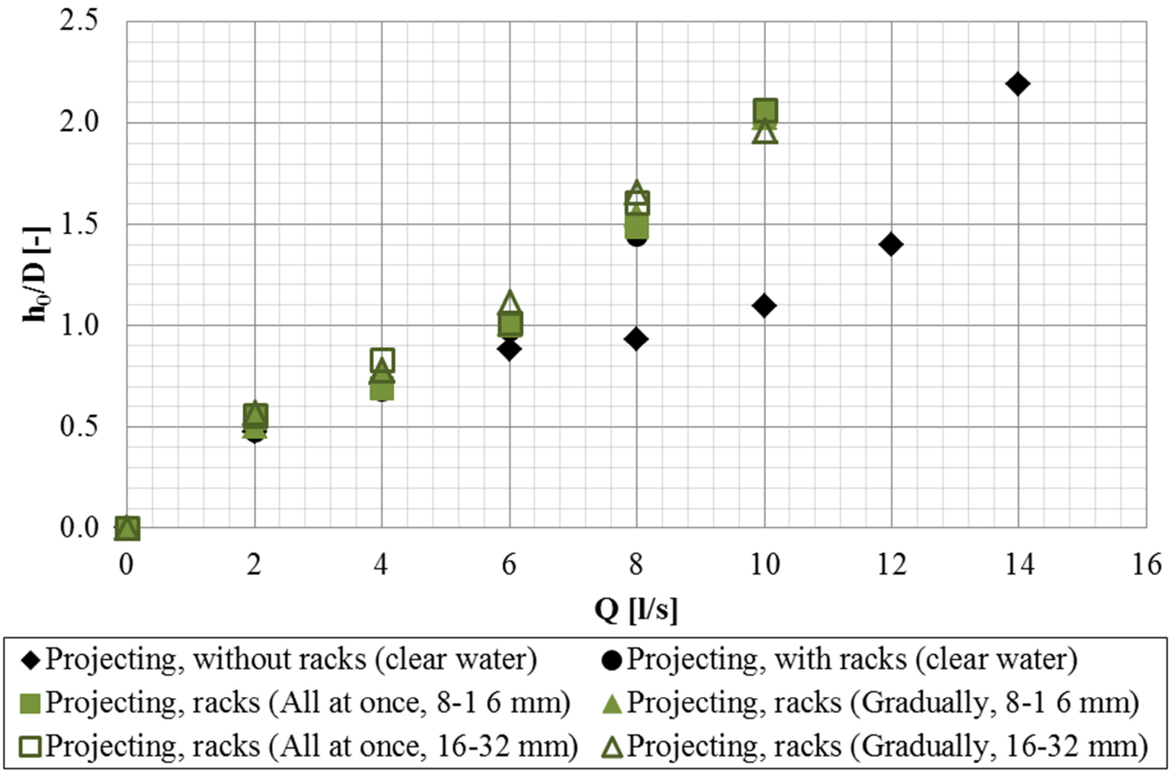

Figure 4.22 Performance curves in case of projecting inlet with trash racks (based on the results of Dirks (2014))

In conclusion, the debris deflector was more efficient in the retention of the sediments but both solutions were suitable to prevent the blockage of the culvert by sediments. The sediments with the smaller grain size were more prone to get through the racks especially when they were fed gradually to the system while with the all at once feeding all the sediments were deposited in the expansion section. In case of applied trash racks the headwater levels were higher when sediments were fed to the model as they were deposited at the culvert entrance. The deposited sediments then formed an obstruction in the flow which resulted in the increase of the headwater. This problem was not noticeable in case of the debris deflectors as the sediment deposition occurred further from the culvert entrance, at the apex of the racks. Figures with the performance curves and with the deposited sediment amounts related to this chapter are presented in Appendix B. (from Figure B.75 to Figure B.85)

4.3.6 Effect of inlet shape

The experiments under sediment transport conditions showed similar results to the clear water experiments regarding the effect of inlet shape. Under the jet regime which was examined in Gotvassli (2013), the wingwalls turned out to be the best inlet configuration as the flow was more stable thus increasing hydraulic capacity and the transported sediment rate (Figure B.86). However, due to embankment safety considerations, this jet dominated flow should be avoided as the flow with high velocity can cause scouring of the embankment. To avoid this undesirable flow pattern milder slope and energy dissipation were used. As a result of these improvements the headwater levels increased and especially when the blocks were used the amount of transported sediment decreased for all inlet types. The energy dissipator blocks had more influence on the hydraulic capacity of the wingwalls and cut inlet thus the projecting inlet turned out to be the most efficient inlet shape (Figure B.87). In case of wingwalls and cut inlet nearly no sediment was transported. With projecting inlet, up to 90% of the fed sediments were transported through the barrel when the sediment was fed gradually at higher discharges (Figure 4.17). At lower discharges this amount was between 10-40% (Figure 4.17). In case of multi-barrel system, the conveyance capacity higher than in case of single barrel, for any given water level, as with the application of the reserve barrel the total barrel cross-section was increased. As a result of the higher velocities, more sediment was transported through the culvert for all inlet types, but still the projecting inlet was the most efficient configuration with regards to hydraulic capacity (Figure B.88) and sediment transport (Figure 4.20, Figure B.73, Figure B.74). The inlet shape did not have a significant effect on the hydraulic capacity when sediment countermeasures were used as those improvements equalized the water levels for the three configurations (Figure B.89). However, in case of projecting inlet, when trash racks were used and the sediment was fed gradually a small amount of sediment passed through the culvert (Figure 4.21). In the other examined cases nearly all of the sediments were deposited in the expansion section (from Figure B.80 to Figure B.85).

In conclusion, similarly to the clear water experiments with a slope 1:9 and energy dissipation, the projecting inlet turned out to be the best configuration for hydraulic performance and in sediment transport. In case of the steeper slope and without energy dissipation headwater levels were lower for all inlet types, and the wingwalls showed the best performance. However, the jet regime which was specific to these experiments should be avoided due to embankment safety reasons.

4.3.7 Effect of sediment feeding method

In all the five theses two feeding methods were applied and investigated, the gradually and the all at once feeding method. The first simulated the steady sediment transport in natural streams while the second one represented the case of a landslide. The expectation was that the hydraulic capacity would be lower in case of landslide (all at once feeding) which was confirmed in most of the experiments. In general, the results from the previous studies showed that the water levels were higher for the all at once feeding as more sediment deposited in the expansion section and increased the headwater level. However, results from Hendler (2014) showed that the headwater levels were similar with the two sediment feeding methods when the energy dissipator blocks were applied (e.g. Figure B.23). Without energy dissipation the results with clear water and with gradually feeding showed similar values (e.g. Figure B.22). In some cases the results without energy dissipation showed that the headwater levels under sediment load were lower than under clear water conditions as the sediments deposited in wings on the two sides of the culvert and directed the jet flow towards the barrel (e.g. Figure B.22).

In Gotvassli (2013) the effect of the different feeding methods was examined on the water level over time in case of wingwalls with 2 l/s discharge. The results showed that in case of gradually feeding, the water level decreased after the sediment feeding started while in case of all at once feeding the water surface rapidly increased after the sediments had been fed to the model (Figure 4.23, Figure 4.24). Presumably the reasons of the water level reduction was the previously mentioned wing shaped deposition in front of the culvert which directed the flow towards the barrel while in case of all at once feeding the sediment deposition right before the culvert caused the water level increase.

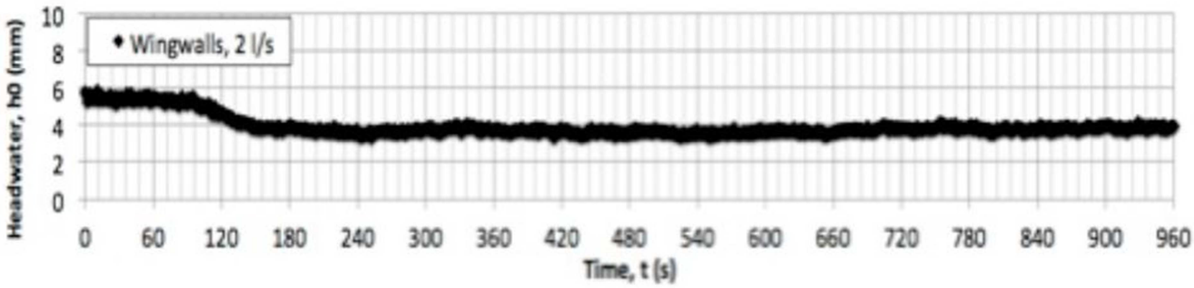

Figure 4.23 Headwater over time for a culvert with wingwalls, Q = 2 l/s, basin length 625 mm, slope 1:5 and 5 kg sediments of 8 – 16 mm fed gradually (Gotvassli, 2013)

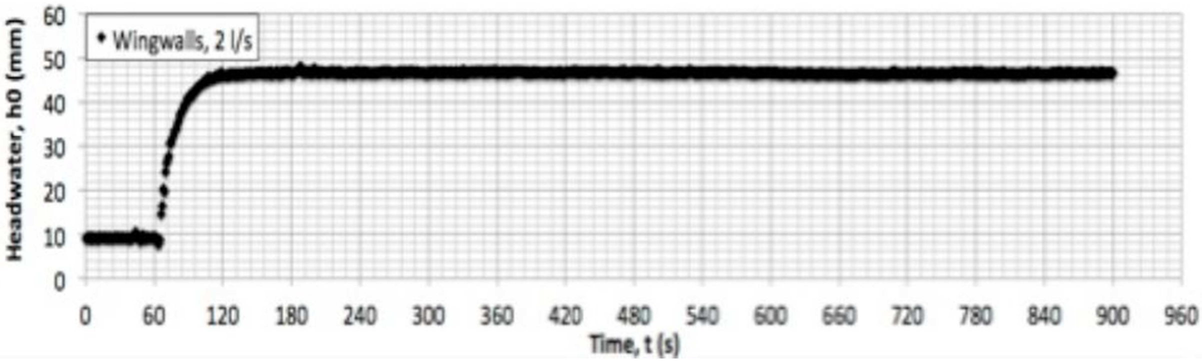

Figure 4.24 Headwater over time for a culvert with wingwalls, Q = 2 l/s, basin length 625 mm, slope 1:5 and 5 kg sediments of 8 - 16 mm added all at once (Gotvassli, 2013)

All in all the sediment transport was more efficient with gradually fed sediment while in general the headwater levels were higher with all at once feeding.

5 Culvert design based on the results

The results of the experiments carried out in the five examined theses, and the unifying analysis in the present study supports an actual design of a culvert in a steep terrain. Consequently, the inlet type, the expansion section geometry and additional structures could be chosen for the first stage of the planning process. Furthermore, besides the hydraulic and sedimentation aspects the embankment safety and cost aspects have also to be taken into account. Sometimes the safety demands are not fulfilled entirely with the optimal intake design hence safety improvement measures are necessary. These measures are chosen and designed by road planners depending on costs and practicality. The cost estimation of a drainage system is complex as many factors influence it beside the inlet configuration. Such economical calculations are therefore outside the scope of this thesis (Sellevold, 2015).

In the followings three different intake configurations are chosen based on the results of the unifying analysis:

- The first design shows the highest hydraulic capacity with high velocity utilized to flush the sediment through the culvert.
- The second design ensures stable flow conditions and enhances embankment safety aspects. It shows relatively high sediment transport efficiency with more stable and less complex flow features.
- The third version sediment countermeasures are used to prevent sedimentation in the barrel.

5.1 General design

Based on the scale model applied in this project the culvert diameter (D) and the overtopping limit (2D) in the prototype according to the model scale (1:10) are 1 metre and 2 metres, respectively. For the prototype the following materials were chosen: natural streambed for approach channel, concrete cover on the expansion section, earthfill embankment and concrete culvert barrel. The applied culvert pipe was chosen from the catalogue of Basal Company. Technical specifications of the applied pipe are the followings: inside diameter 1000 mm, wall thickness 125 mm (BASAL, 2012). Figure 5.1 shows an image about the applied culvert barrel.

Figure 5.1 Applied culvert pipe (BASAL, 2012)

5.2 Type 1 – best hydraulic capacity

The best hydraulic capacity and the highest sediment transport capacity could be obtained by applying wingwalls with 1:5 approach channel slope and without energy dissipation (Gotvassli, 2013). The experiments with a focus on expansion section geometry showed that the basin length and width had slight effect on the hydraulic capacity when using wingwalls (Gotvassli, 2013; Putri, 2014). Consequently, due to lower costs, the shortest examined length and width were chosen for this intake configuration i.e. 315 mm length and 292 mm width. According to the model scale the length and the width of the prototype are 3.15 m and 2.92 m, respectively.

Experimental setup with steep slope and without energy dissipation resulted in a jet dominated flow in the expansion section which conveyed the flow and the sediments efficiently through the barrel. The high flow velocities however, enhance the risk of the embankment failure as locally scour development can occur around the inlet. Therefore, this flow condition should be avoided or additional erosion and scour protection should be applied. Furthermore, the construction cost of wingwalls is higher than in case of cut or projecting inlet due to the applied precast concrete inlet. Figure 5.2 present the configuration of a wingwalls inlet from the catalogue of Basal Company.

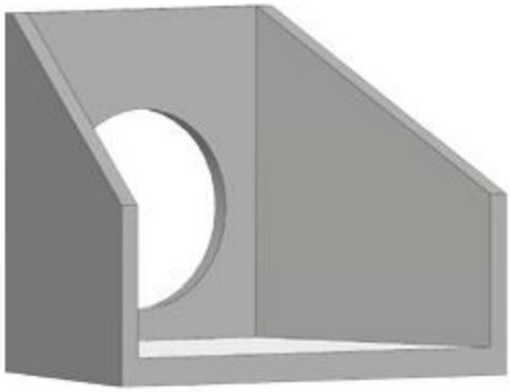

Figure 5.2 Precast wingwalls (BASAL, 2012)

5.3 Type 2 – higher embankment safety

In order to avoid the jet dominated flow milder slope (1:9) and energy dissipator blocks were used in the experiments. Based on the results of these experiments the projecting inlet was found to be the best inlet configuration (Hendler, 2014; Putri, 2014; Faqiri, 2014). According to the model scale (1:10) the size of the energy dissipator blocks (3 pieces) in case of the prototype is 20x20x20 cm and the applied material is concrete. The experiments focusing on the width effect clearly showed that the hydraulic capacity was higher when wider basin was used. Consequently, the widest examined width, 876 mm was chosen for the further work which is 8.76 m in the prototype. The length effect was examined under jet regime thus the oscillating jet influenced the hydraulic capacity of the projecting inlet. As a result, the 625 mm long basin showed the lowest capacity, while the two other examined lengths gave similar results. Therefore, the shorter expansion section has been chosen for the culvert design having lower costs with this solution. In conclusion, the chosen expansion length is 315 mm which means 3.15 m in case of the prototype.

The experiments with multi-barrel system showed that an additional culvert which is placed on a higher level than the main culvert can improve the safety of the structure against clogging by sediments (Faqiri, 2014). Beside this, as a result of the increased total barrel section at the same headwater level, the discharges and the flow velocities were increased compared to the ones with single barrels. Therefore, the designed intake was supplemented with a reserve barrel which was scaled up from the model version so the applied diameter is 60 cm and the elevation of the barrel bottom is 40 cm from the embankment toe. According to the catalogue of Basal Company the wall thickness of the barrel is 94 mm (BASAL, 2012). The centre-to-centre distance between the two culverts was 420 mm in the model but as a smaller width (876 mm) has been chosen in comparison to the one which was used in the model (1100 mm), this distance has been reduced to 300 mm meaning 3 metre in the prototype.

5.4 Type 3 – no sediment in the barrel

In some cases in order to avoid sediment deposition in the barrel and increase the embankment safety, sediment countermeasures are applied. The prevention of the sediment deposition in culvert can at the same time reduce the necessary culvert diameter (Sellevold, 2015). The experiments carried out in Dirks (2014) showed that both trash racks and debris deflectors are efficient in sediment retention but the application of these structures increases not only the construction but also the operating costs as the deposited sediment has to be excavated and handled regularly. Therefore, a detailed cost-benefit calculation is necessary to make the right decision.

5.5 Discussion and conclusion

Culvert design is a complex process as not only the hydraulic capacity has to be taken account but also embankment safety and economical aspects. All the three previously presented intake configurations are unique from certain aspects. Type 1 presents the best hydraulic capacity and sediment transport efficiency, but due to the jet dominated flow with high velocities the embankment safety demands are not fulfilled. Moreover the construction cost of a wingwalls inlet is higher than in case of cut or projecting inlet. Type 3 gives a solution to prevent sediment accumulation in the culvert with application of additional sediment countermeasures. These structures are efficient in sediment retention but also increase the construction and operating costs. Type 2 presents the optimal configuration based on the result of this thesis. Relatively high hydraulic capacity, stable flow conditions and sediment transport efficiency, together with reasonable costs. Application of the projecting inlet has lower costs than wingwalls or cut inlet as no modification on the barrel (additional inlet structure – wingwalls; mitering of the barrel end) is necessary. The construction of energy dissipation elements increases the costs, but the resulted less turbulent flow features support embankment safety. The reserve barrel also means an extra cost, but increases the structure safety against clogging by sediments. In conclusion, Type 2 with application of reserve barrel was chosen as designed culvert configuration. The detailed drawings are shown on D1 and D2 drawings.

6 Conclusion

The present study identified the favourable culvert inlet design under sediment transport conditions, as the result of an overarching analysis of available data from five previous theses which were carried out on a scale model in the framework of the NIFS-project. The culvert's hydraulic capacity was investigated with different boundary conditions, under both clear water condition and sediment load. The experiments were carried out with three different inlet types (cut, projecting, wingwalls) focusing on the effects of the following parameters: expansion section geometry, reserve barrel, sediment countermeasures, feeding method, sediment size and sediment amount.

Based on clear water experiments it was found that a wingwall-inlet provided the highest hydraulic capacity under jet dominated flow. However, this flow condition should be avoided due to embankment safety reasons. Therefore, to prevent the jet dominated flow in the expansion section milder slope and energy dissipation structure were installed to the model (Hendler, 2014). These improvements decreased the energy level and flow velocity in the expansion section, and as a consequence increased the headwater level. Installation of energy dissipator blocks had bigger effect on the hydraulic capacity than changes of the approach channel slope. Experiments with a milder slope (1:9) and energy dissipation showed that the highest hydraulic capacity was obtained by installing a projecting inlet. This is different from existing hydraulic theory, as for example in the guideline from Statens Vegvesen, the wignwalls inlet gives the highest hydraulic capacity (Statens Vegvesen, 2011). This difference can be related to the model setup, since the entrance of the projecting inlet was closer to the approach channel end than the entrance of the wingwalls. Therefore, the effective basin length was also shorter in case of projecting inlet, which means the flow was directed towards the culvert. The evaluation of the expansion section geometry effect showed, that both basin length and width influenced the culvert's performance. Experiments focusing on the basin length effect were carried out under jet dominated flow resulting from supercritical flow conditions in the steep and smooth approach channel. In the jet regime flow conditions were more stable in case of the experiments with the wingwall-inlet, thus the highest hydraulic capacity was obtained by this inlet type. The use of wingwalls gave similar performance curves for all three examined basin lengths. In case of the other two inlet configurations (cut and projecting), the highest capacity was obtained for the shortest basin length (315 mm) as the travel distance (i.e. the distance between the end of the approach channel and the culvert entrance) was shorter and the oscillating jet was directed towards the culvert. Experiments with the longest basin length (876 mm) and with the shortest length gave similar results for all three inlet types, while with 625 mm basin, hydraulic capacity was lower. The effect of the basin width on culvert performance was examined under more stable flow conditions. The highest hydraulic capacity was obtained by projecting inlet with the widest basin configuration (876 mm), as the headwater level was increased by backwater effect in case of narrower basins. In case of wingwalls and cut inlet, the varying basin width only had a slight effect on the hydraulic capacity.

Experiments with sediment, similarly to clear water tests showed that under jet dominated flow the wingwall-, while under more stable flow conditions the projecting inlet showed the best performance. The main influencing factors of the culvert's hydraulic capacity were the inlet shape and the hydraulic conditions which were partly governed by the presence and location of a hydraulic jump. These factors affected the deposited sediment amount, which in turn increased the headwater level in the basin. In the studies two different feeding methods were used: gradual and all at once feeding. The first simulated a steady sediment transport while the second simulated extreme sediment yield conditions which may occur during a landslide event. The headwater levels were generally higher in case of all at once feeding as more sediment deposited in front of the culvert entrance. Under jet dominated flow only a small amount of sediment accumulated in the expansion section, therefore experiments with clear water and sediment showed similar results. The use of a milder approach channel slope increased the deposited amount of the sediment especially in case of all at once feeding. However, clear water and gradually fed sediment experiments still showed similar hydraulic capacities. Installation of energy dissipation had a large effect on sediment deposition, as nearly all fed sediment accumulated in the expansion section with both feeding methods. Although sediment size and amount had only a slight effect on the culvert performance, the water level was generally higher when more sediment (7 kg) was fed to the model, as more sediment accumulated in the expansion section. Additionally, the projecting inlet showed bigger differences in headwater level, between the test series with two different sediment amounts.

The installation of a reserve barrel increased the conveyance capacity for the same headwater level, thus culvert's hydraulic capacity and sediment transport were also increased. In addition the installation of the reserve barrel, located at a higher level compared to the main culvert, increased the safety of the structure as it was less prone to be blocked by sediments.

Experiments with sediment countermeasures showed that both trash racks and debris deflectors are efficient in sediment retention. However, installation of these structures decreased the culvert's hydraulic capacity. The highest headwater levels occurred with debris deflectors as more sediment was retained by this sediment countermeasure.

Based on all these conclusions, culvert design was carried out in Chapter 5. As the optimal configuration the projecting inlet with slope 1:9, with energy dissipation, with a 3.15 m long and 8.76 m wide expansion section was chosen. In addition a reserve barrel with a diameter of 60 cm was chosen to increase the safety of structure against blockage by sediment. For this chosen configuration, sketches have been developed (D1 and D2 drawings).

7 Further work

The present study gives a promising foundation for a new culvert design guideline which will take into account the effect of sediment transport processes at the culverts. Such a procedure could greatly support and improve culvert designing activities at places where high sediment load is expected, at mountains regions, for instance, where bedload can significantly influence the operation of culverts. There are, however, a few more issues to deal with to have a clear picture on the hydrodynamic and sediment transport processes at culverts.

As for now the main focus was on sediment movements, but the characteristic flow and turbulence features should also be studied. Several up-to-date flow measurement methods were tested in similar studies, such as the use of Large-Scale Particle Image Velocimetry (LSPIV). For instance, Muste et al. (2008) applied LSPIV for both field and laboratory experiments to quantify 2D and 3D flow features that can be related to important morphologic and hydrodynamic aspects of natural rivers. Acoustic Doppler Velocimetry (ADV) could be applied to estimate the rate of turbulence, which certainly influences the sediment transport capacity. The hydrodynamic characterization of the culvert flow would also point out the scale effect related problems of laboratory models. The scaling of turbulence and sediment features is far not straightforward both having great importance in the current study. In addition, different sediment mixtures and feeding methods should be also examined to represent more realistic conditions.

Regarding the culvert geometry the basin length effect should be investigated also without jet dominated flow and as a next step of this project, a more realistic stream approach channel should be examined. Furthermore, besides the suspended sediment and bedload, the debris flow also influences the culvert capacity. Therefore, the effect of debris also should be examined, in the framework of this project.

8 References

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Appendix

A. Clear water experiments

This section presents the effect diagrams for the clear water experiments for the different setups.

Energy dissipation and slope effect: Basin length: 876 mm, Basin width: 1100 mm

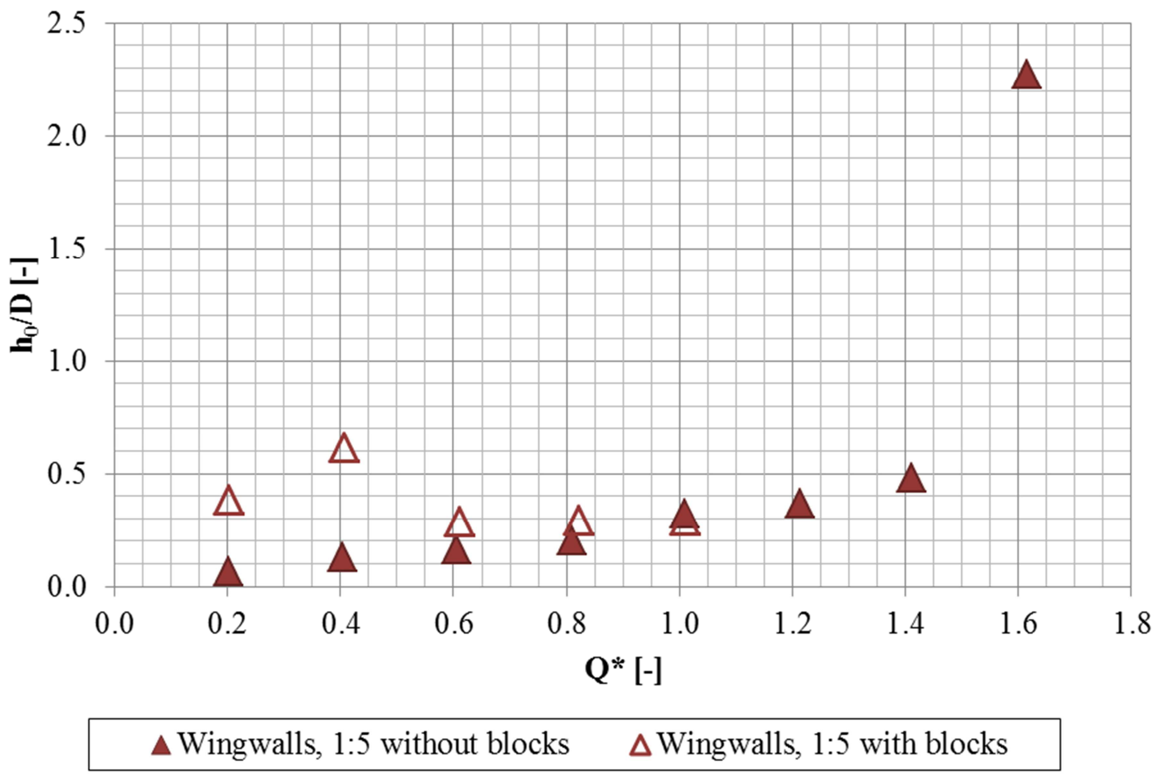


Figure A.1 Effect of the energy dissipation at wingwalls with slope 1:5 (based on the results of Gotvassli (2013) and Hendler (2014))

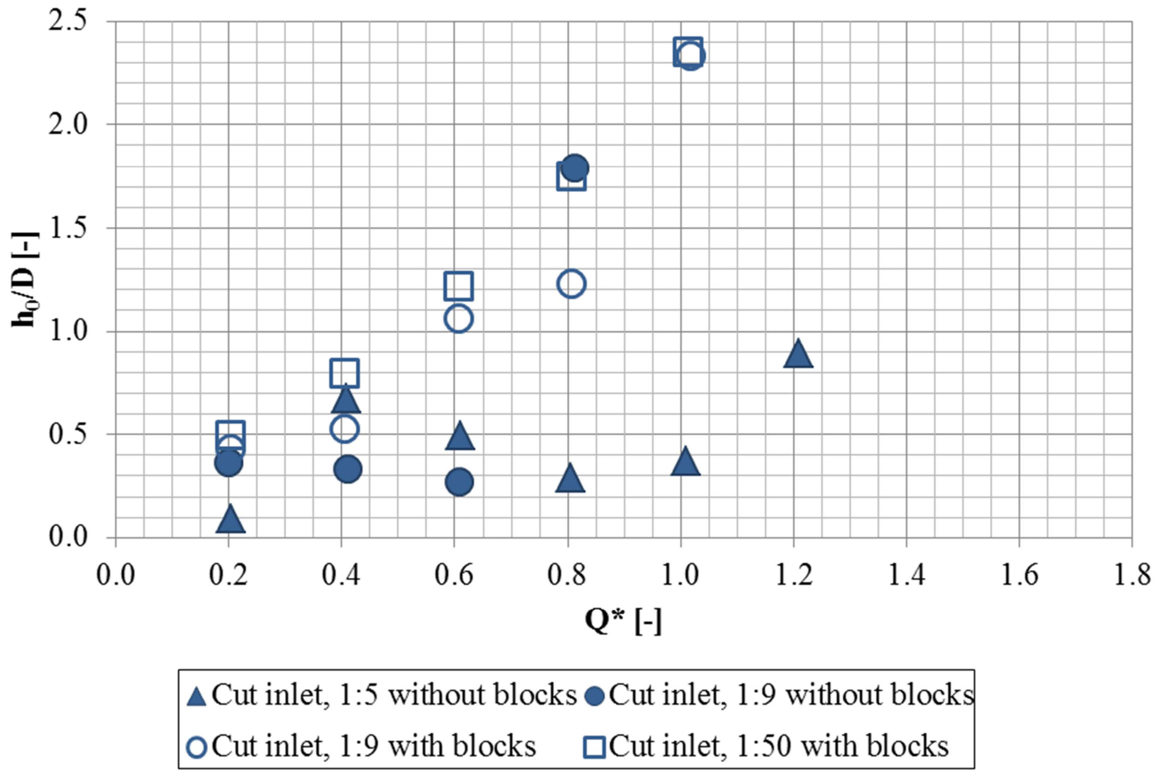


Figure A.2 Energy dissipation and slope effect at cut inlet (based on the results of Gotvassli (2013) and Hendler (2014))

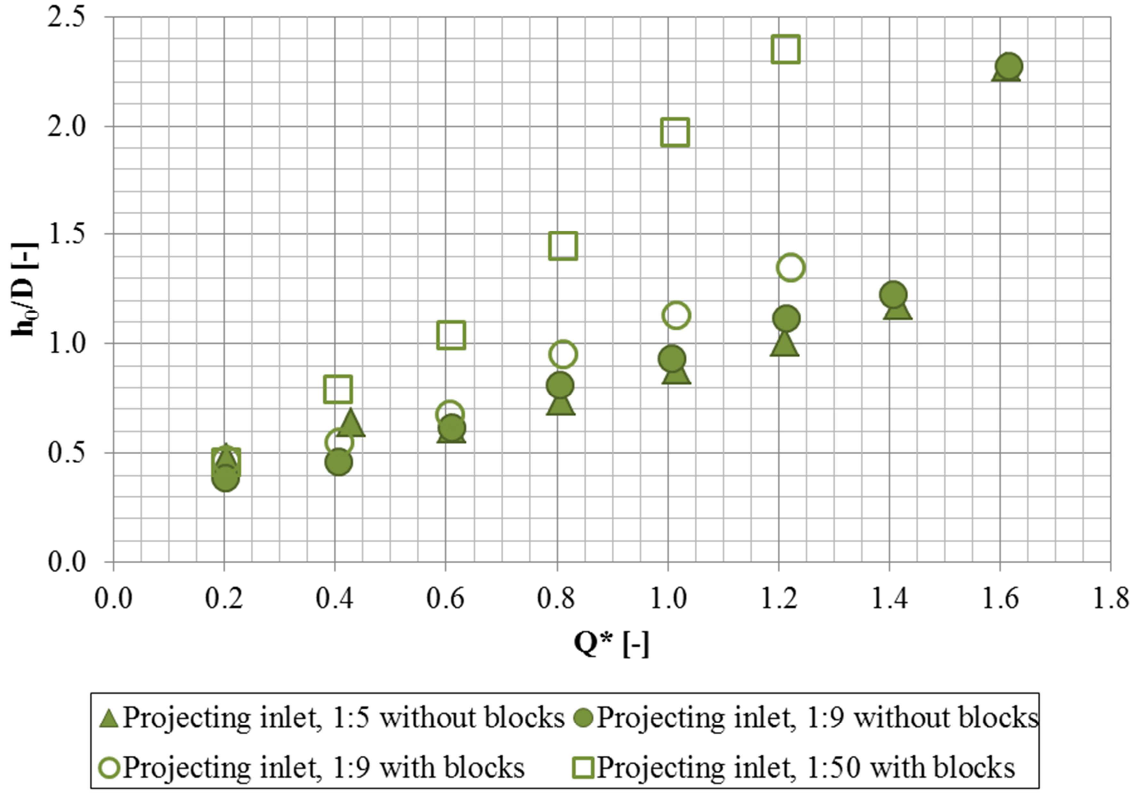


Figure A.3 Energy dissipation and slope effect at projecting inlet (based on the results of Gotvassli (2013) and Hendler (2014))

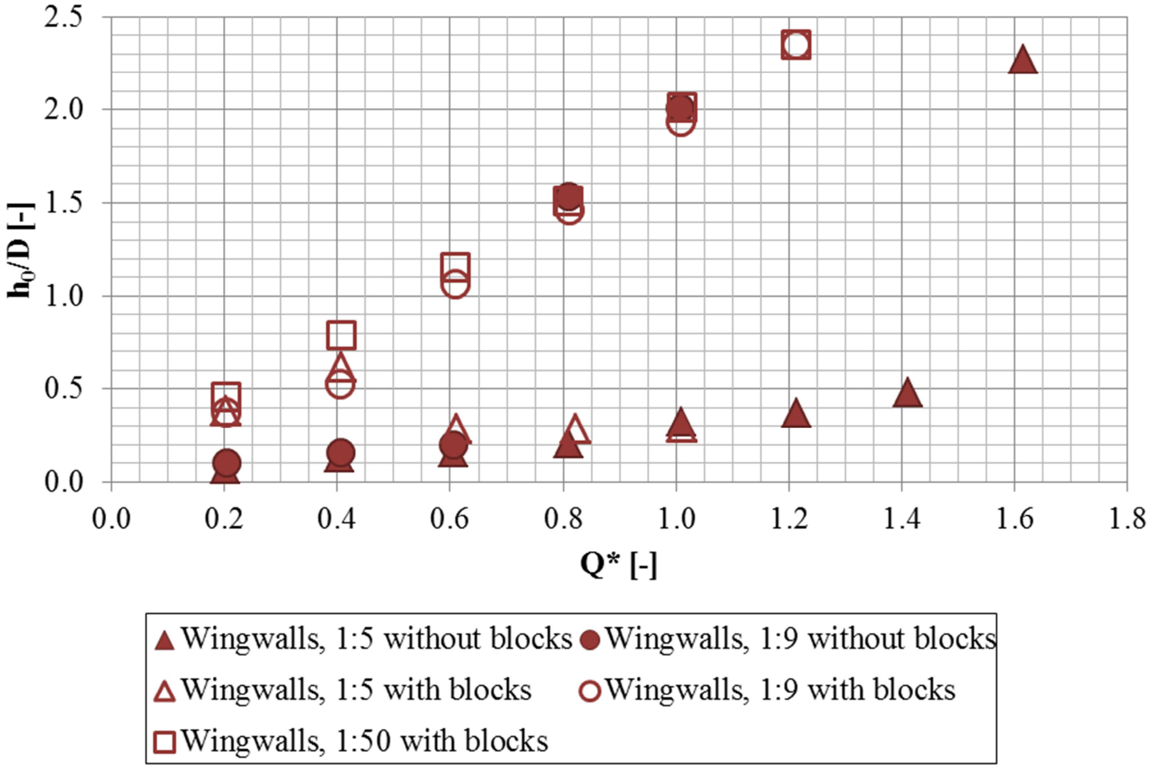


Figure A.4 Energy dissipation and slope effect at wingwalls (based on the results of Gotvassli (2013) and Hendler (2014))

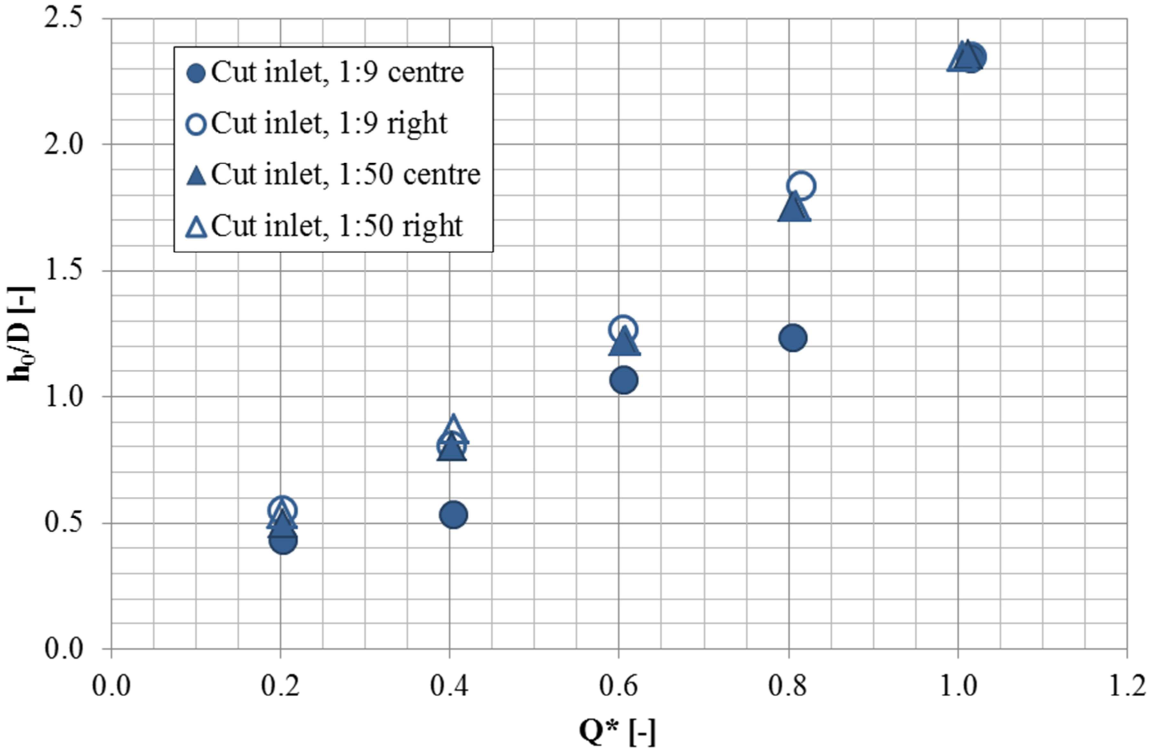


Figure A.5 Effect of culvert displacement in case of cut inlet (based on the results of Hendler (2014))

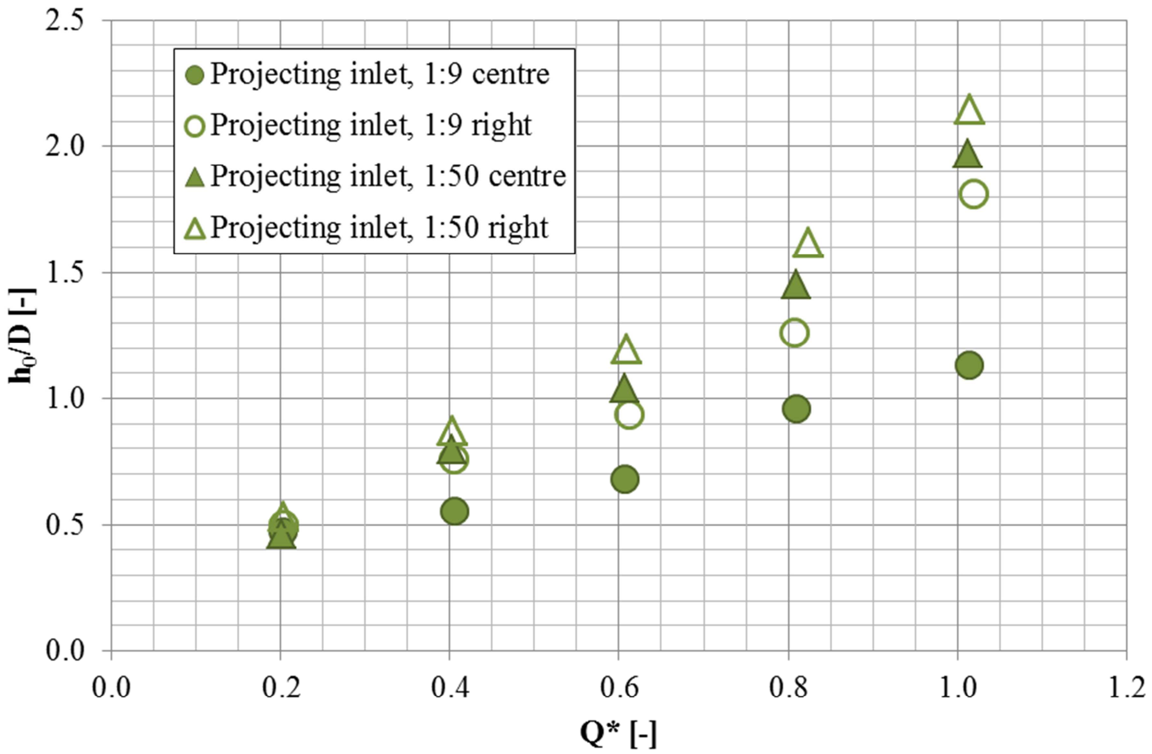


Figure A.6 Effect of culvert displacement in case of projecting (based on the results of Hendler (2014))

Basin length effect: Slope: 1:5, Basin width: 1110 mm, without energy dissipation

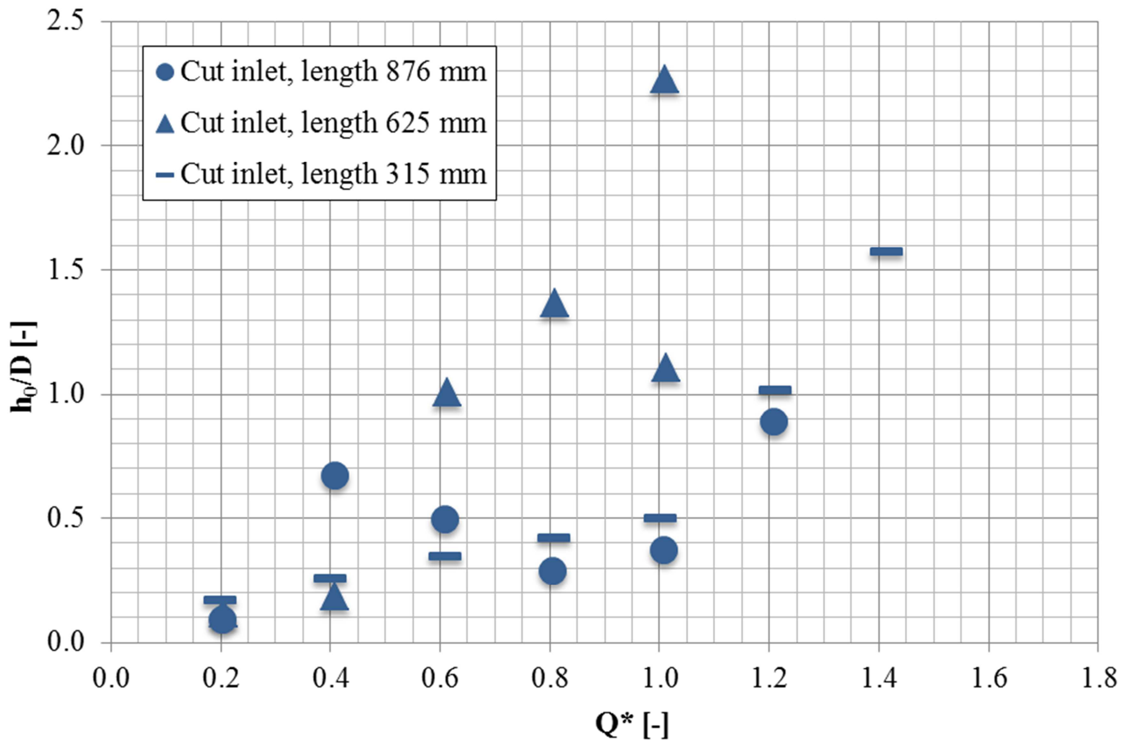


Figure A.7 Basin length effect with cut inlet, slope 1:5 (based on the results of Gotvassli (2013))

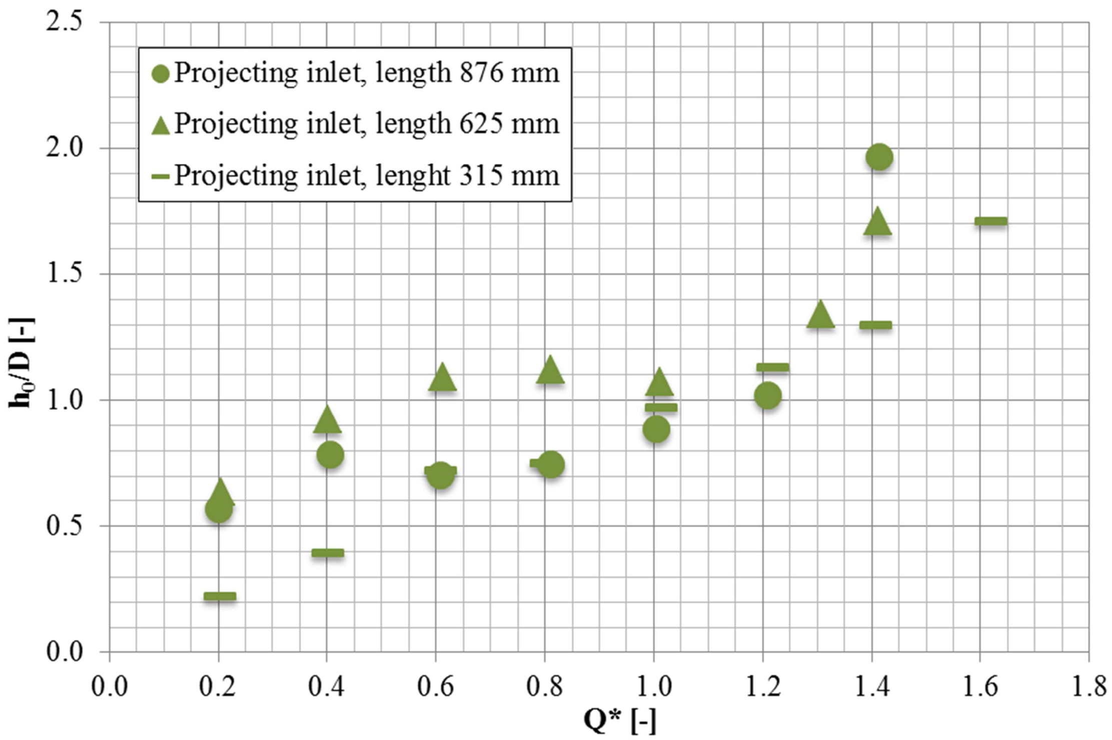


Figure A.8 Basin length effect with projecting inlet, slope 1:5 (based on the results of Gotvassli (2013))

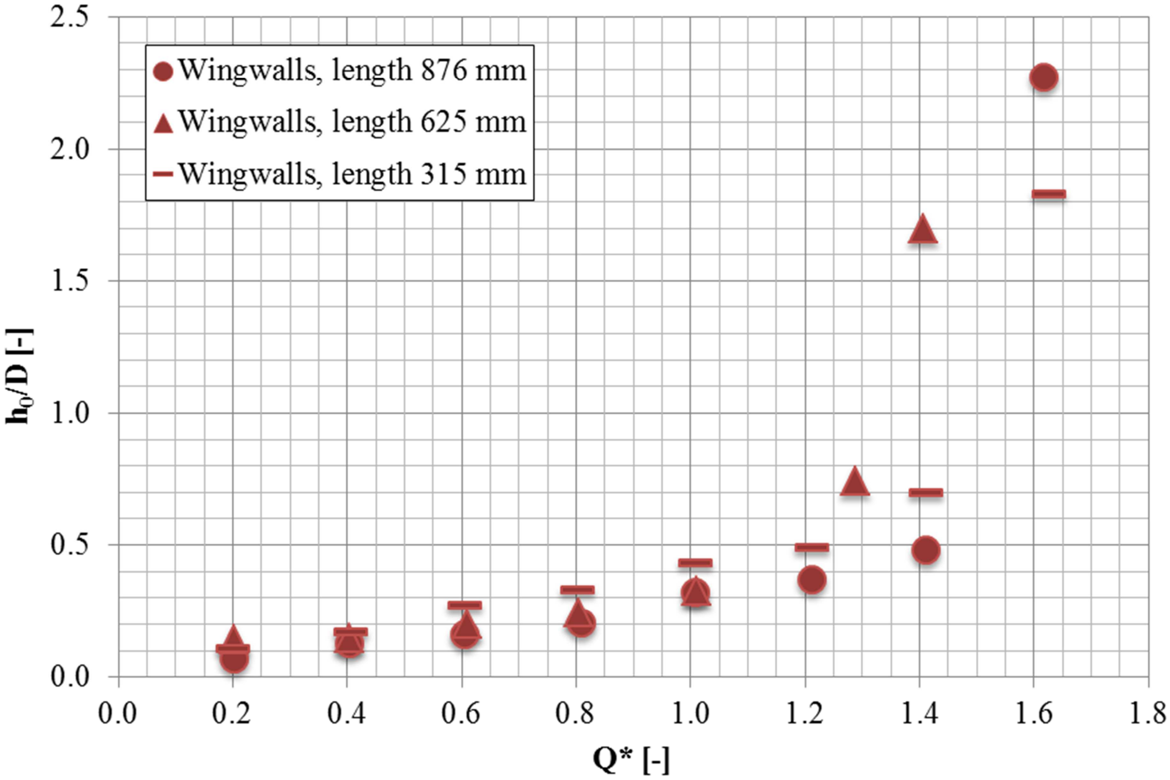


Figure A.9 Basin length effect with wingwalls, slope 1:5 (based on the results of Gotvassli (2013))

Basin width effect: Slope: 1:9, Basin length: 876 mm, with energy dissipation

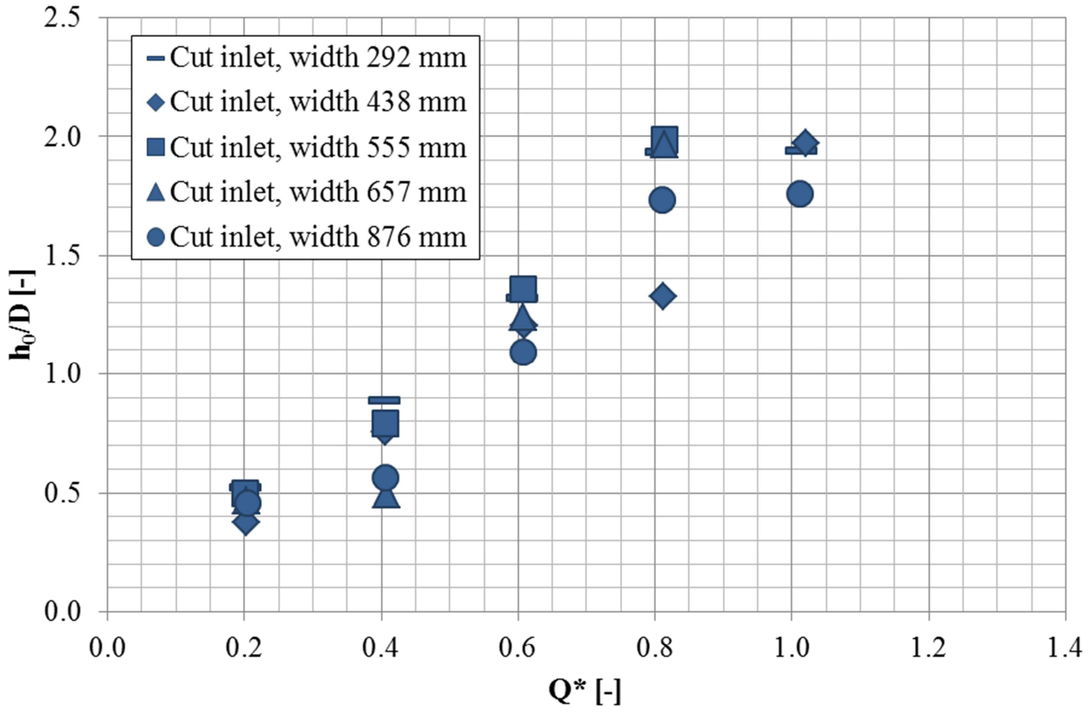


Figure A.10 Basin width effect with cut inlet, slope 1:9 (based on the results of Putri (2014))

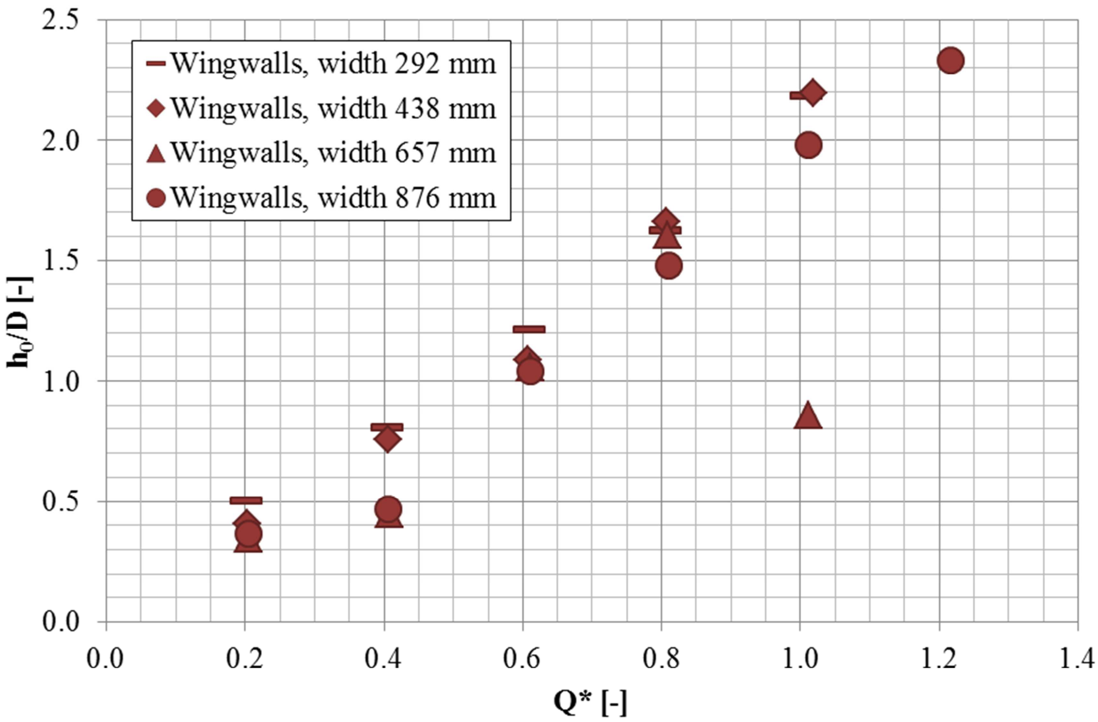


Figure A.11 Basin width effect with wingwalls, slope 1:9 (based on the results of Putri (2014))

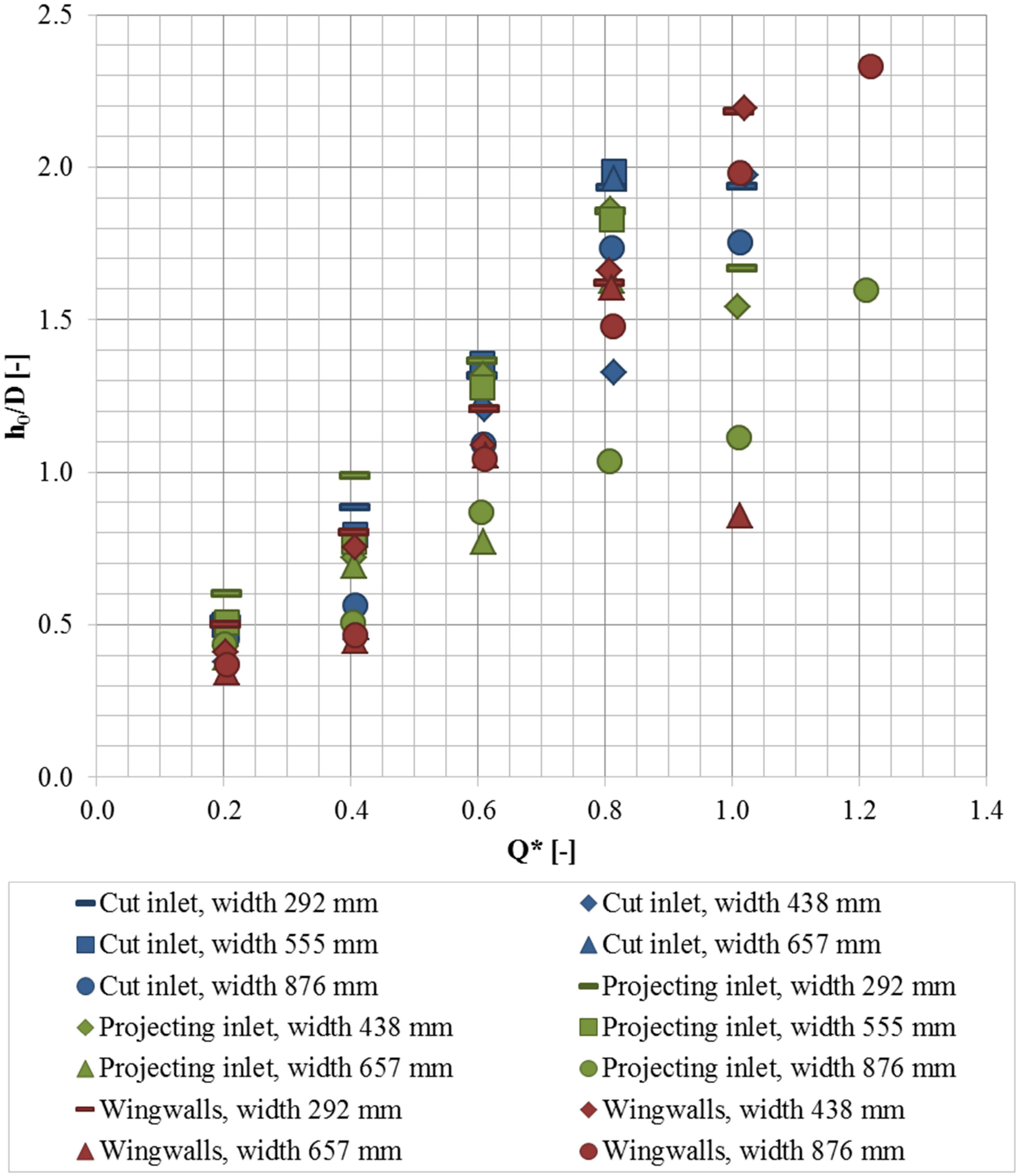


Figure A.12 Basin width effect with slope 1:9 (based on the results of Putri (2014))

Effect of reserve barrel: Slope: 1:9, Basin length: 876 mm, Basin width: 1100 mm, with energy dissipation

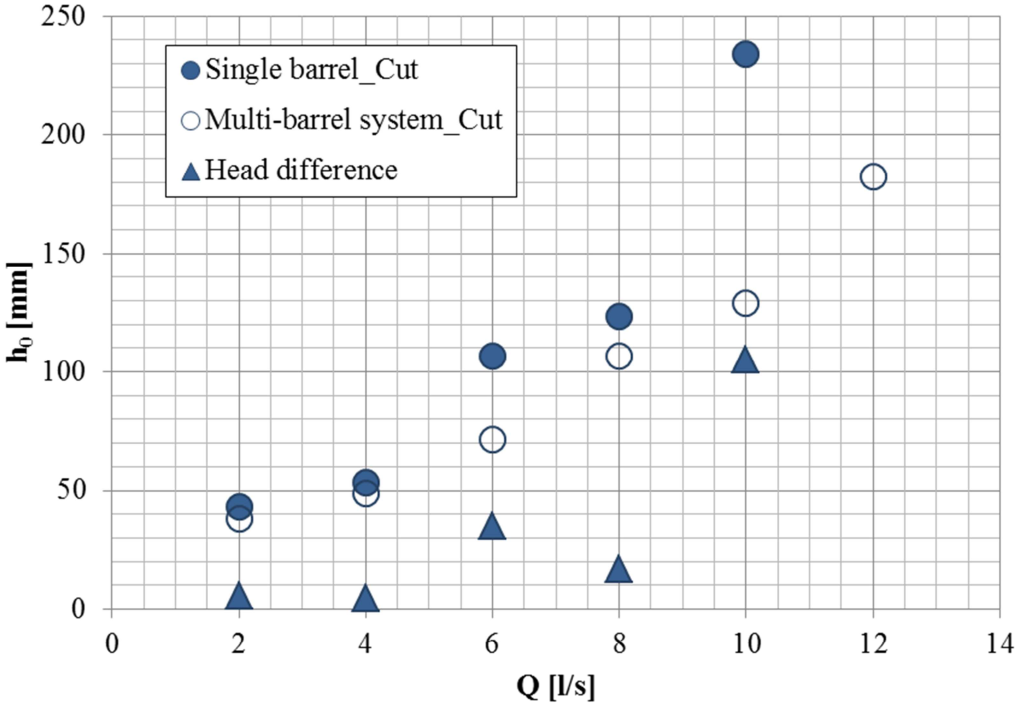


Figure A.13 Effect of the reserve barrel with cut inlet (based on the results of Faqiri (2014))

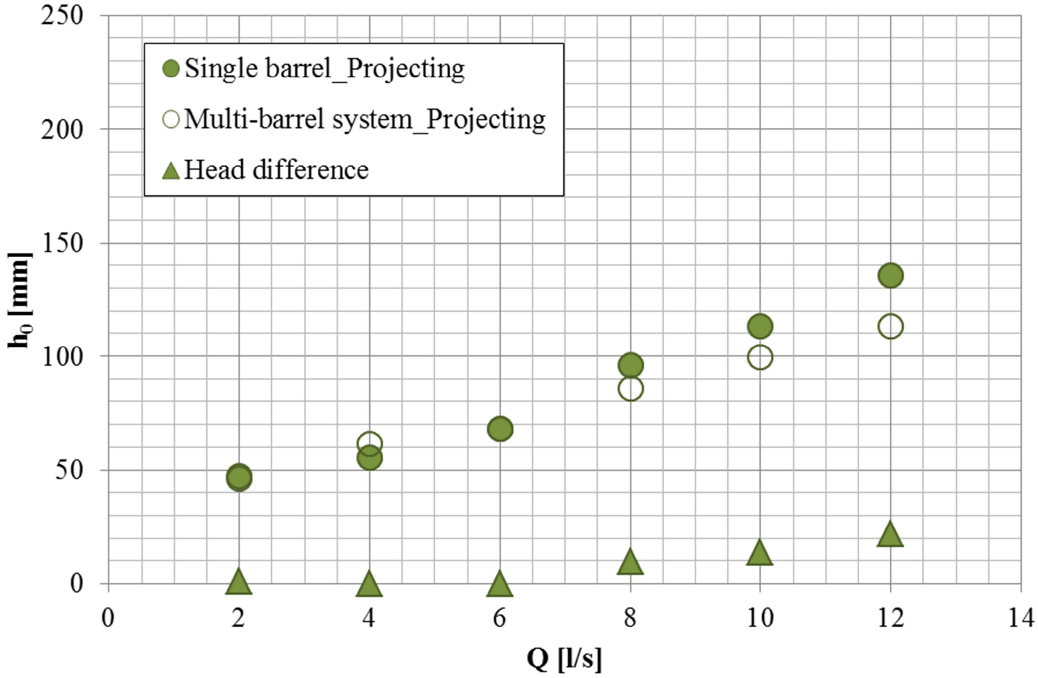
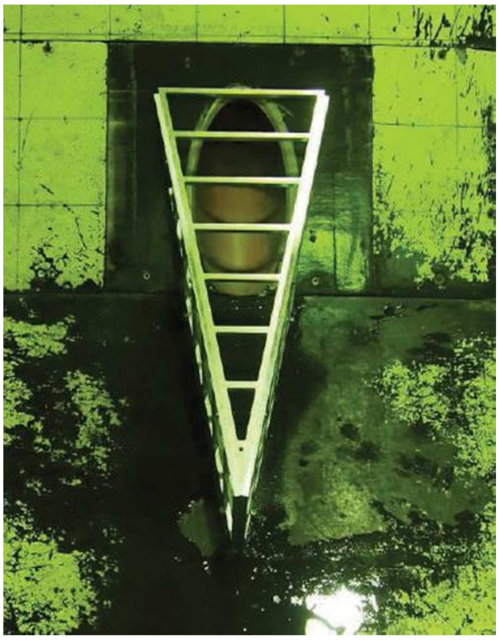


Figure A.14 Effect of the reserve barrel with projecting inlet (based on the results of Faqiri (2014))

Applied trash racks and debris deflectors:



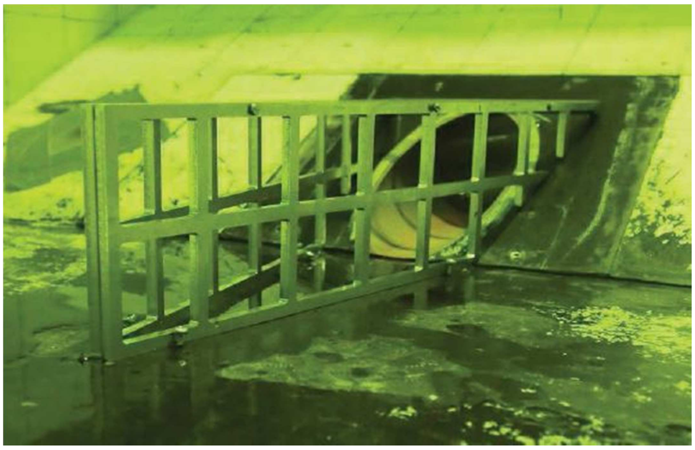
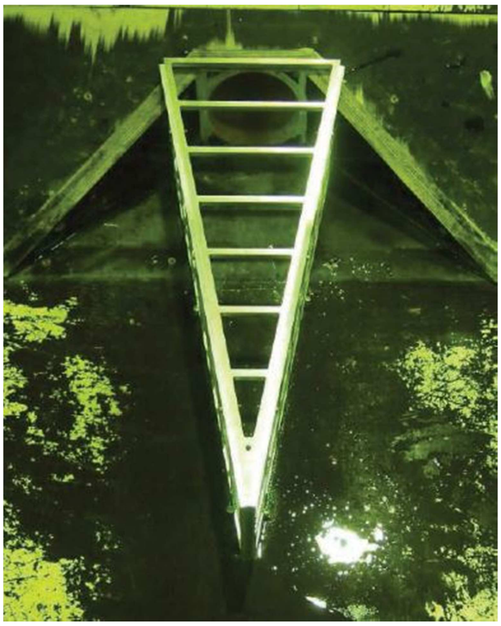


Figure A.15 Debris deflector at cut inlet: plan view (left), side view (right) (Dirks, 2014)



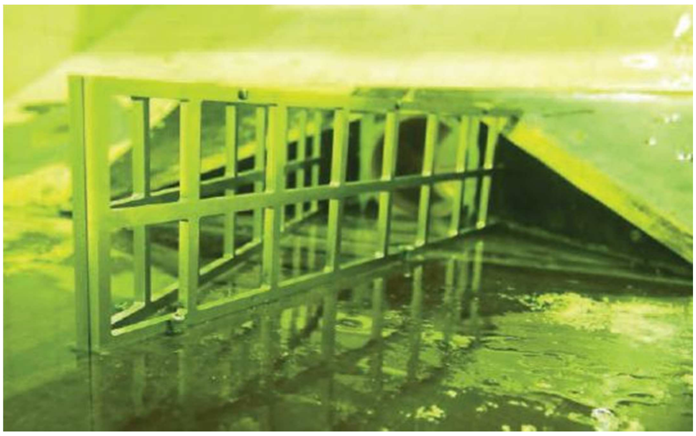


Figure A.16 Debris deflector at wingwalls: plan view (left), side view (right) (Dirks, 2014)

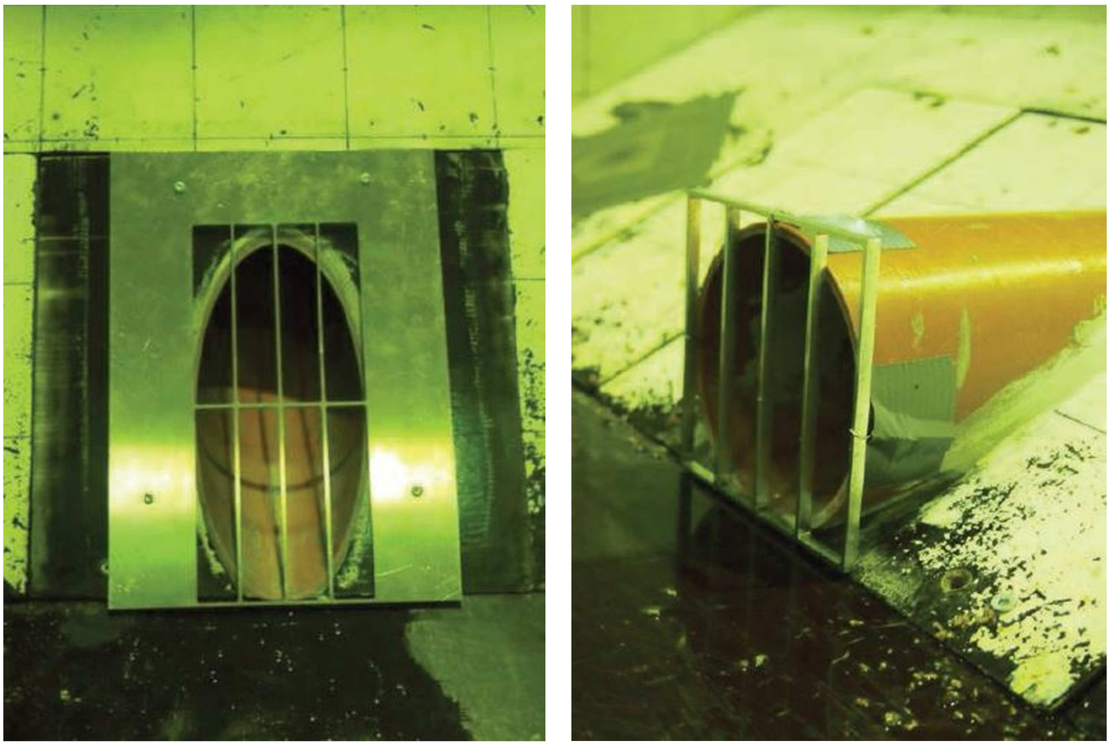


Figure A.17 Trash racks at cut (left) and projecting (right) inlet (Dirks, 2014)

Figure A.18 Trash racks at wingwalls (Dirks, 2014)

Effect of trash racks and debris deflector: Slope: 1:9, Basin length: 876 mm, Basin width: 1100 mm, with energy dissipation

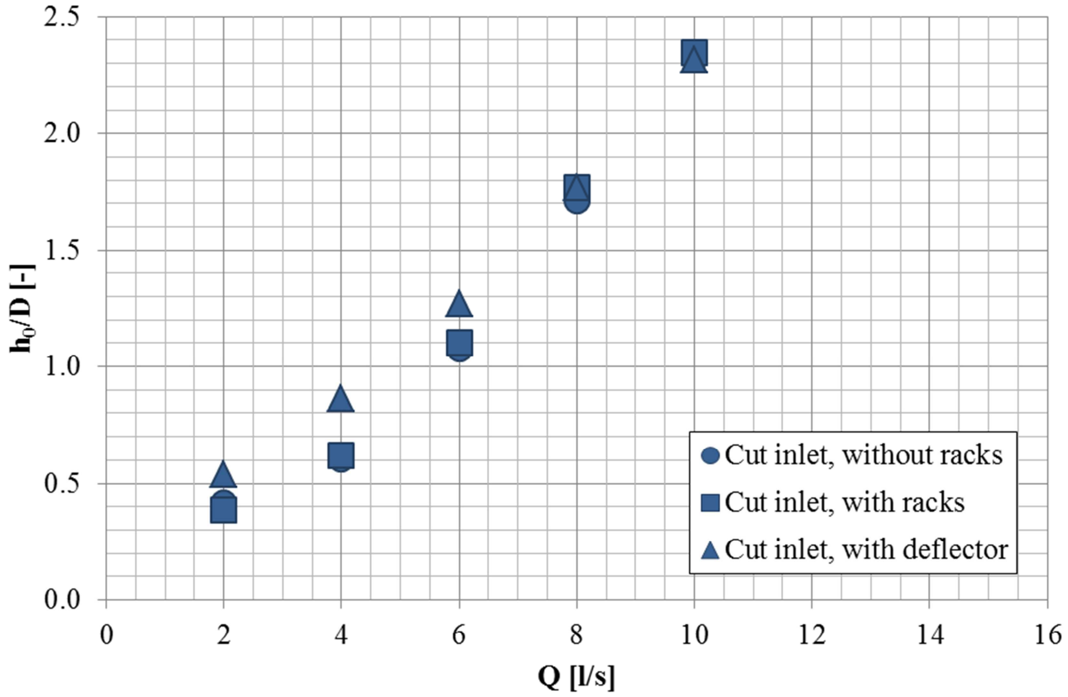


Figure A.19 Effect of sediment countermeasures at cut inlet (based on the results of Dirks (2014))

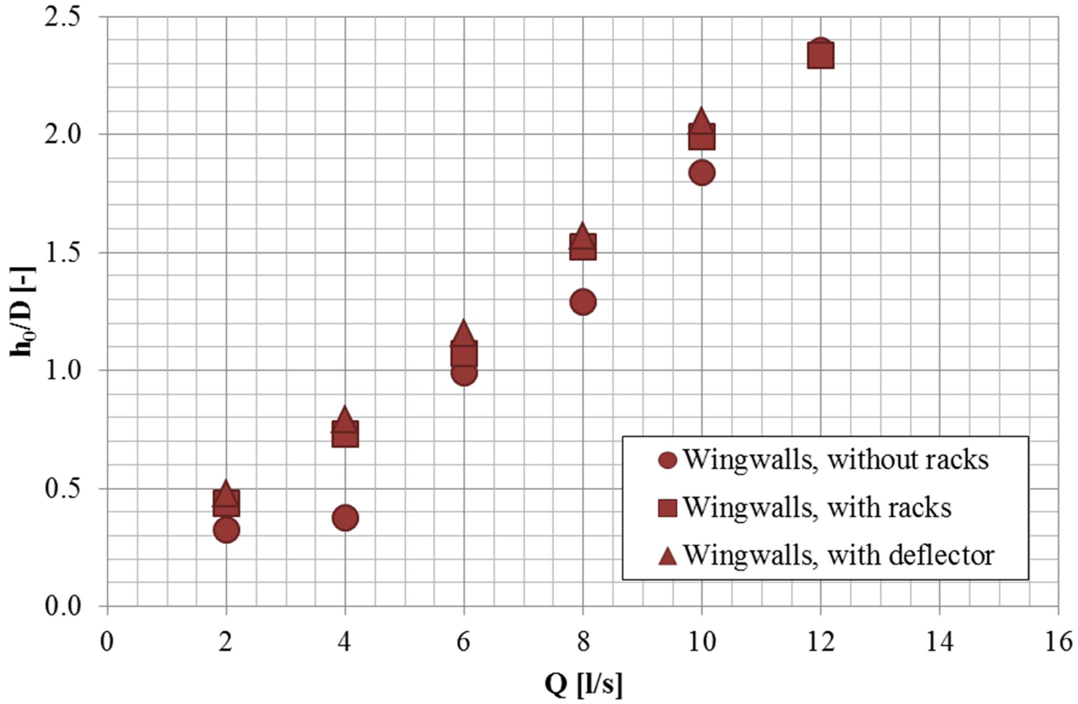


Figure A.20 Effect of sediment countermeasures at wingwalls (based on the results of Dirks (2014))

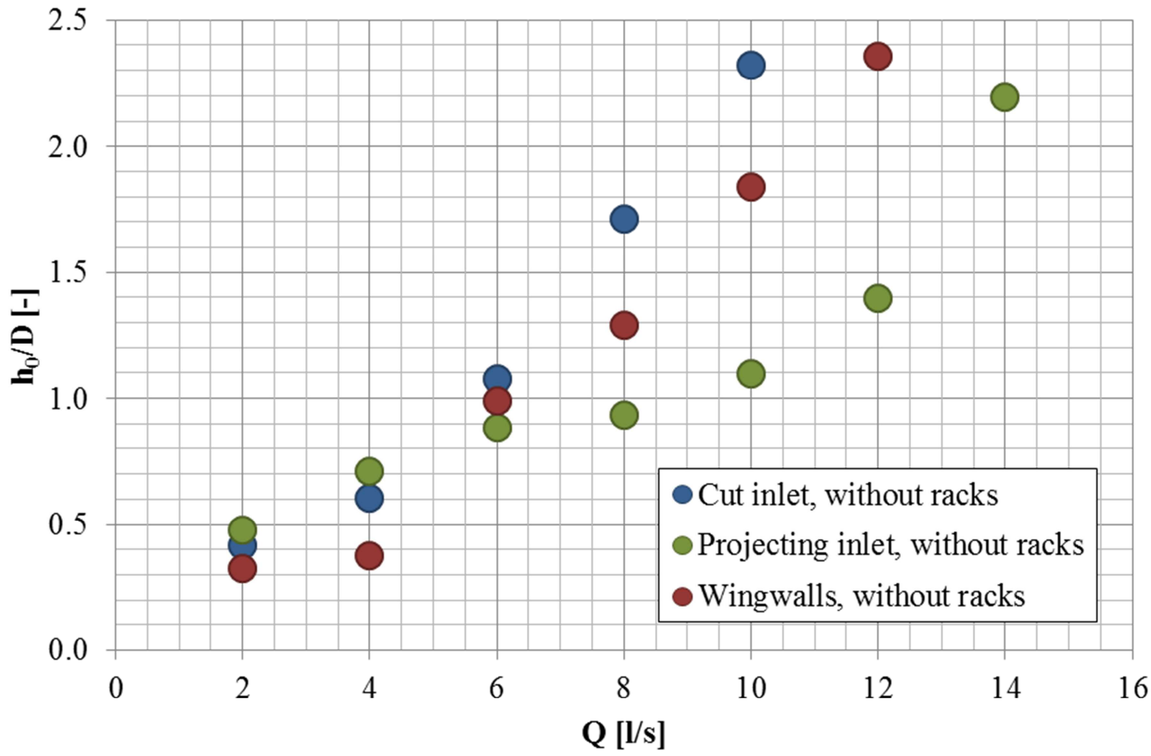


Figure A.21 Performance curves without sediment countermeasures (based on the results of Dirks (2014))

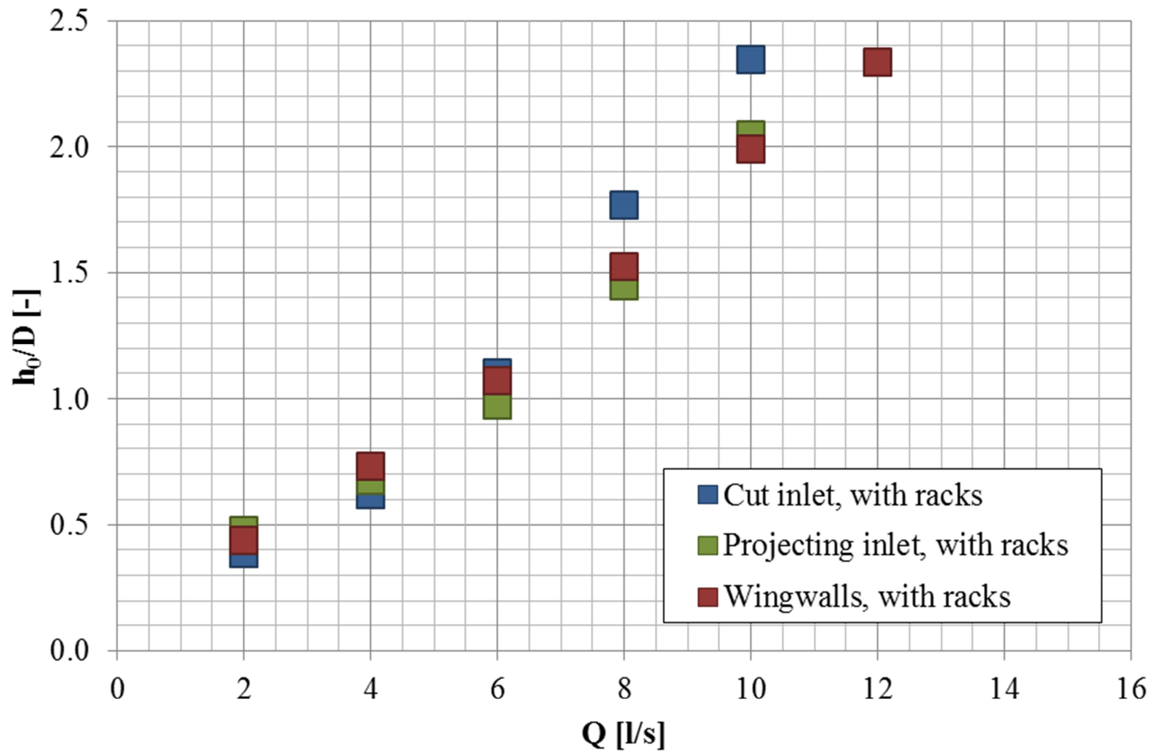


Figure A.22 Performance curves with trash racks (based on the results of Dirks (2014))

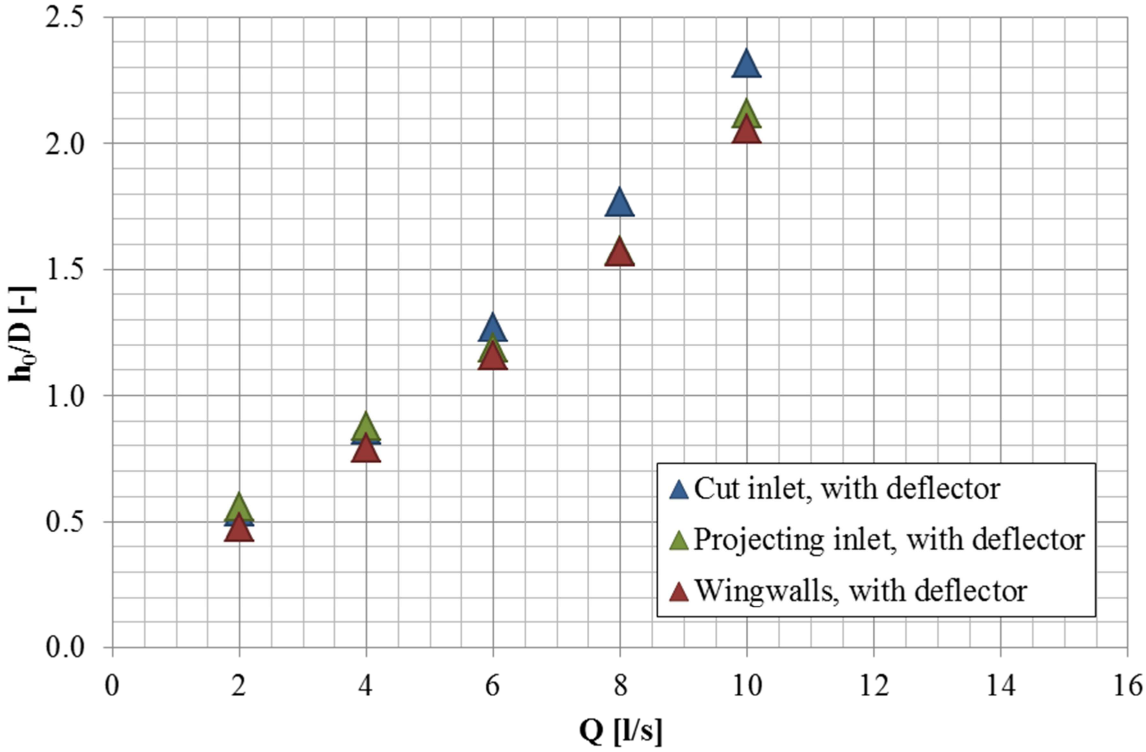


Figure A.23 Performance curves with debris deflector (based on the results of Dirks (2014))

B. Experiments with sediments

This section presents the effect diagrams for the experiments which were carried out with sediments for the different setups.

Effect of sediment size:

Slope: 1:5, Basin length: 625 mm, Basin width: 1110 mm, without energy dissipation, 5 kg gradually fed sediment

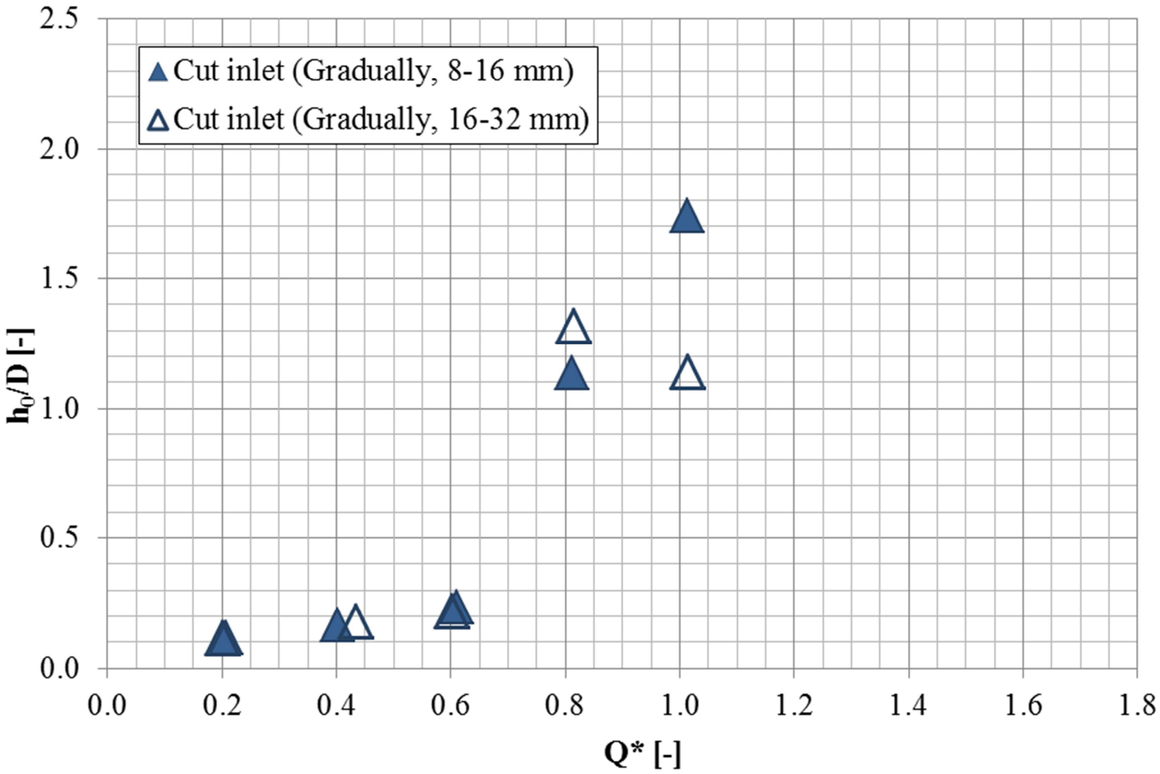


Figure B.1 Sediment size effect on the culvert capacity – Cut inlet (based on the results of Gotvassli (2013))

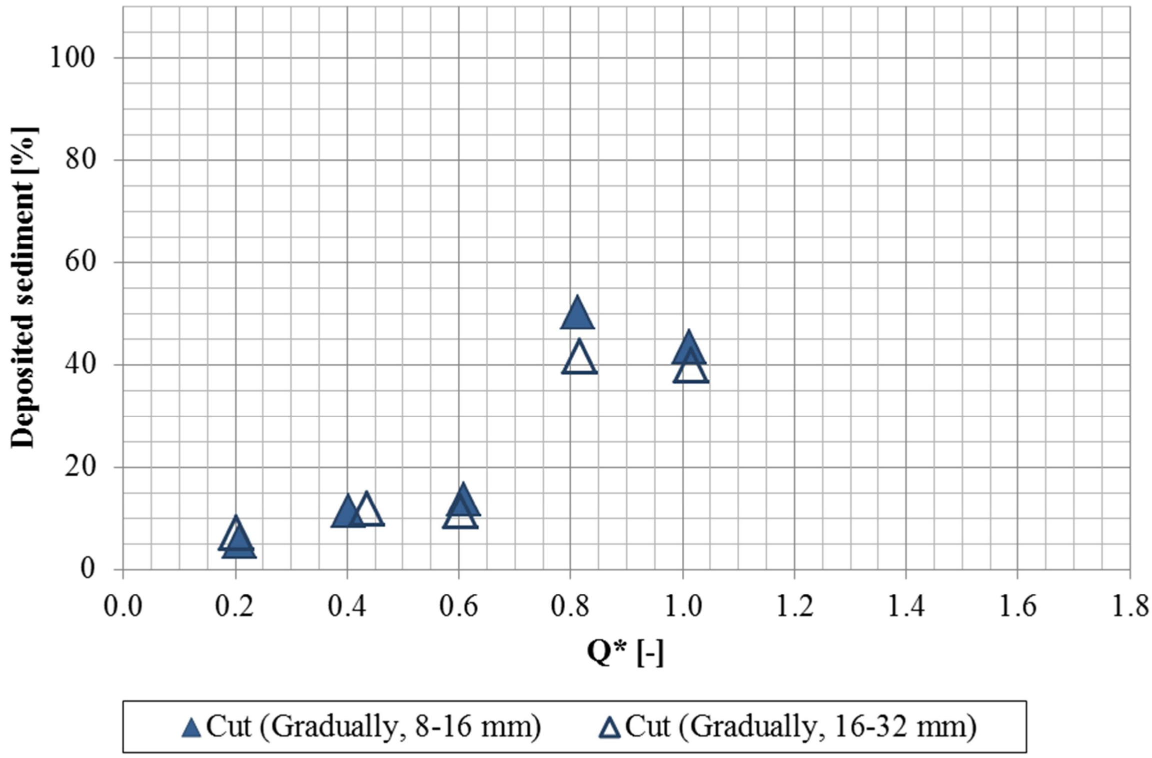


Figure B.2 Sediment size effect on the deposited sediment amount – Cut inlet (based on the results of Gotvassli (2013))

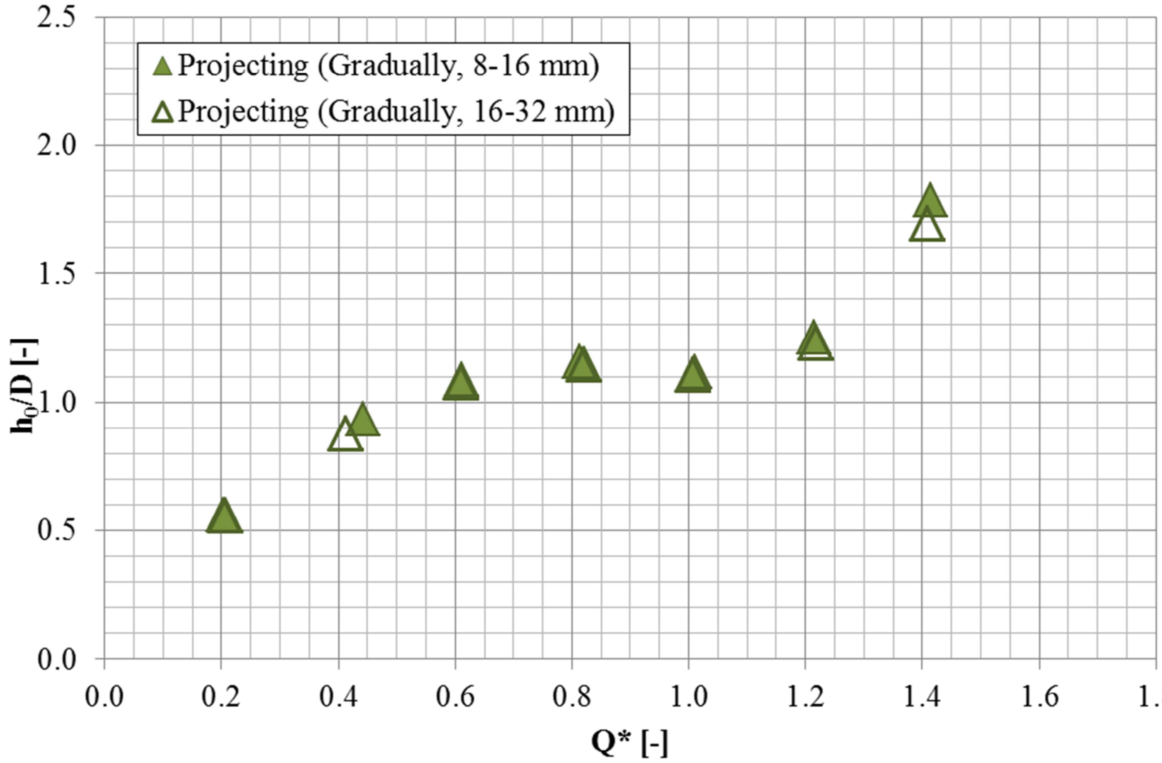


Figure B.3 Sediment size effect on the culvert capacity – Projecting inlet (based on the results of Gotvassli (2013))

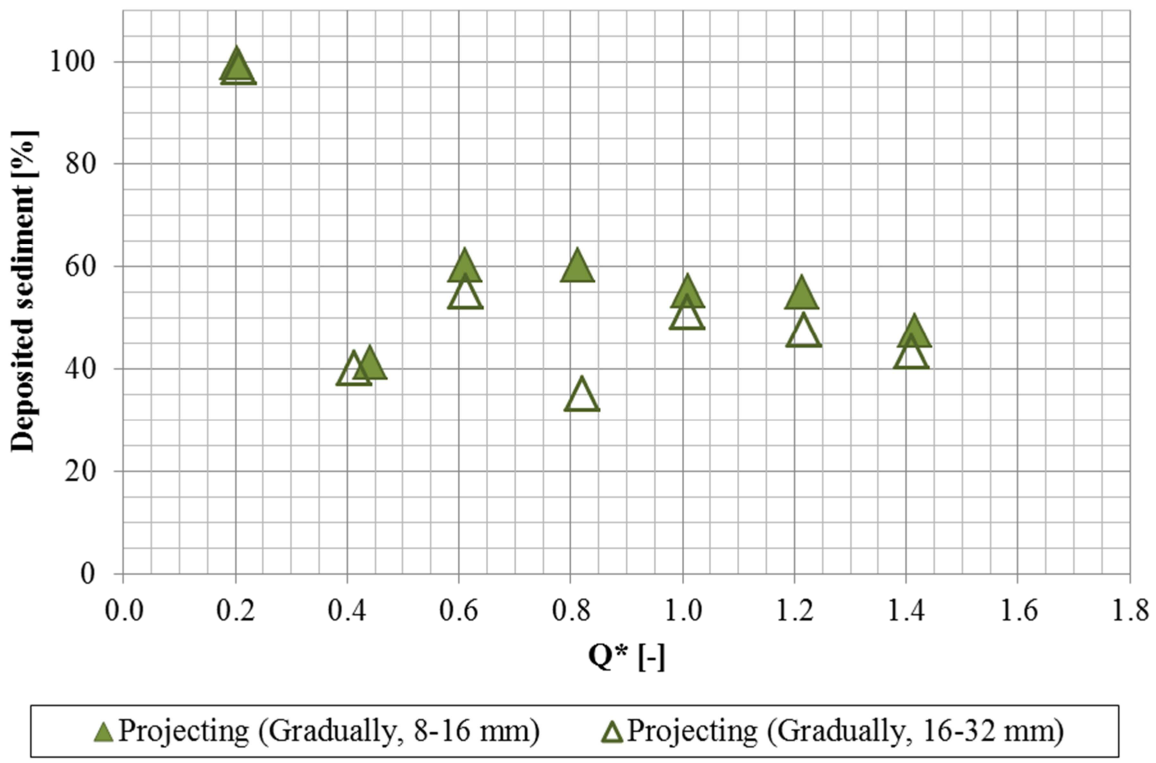


Figure B.4 Sediment size effect on the deposited sediment amount – Projecting inlet (based on the results of Gotvassli (2013))

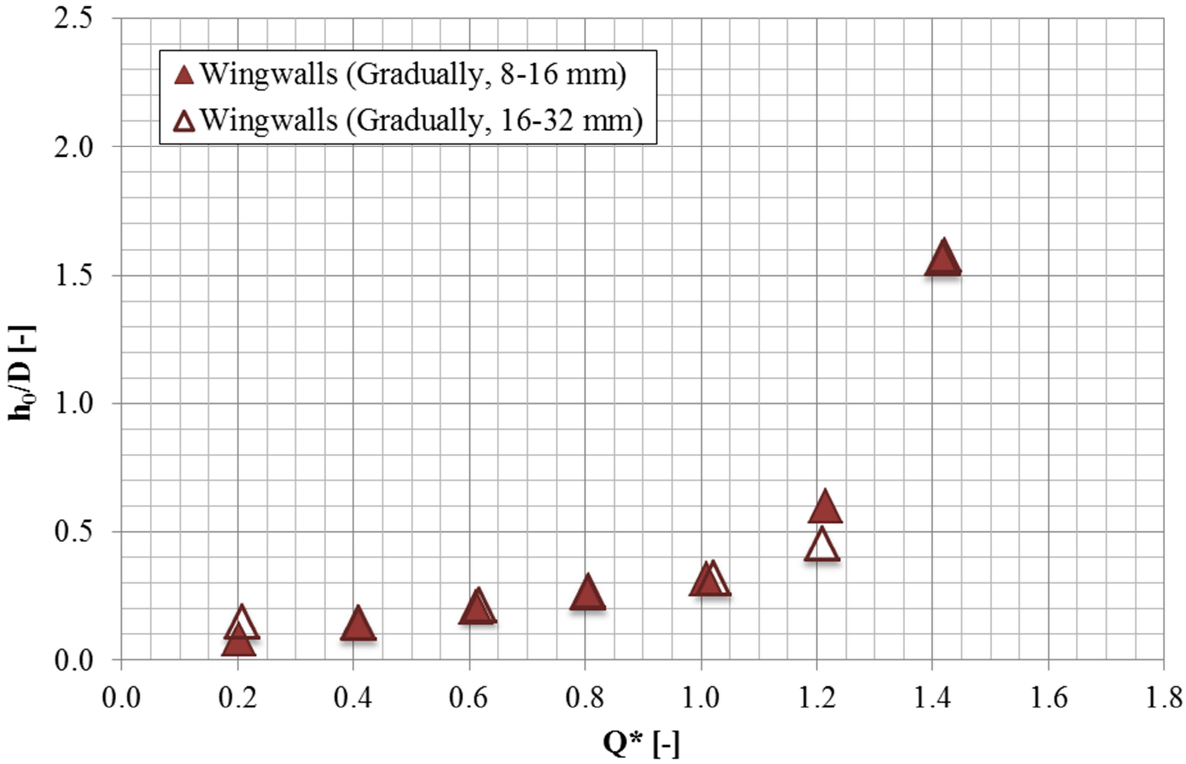


Figure B.5 Sediment size effect on the culvert capacity – Wingwalls (based on the results of Gotvassli (2013))

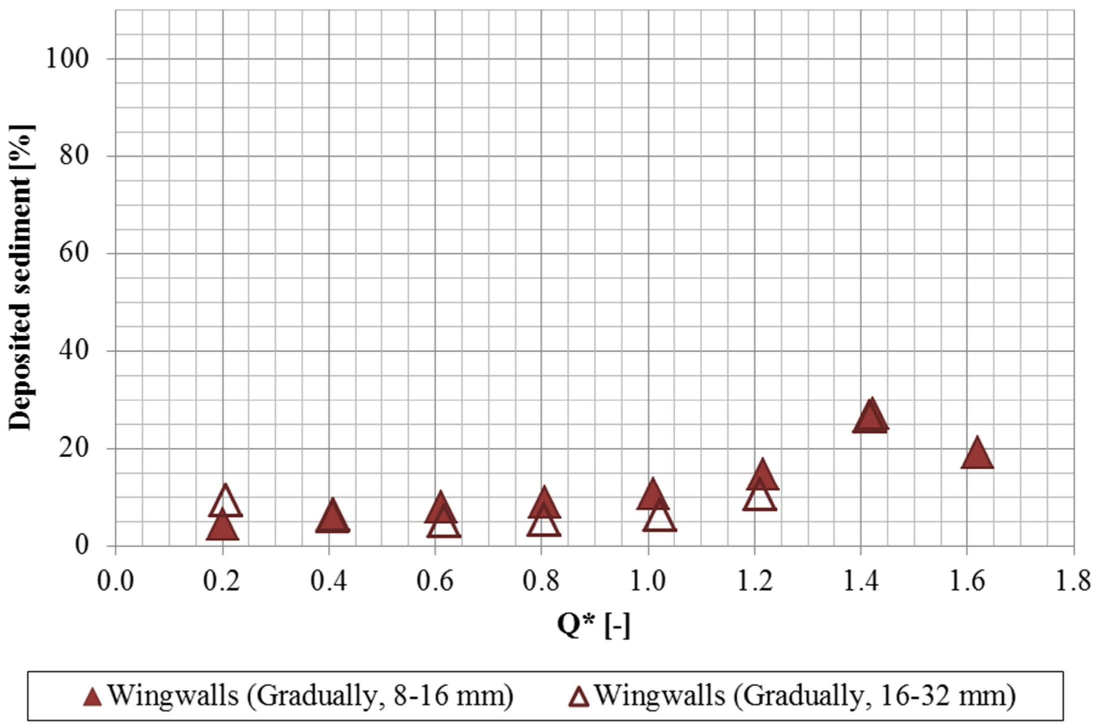


Figure B.6 Sediment size effect on the deposited sediment amount – Wingwalls (based on the results of Gotvassli (2013))

Slope: 1:9, Basin length: 876 mm, Basin width: 876 mm, with energy dissipation, 7 kg sediment

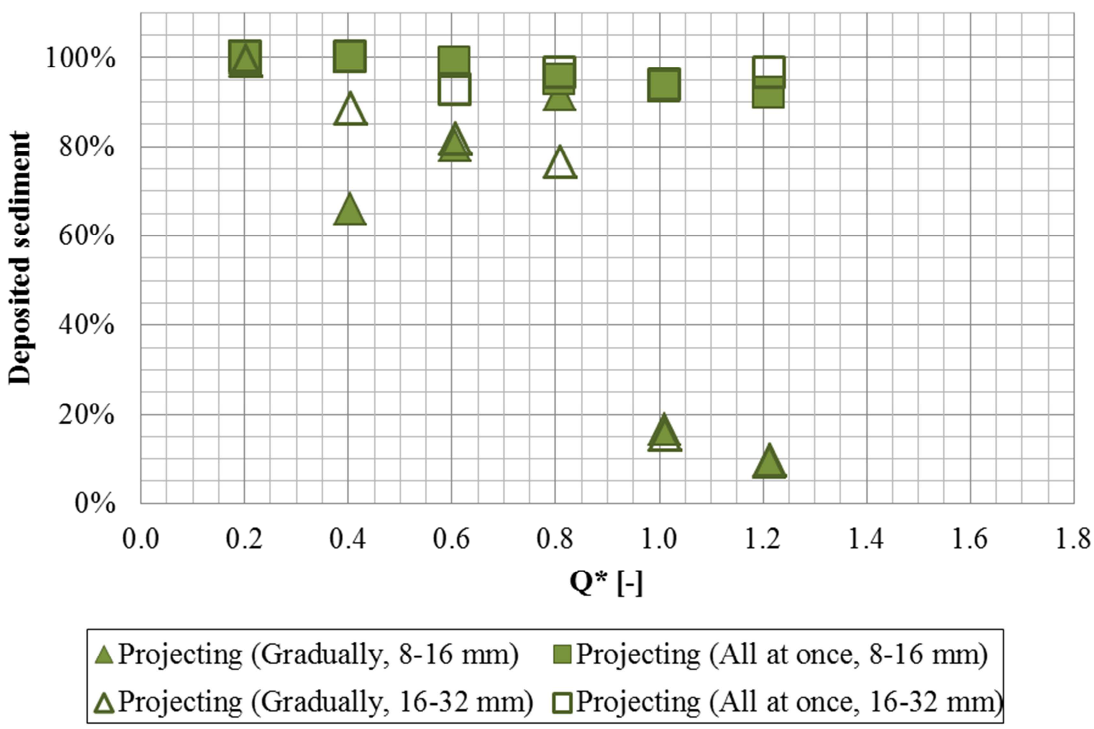


Figure B.7 Sediment size effect on the deposited sediment amount – Projecting inlet (based on the results of Putri (2014))

Effect of sediment amount:

Slope: 1:5, Basin length: 876 mm, Basin width: 1110 mm, without energy dissipation, gradually fed sediment

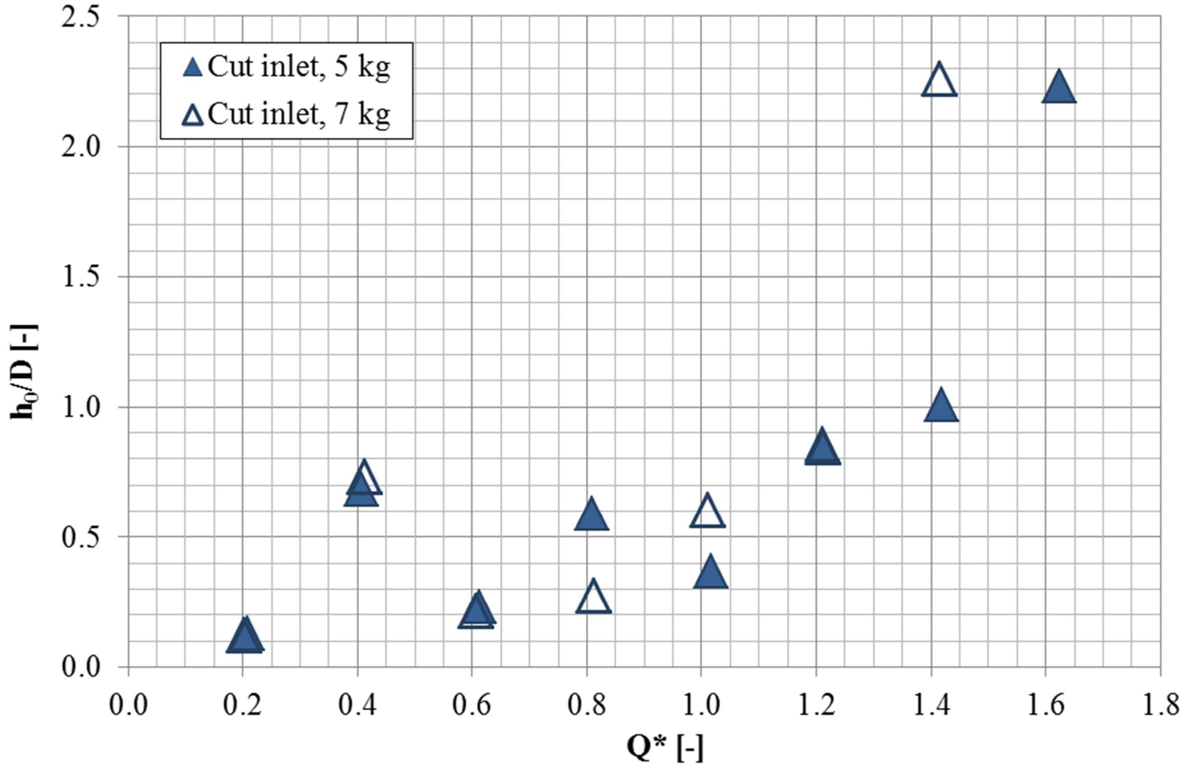


Figure B.8 Sediment amount effect on the culvert capacity – Cut inlet (based on the results of Gotvassli (2013))

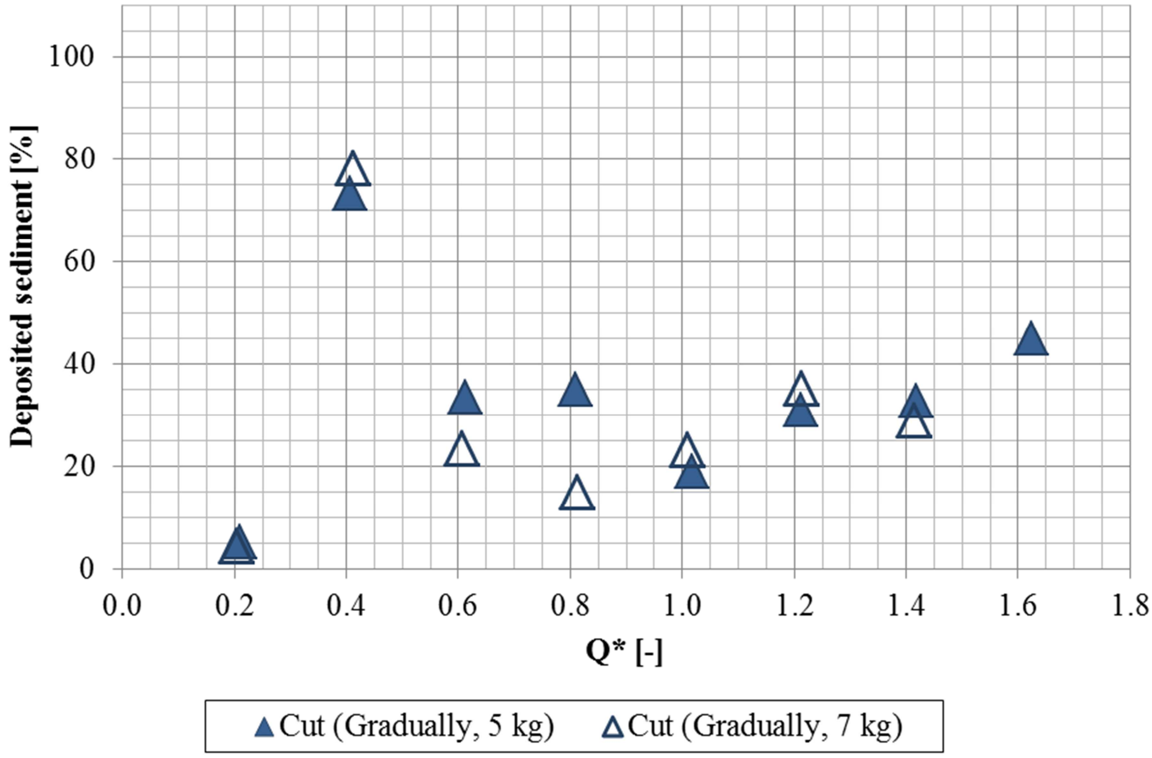


Figure B.9 Sediment amount effect on the deposited sediment amount – Cut inlet (based on the results of Gotvassli (2013))

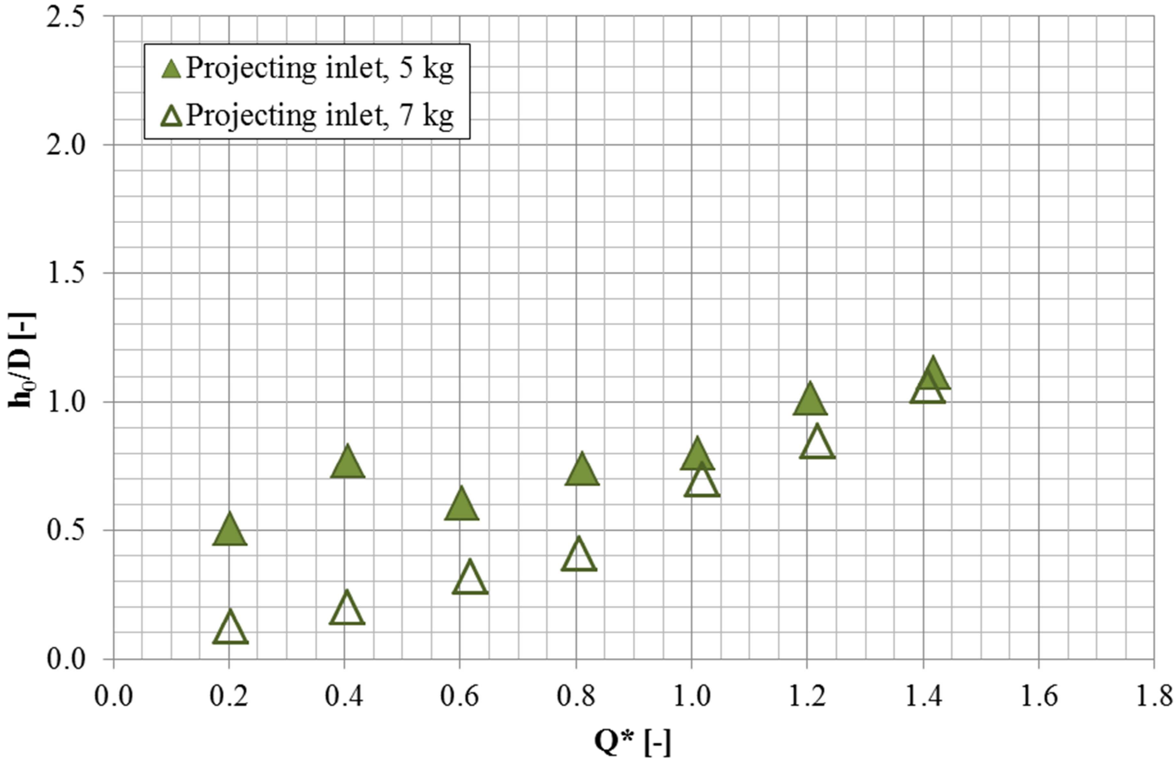


Figure B.10 Sediment amount effect on the culvert capacity – Projecting inlet (based on the results of Gotvassli (2013))

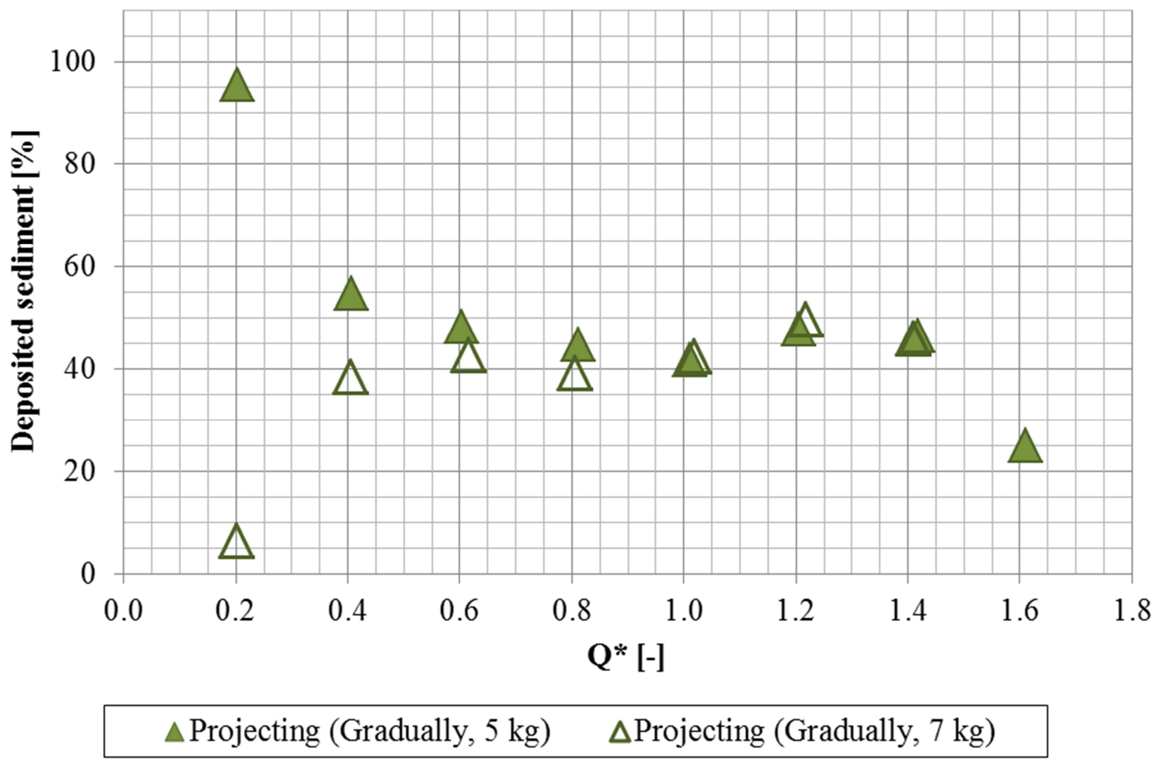


Figure B.11 Sediment amount effect on the deposited sediment amount – Projecting inlet (based on the results of Gotvassli (2013))

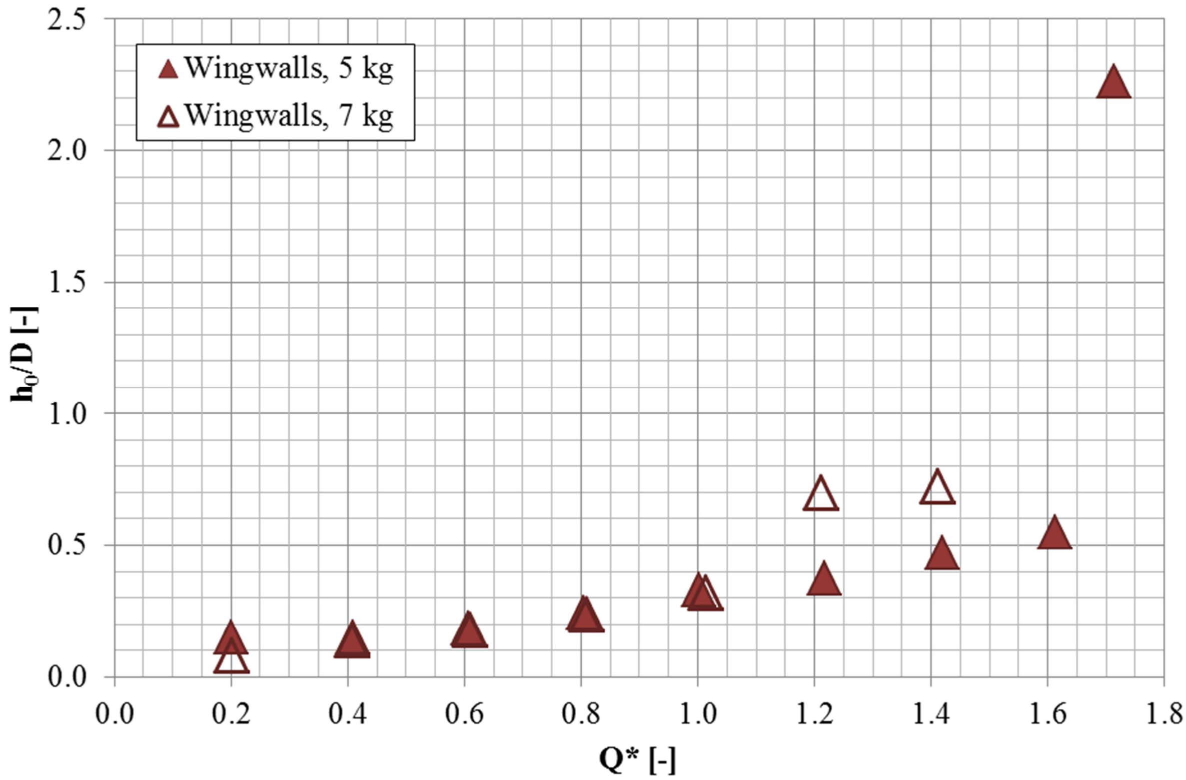


Figure B.12 Sediment amount effect on the culvert capacity – Wingwalls (based on the results of Gotvassli (2013))

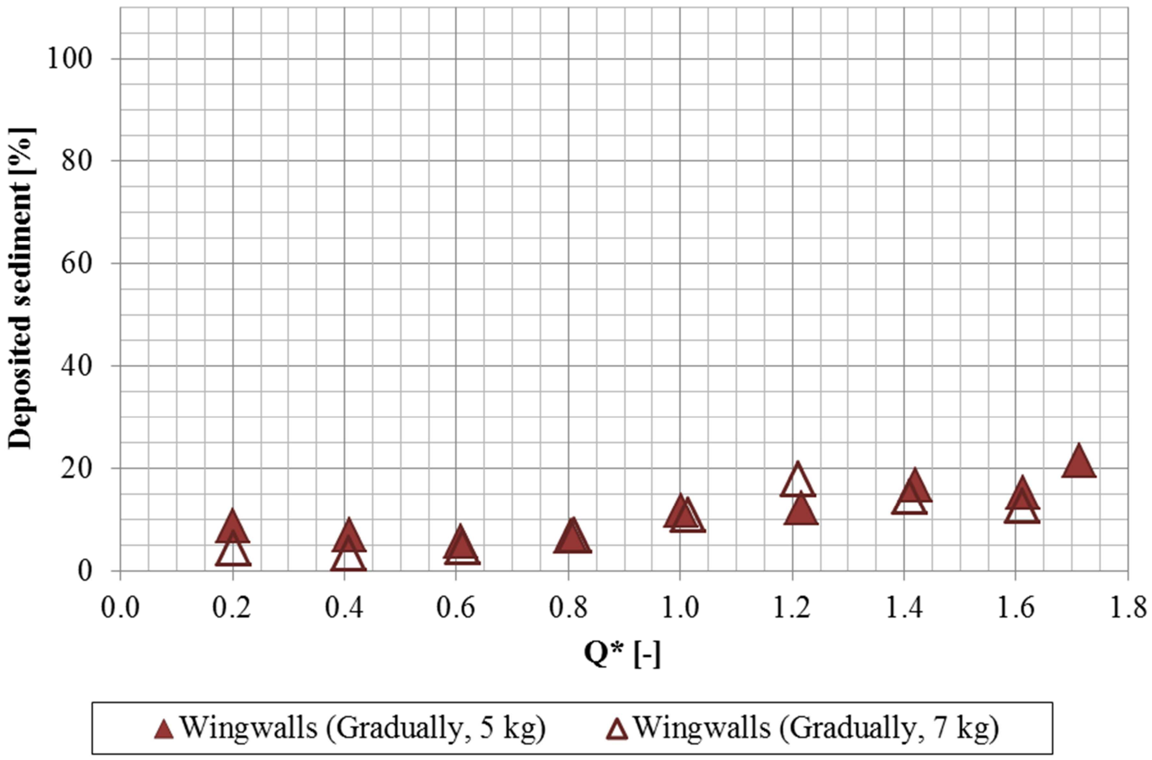


Figure B.13 Sediment amount effect on the deposited sediment amount – Wingwalls (based on the results of Gotvassli (2013))

Slope: 1:9, Basin length: 876 mm, Basin width: 876 mm, with energy dissipation, 8-16 mm sized sediment

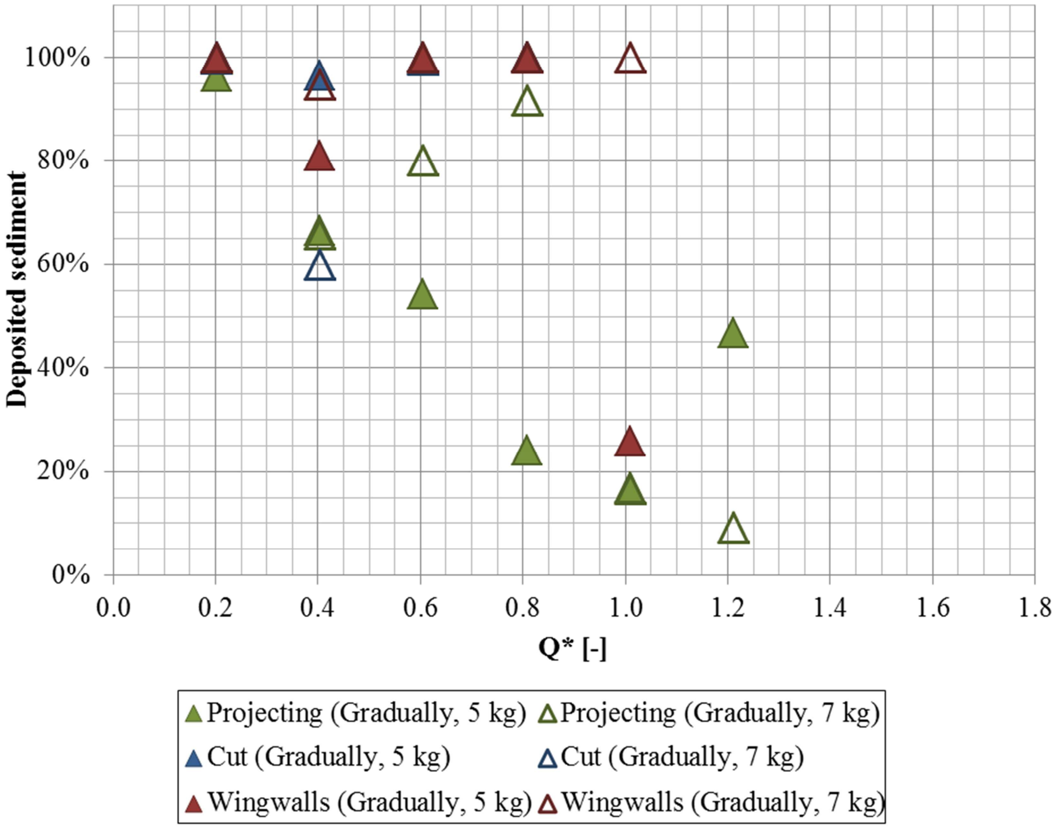


Figure B.14 Sediment amount effect on the deposited sediment amount – Gradually fed sediment (based on the results of Putri (2014))

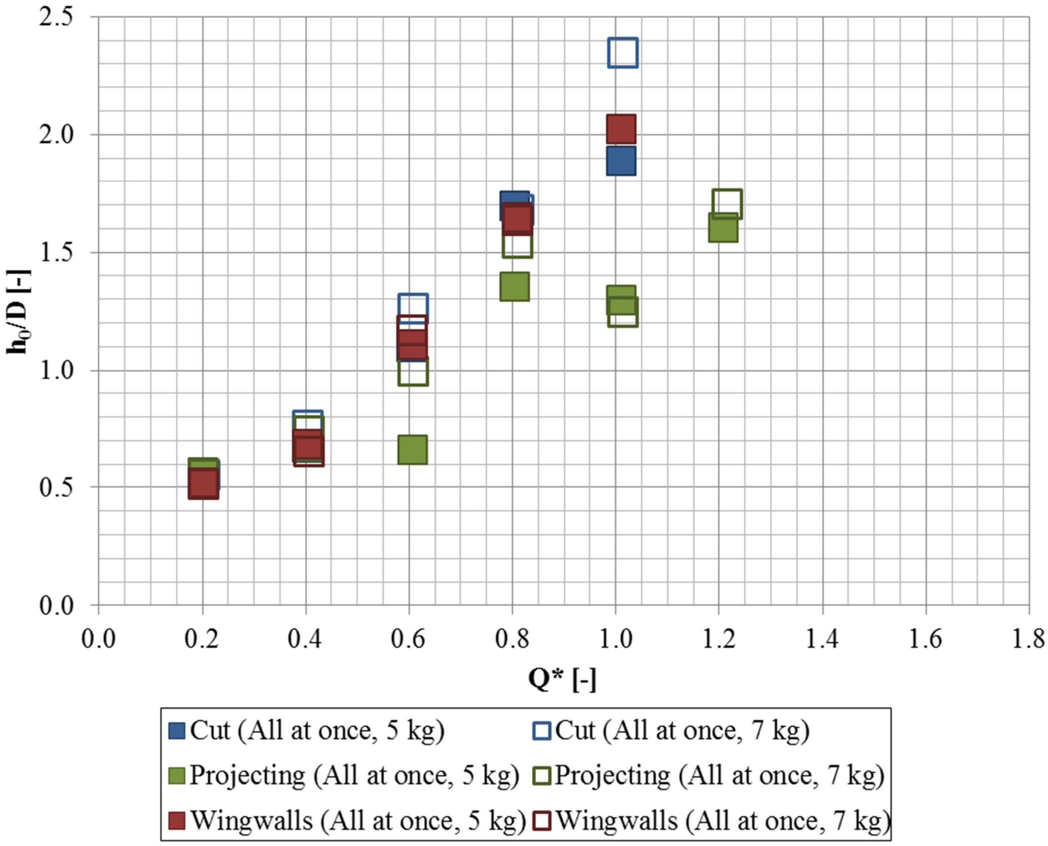


Figure B.15 Sediment amount effect on the culvert capacity – All at once fed sediment (based on the results of Putri (2014))

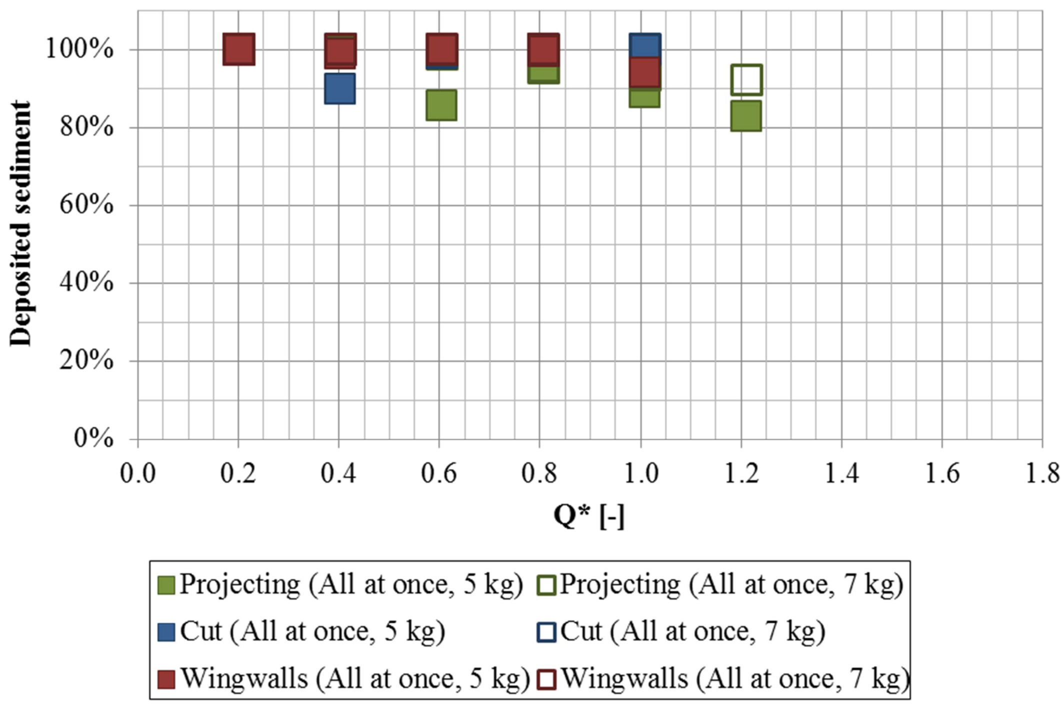


Figure B.16 Sediment amount effect on the deposited sediment amount – All at once fed sediment (based on the results of Putri (2014))

Slope: 1:9, Basin length: 876 mm, Basin width: 1100 mm, with energy dissipation, 8-16 mm sized gradually fed sediment (Faqiri)

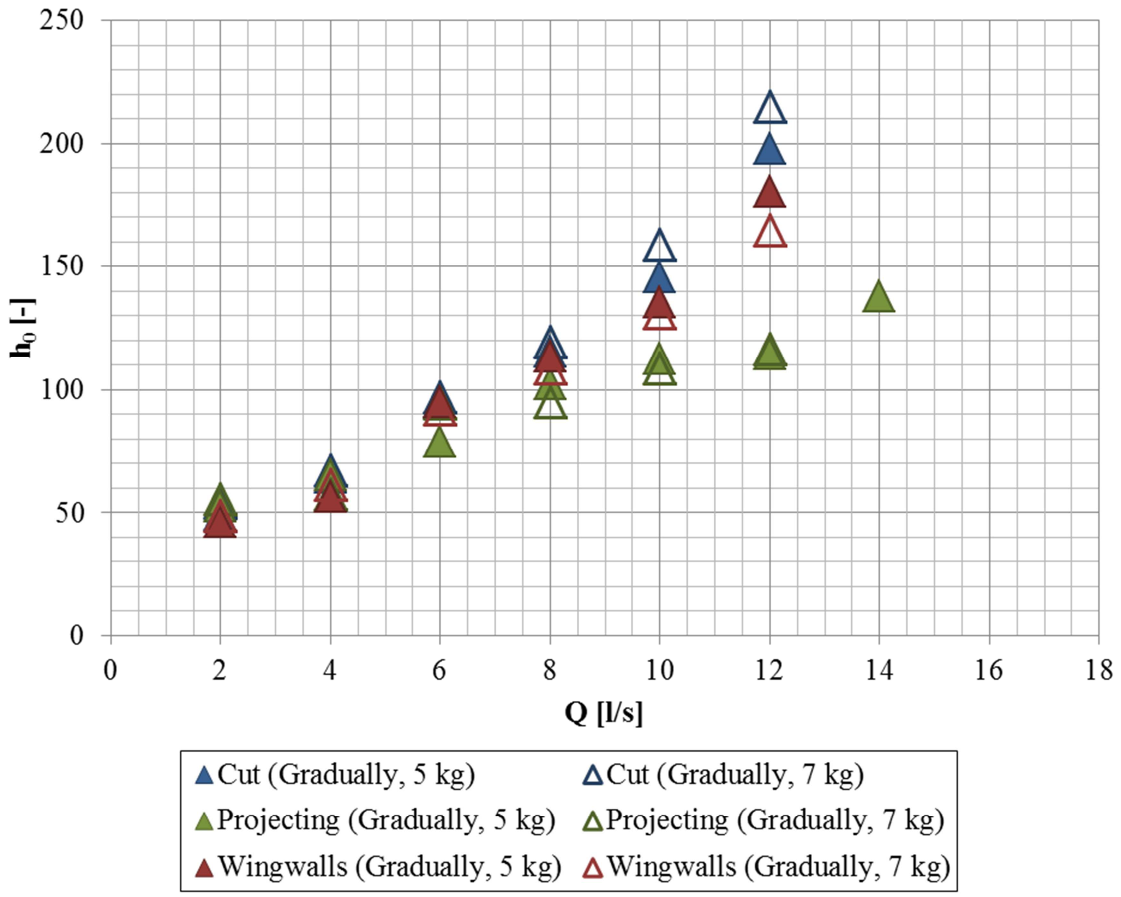


Figure B.17 Sediment amount effect on the culvert capacity (based on the results of Faqiri (2014))

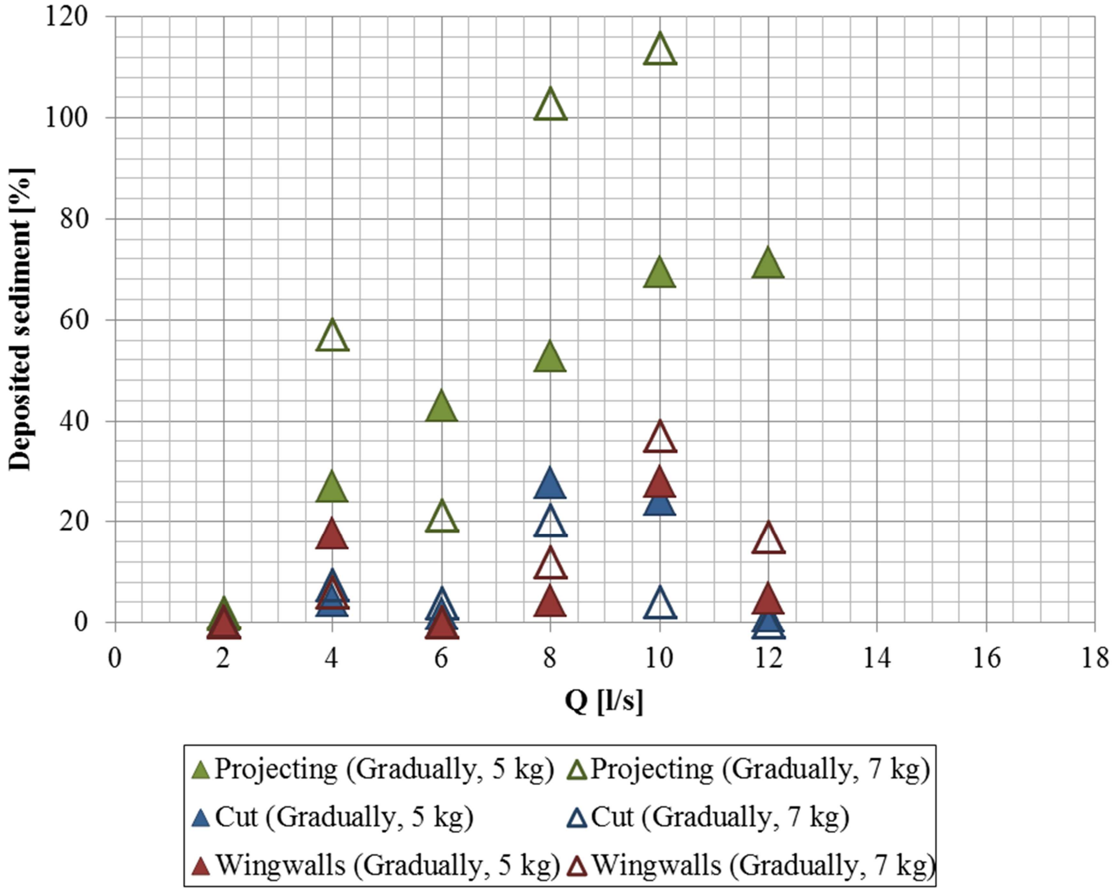


Figure B.18 Sediment amount effect on the deposited sediment amount (based on the results of Faqiri (2014))

Energy dissipation and slope effect: Basin length: 876 mm, Basin width: 1100 mm

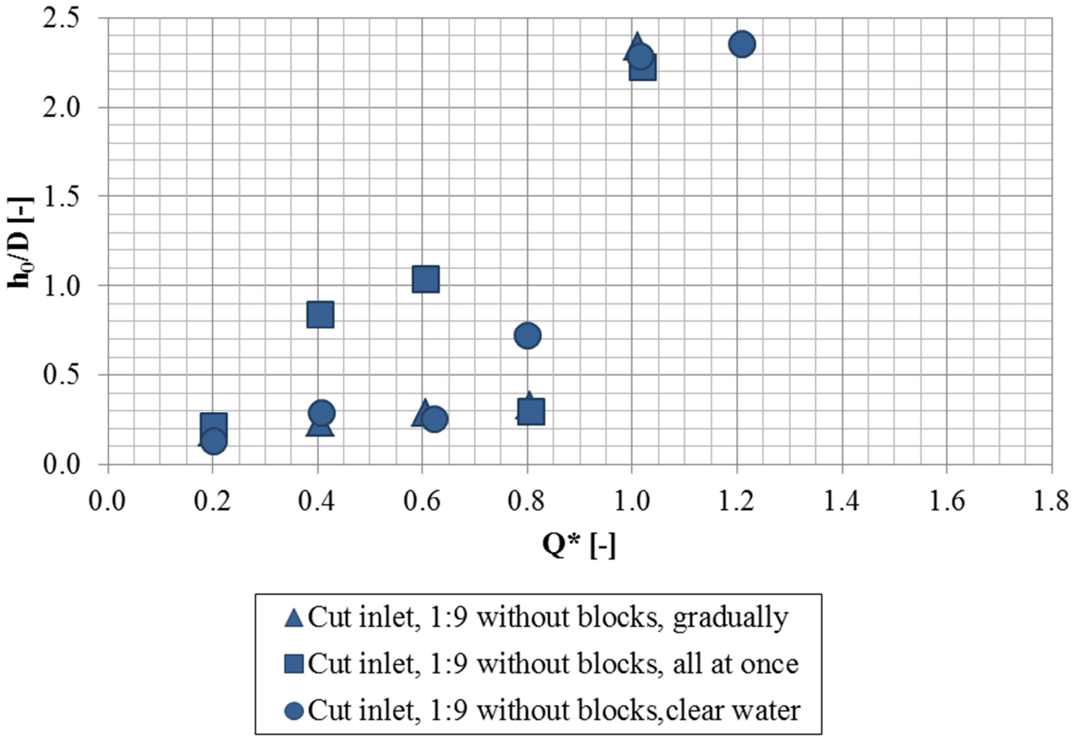


Figure B.19 Culvert capacity with cut inlet under sediment transport – slope 1:9 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

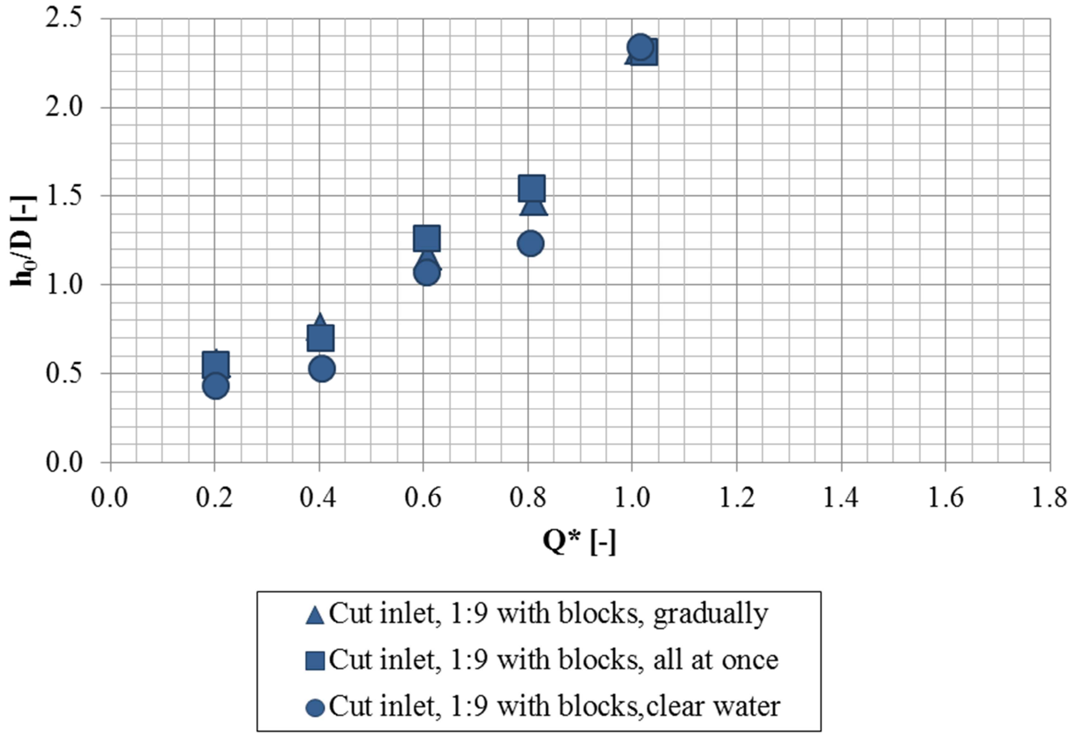


Figure B.20 Culvert capacity with cut inlet under sediment transport – slope 1:9 with blocks (based on the results of Gotvassli (2013) and Hendler (2014))

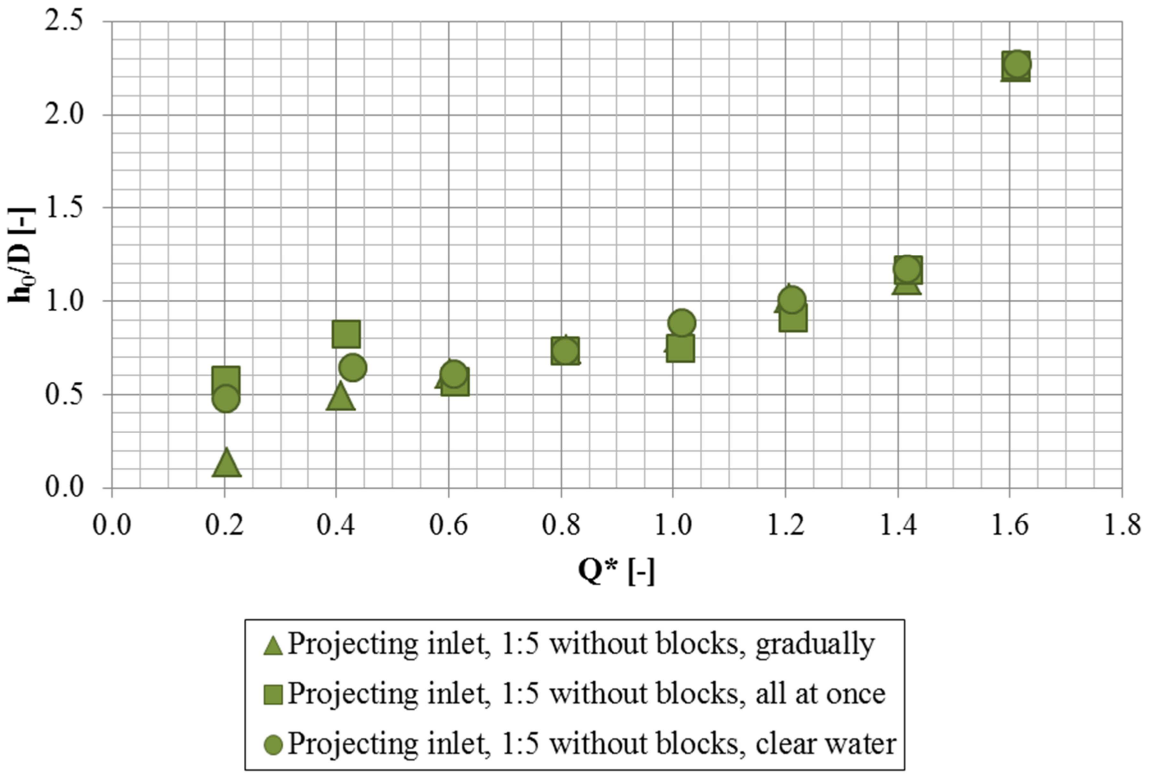


Figure B.21 Culvert capacity with projecting inlet under sediment transport – slope 1:5 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

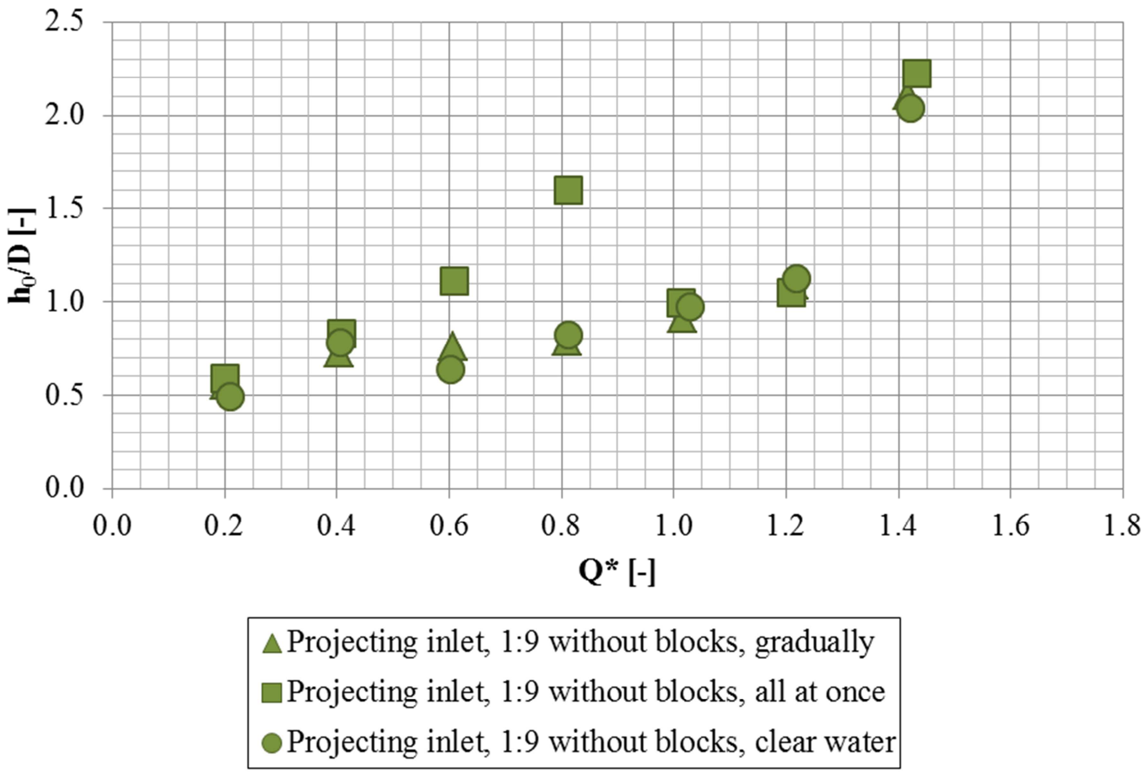


Figure B.22 Culvert capacity with projecting inlet under sediment transport – slope 1:9 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

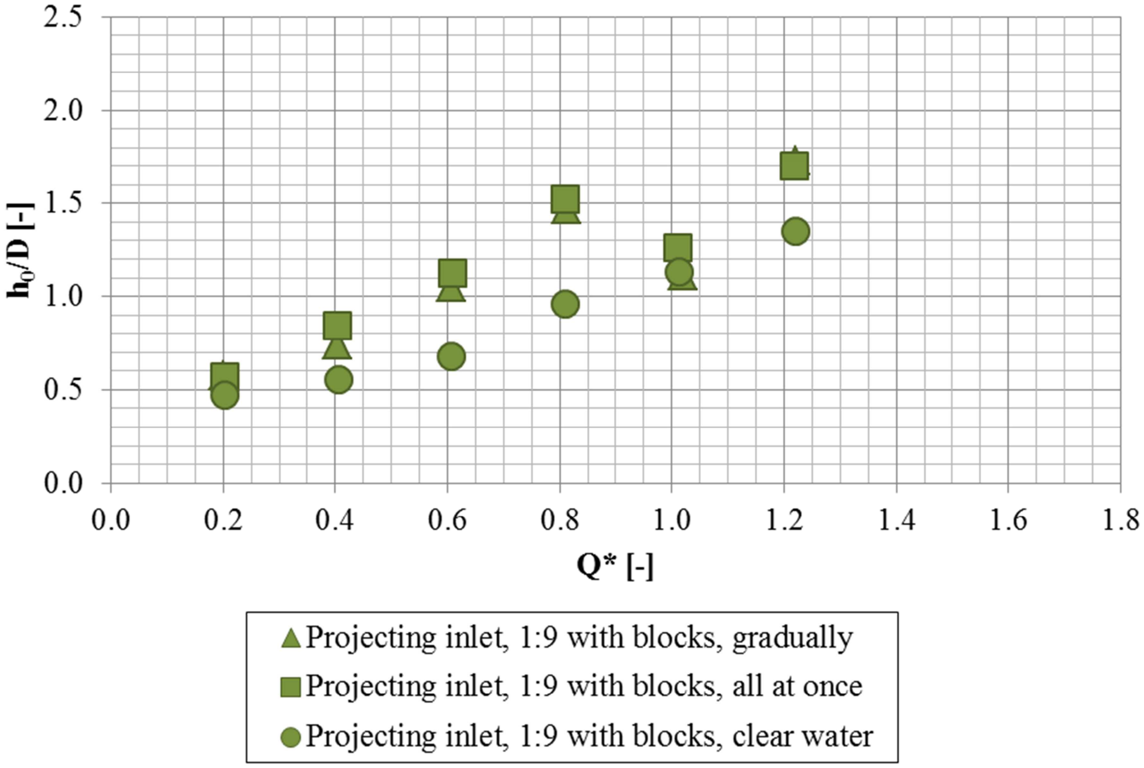


Figure B.23 Culvert capacity with projecting inlet under sediment transport – slope 1:9 with blocks (based on the results of Gotvassli (2013) and Hendler (2014))

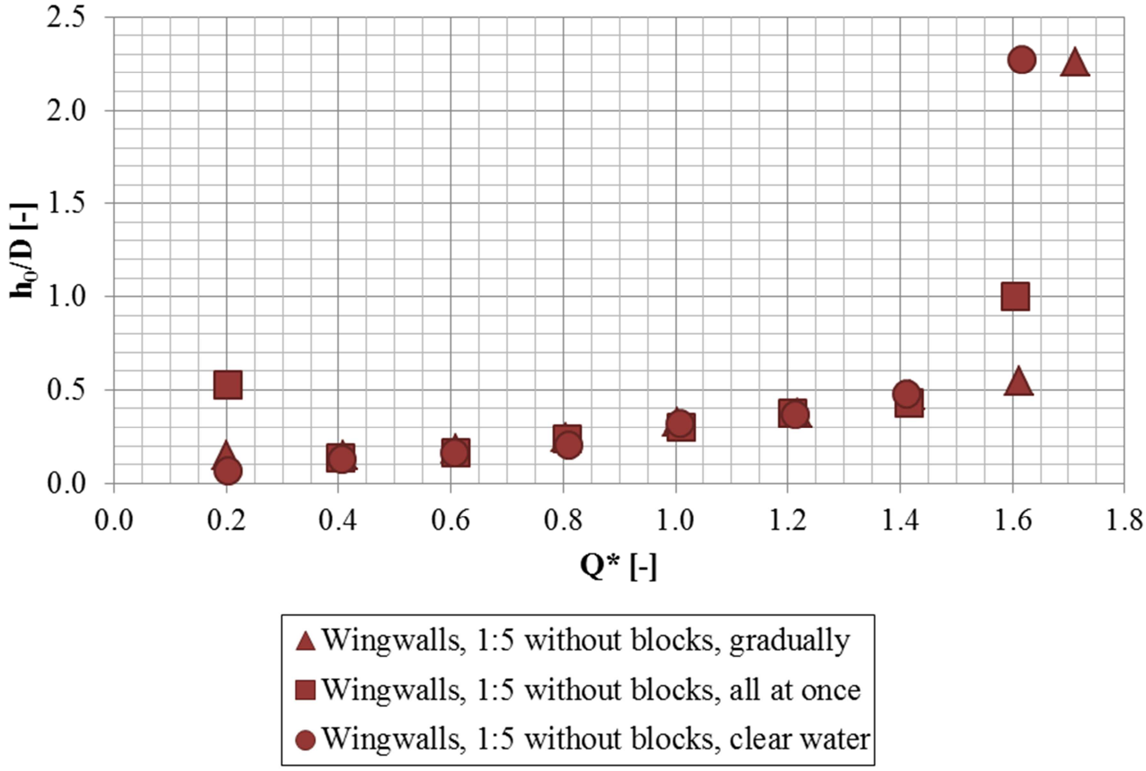


Figure B.24 Culvert capacity with wingwalls under sediment transport – slope 1:5 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

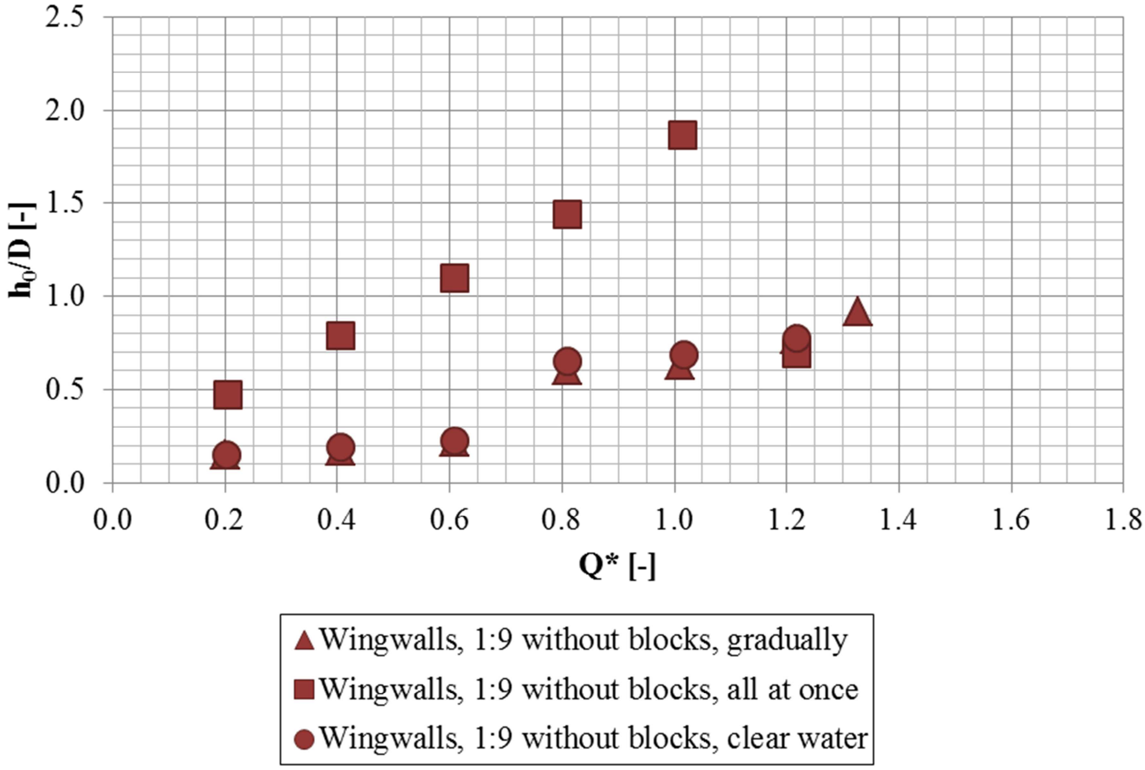


Figure B.25 Culvert capacity with wingwalls under sediment transport – slope 1:9 without blocks (based on the results of Gotvassli (2013) and Hendler (2014))

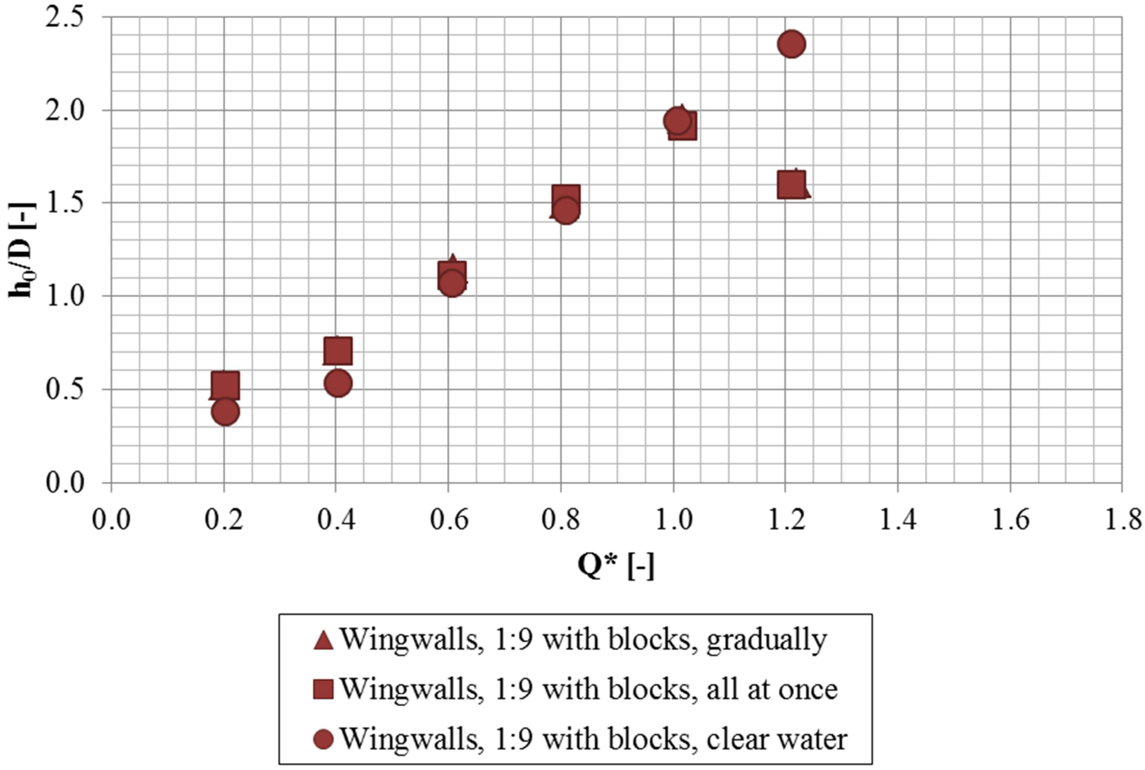


Figure B.26 Culvert capacity with wingwalls under sediment transport – slope 1:9 with blocks (based on the results of Gotvassli (2013) and Hendler (2014))

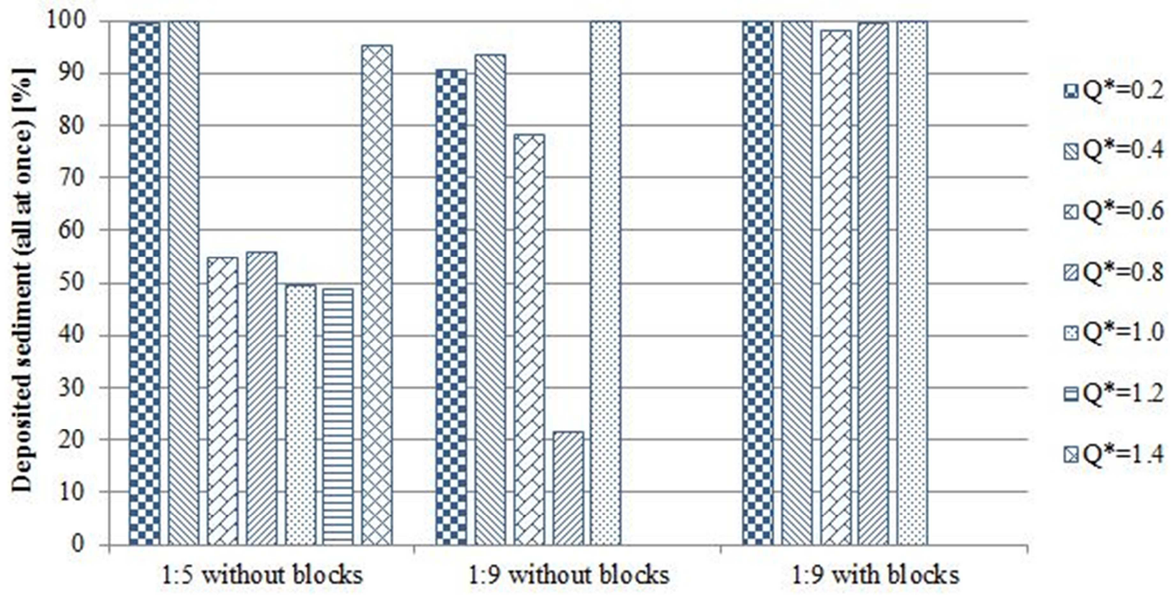


Figure B.27 Deposited sediment amount in case of cut inlet with all at once feeding slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

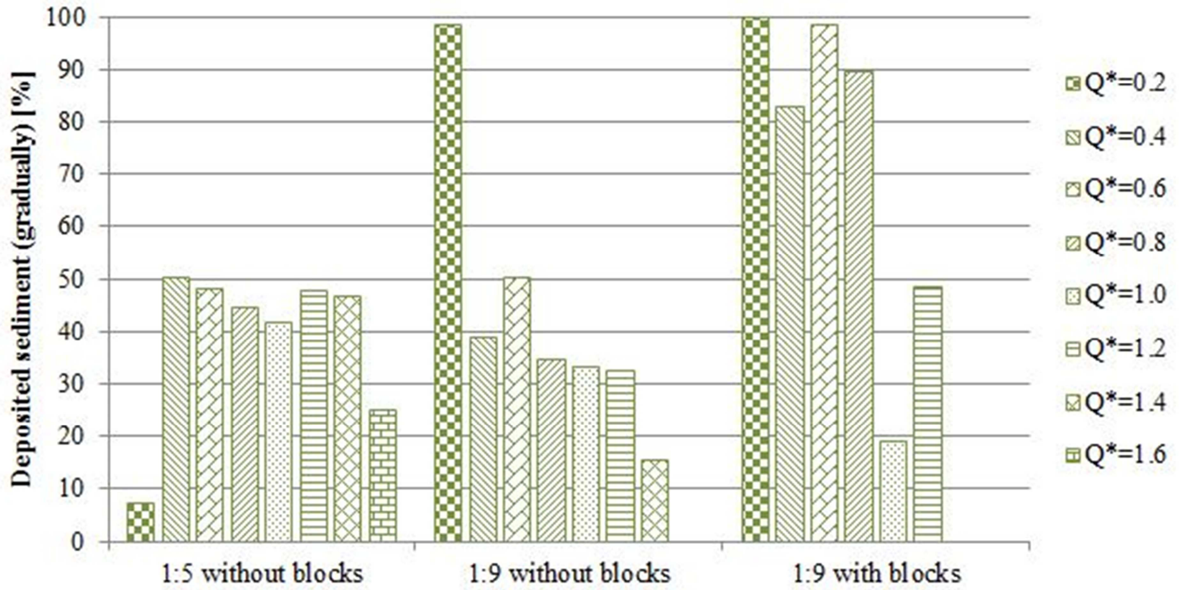


Figure B.28 Deposited sediment amount in case of projecting inlet with gradually feeding slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

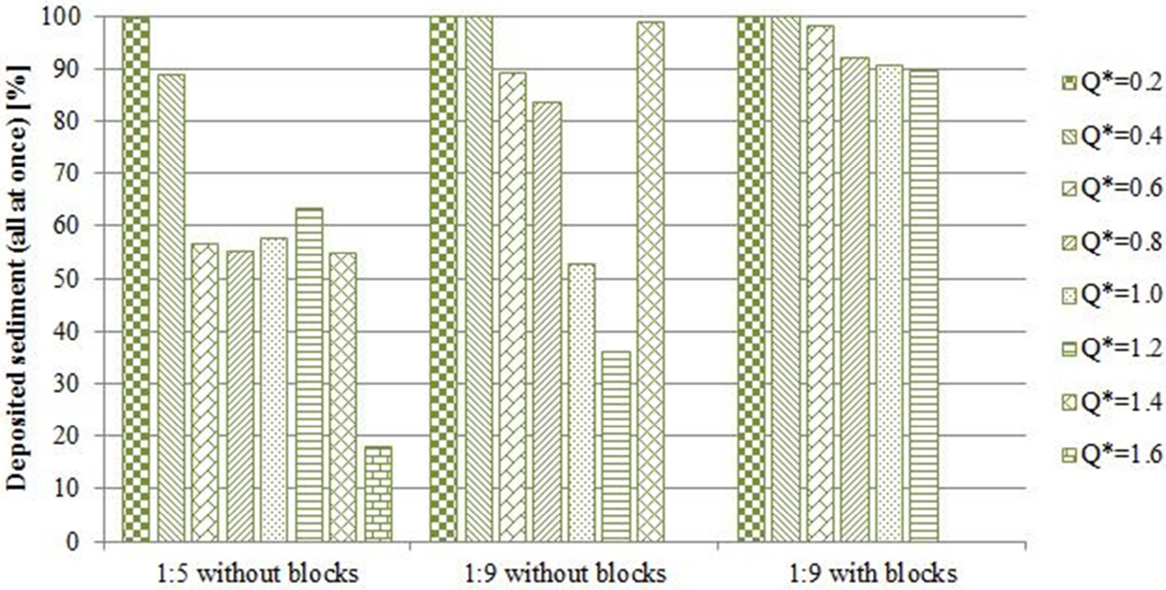


Figure B.29 Deposited sediment amount in case of projecting inlet with all at once feeding slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

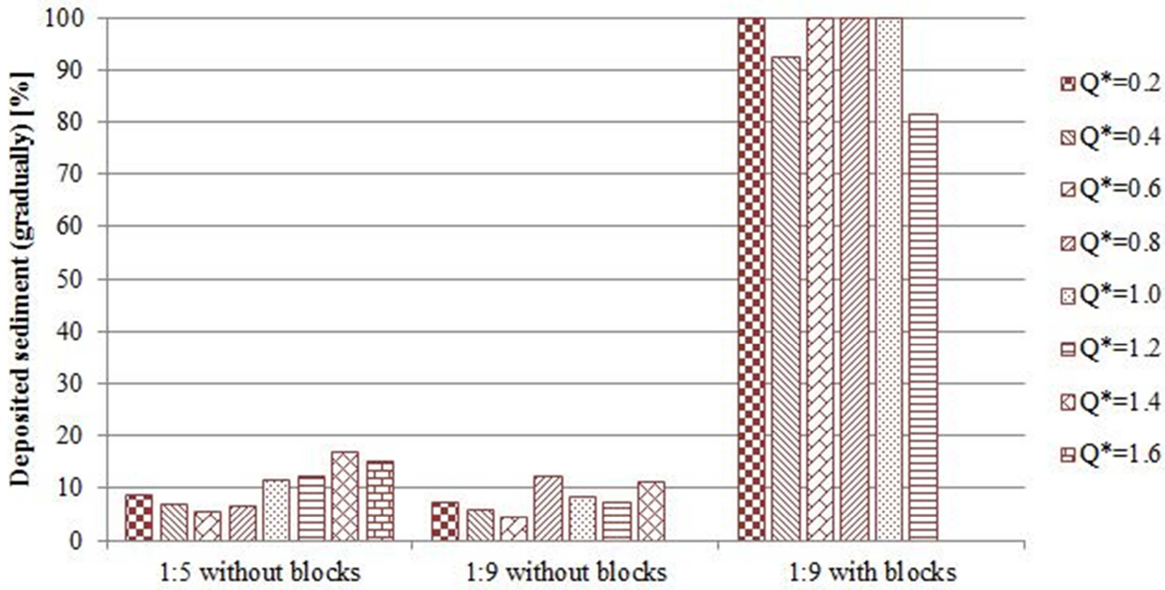


Figure B.30 Deposited sediment amount in case of wingwalls with gradually feeding slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

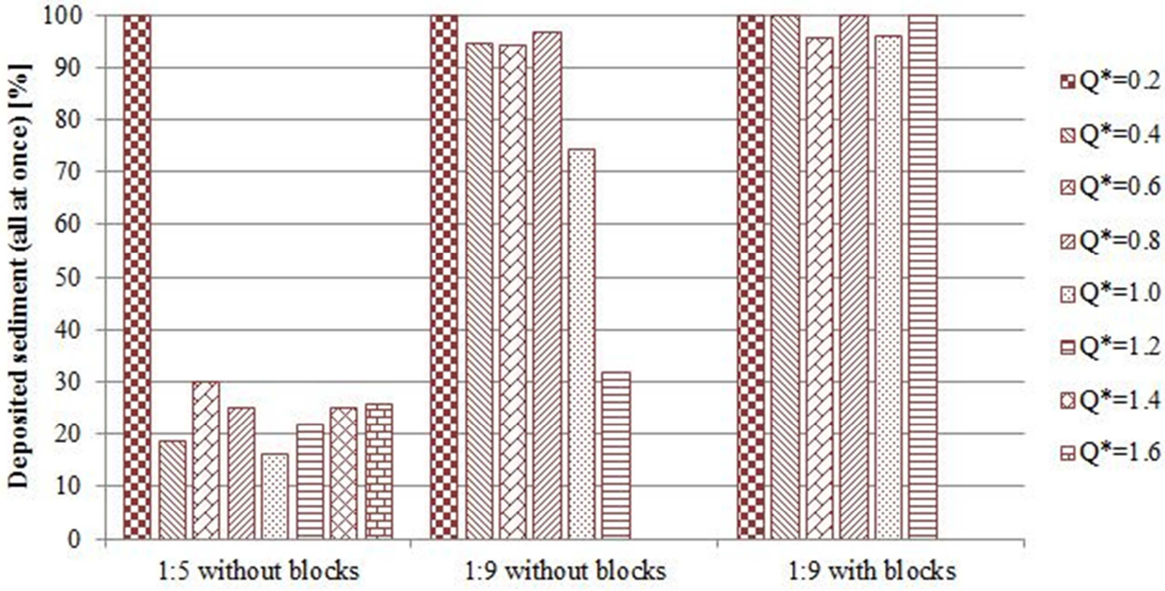


Figure B.31 Deposited sediment amount in case of wingwalls with all at once feeding slope effect (based on the results of Gotvassli (2013) and Hendler (2014))

Basin length effect: Slope: 1:5, Basin width: 1110 mm

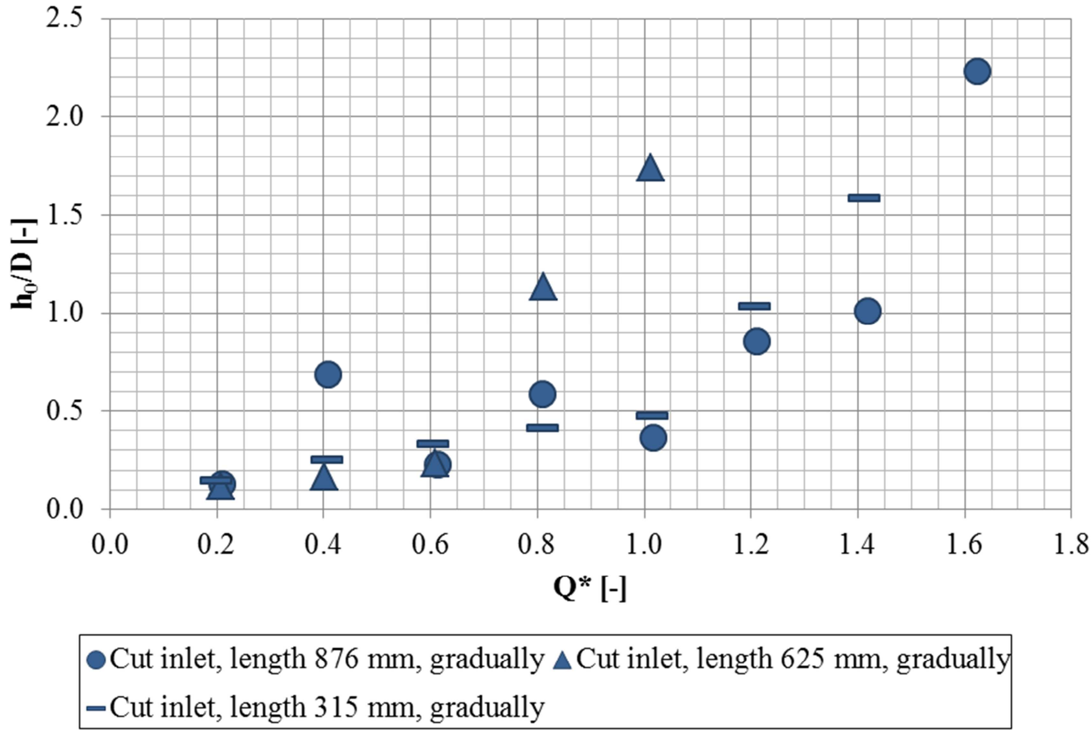


Figure B.32 Culvert capacity with cut inlet under sediment transport – length effect with gradually feeding (based on the results of Gotvassli (2013))

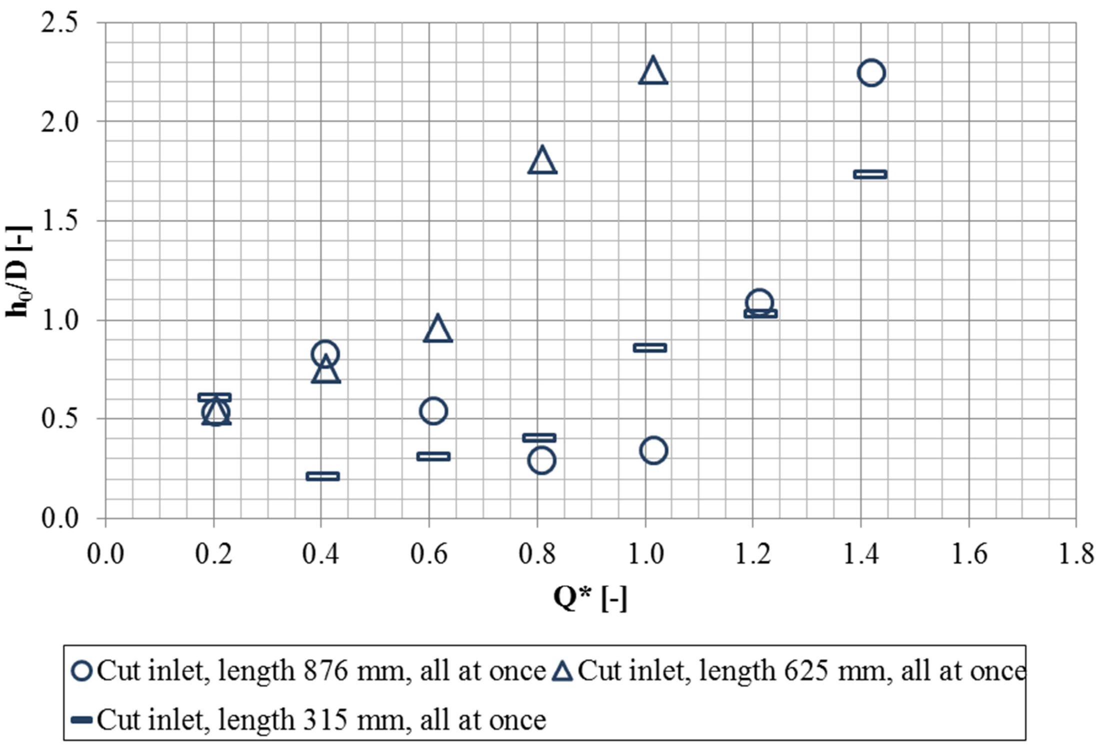


Figure B.33 Culvert capacity with cut inlet under sediment transport – length effect with all at once feeding (based on the results of Gotvassli (2013))

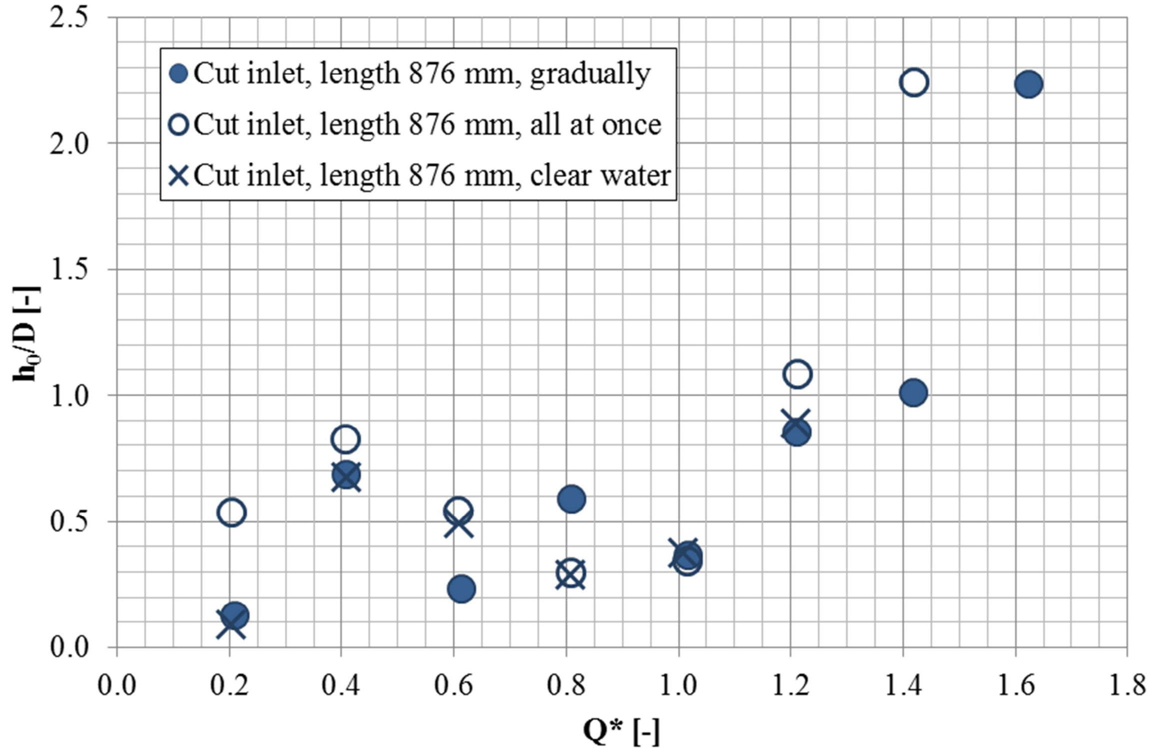


Figure B.34 Culvert capacity with cut inlet under sediment transport – feeding effect with 876 mm basin length (based on the results of Gotvassli (2013))

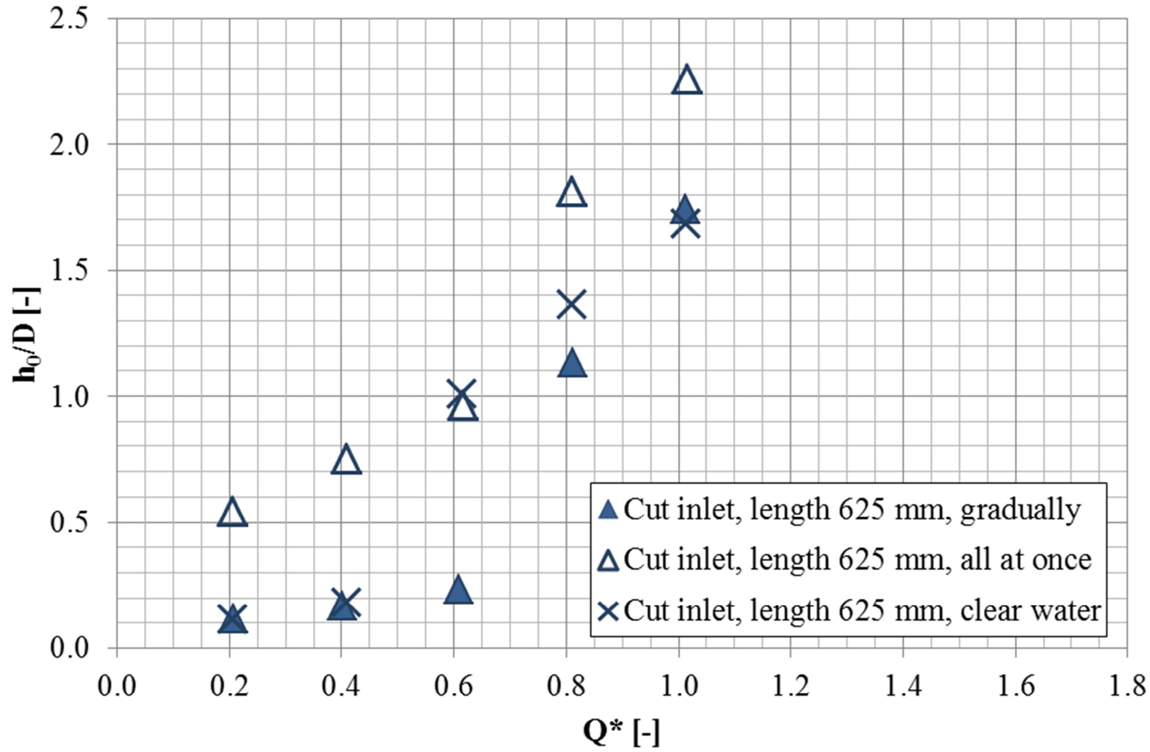


Figure B.35 Culvert capacity with cut inlet under sediment transport – feeding effect with 625 mm basin length (based on the results of Gotvassli (2013))

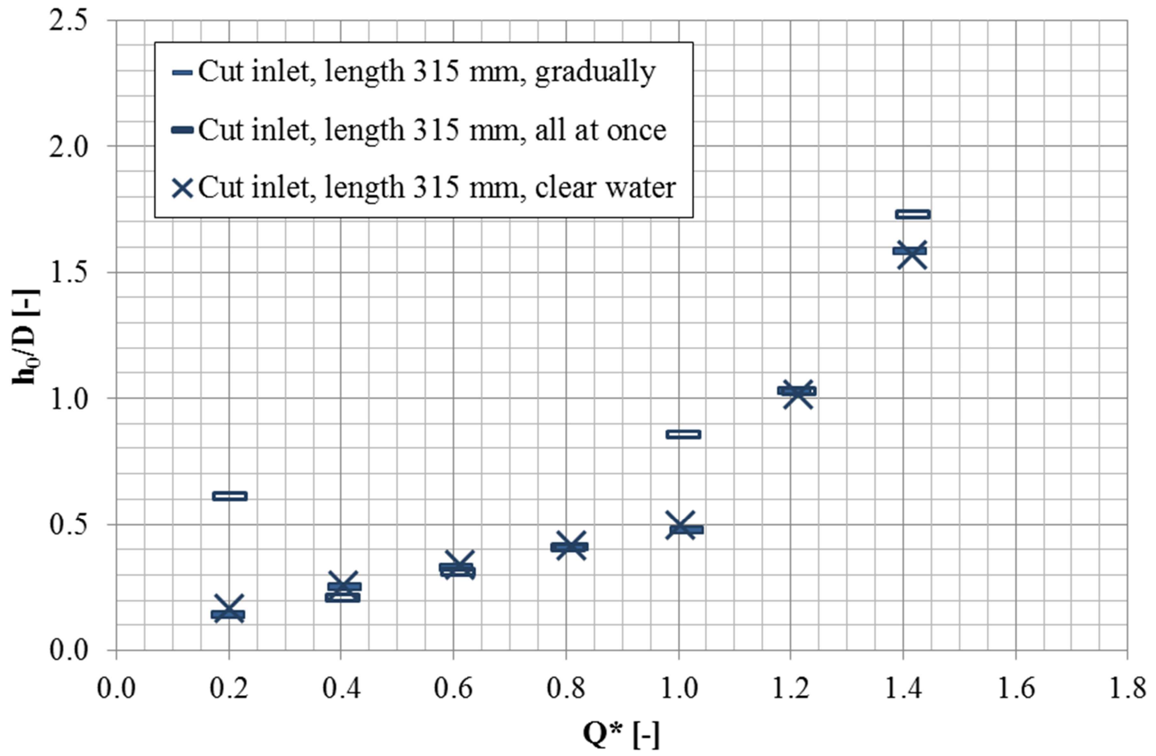


Figure B.36 Culvert capacity with cut inlet under sediment transport – feeding effect with 315 mm basin length (based on the results of Gotvassli (2013))

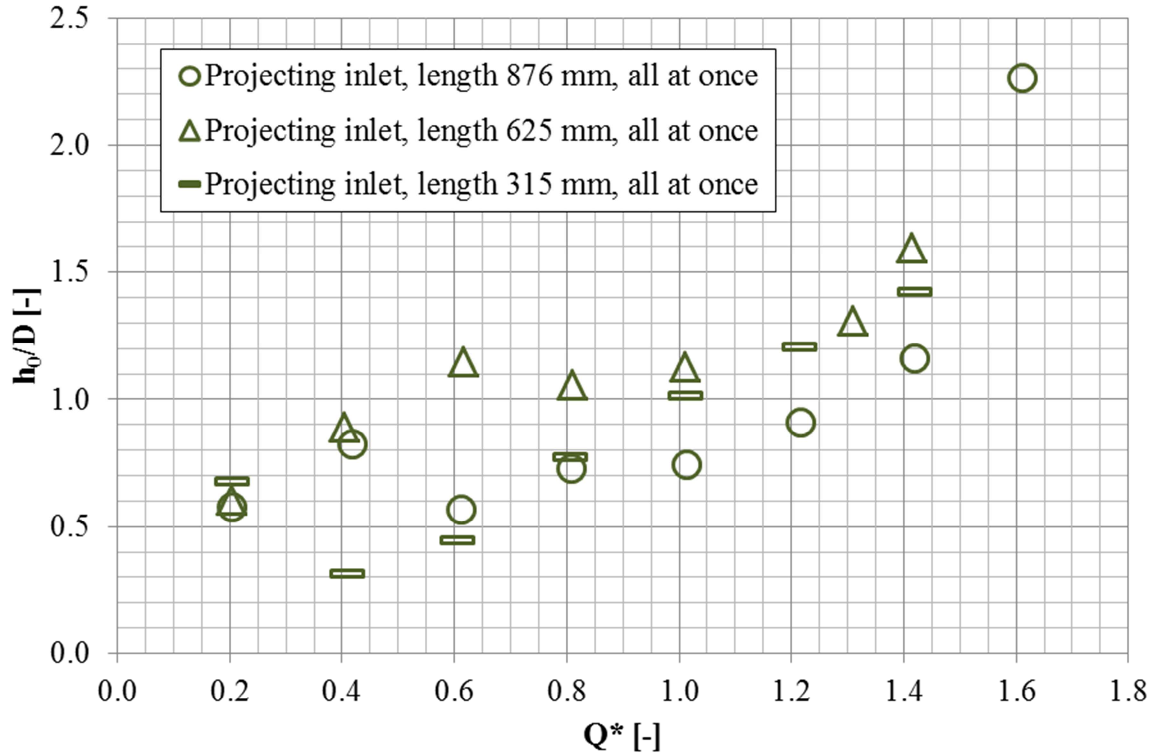


Figure B.37 Culvert capacity with projecting inlet under sediment transport – length effect with all at once feeding (based on the results of Gotvassli (2013))

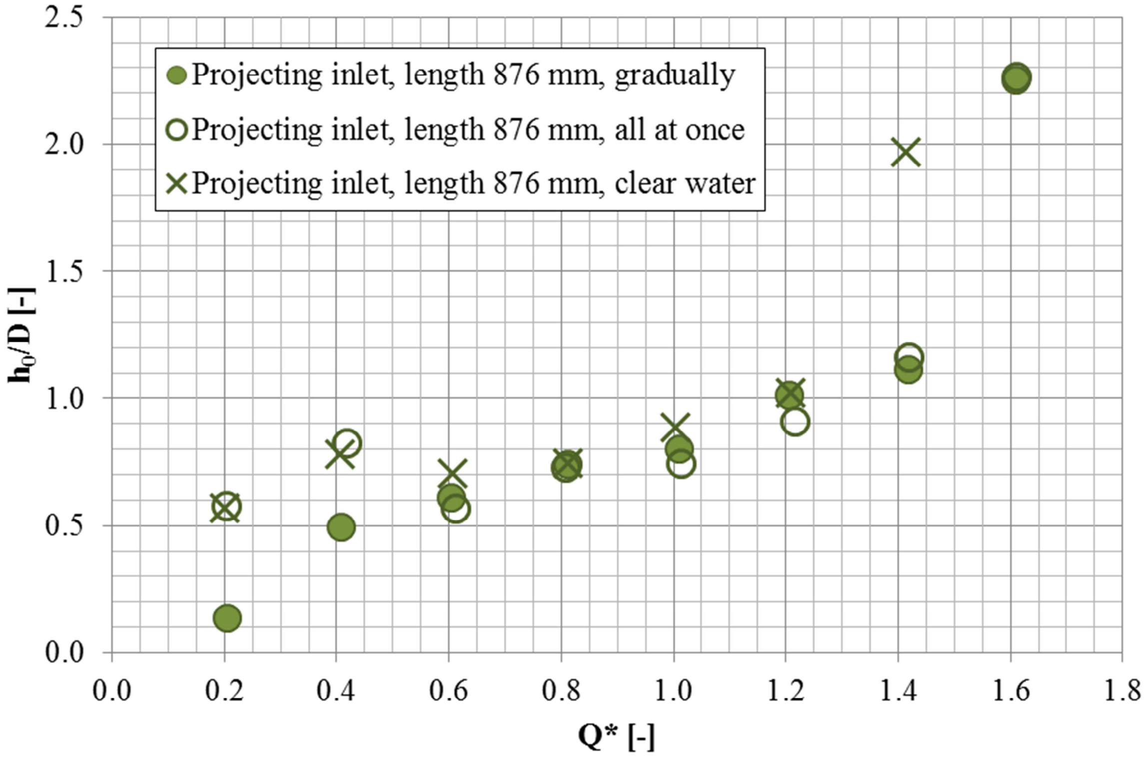


Figure B.38 Culvert capacity with projecting inlet under sediment transport – feeding effect with 876 mm basin length (based on the results of Gotvassli (2013))

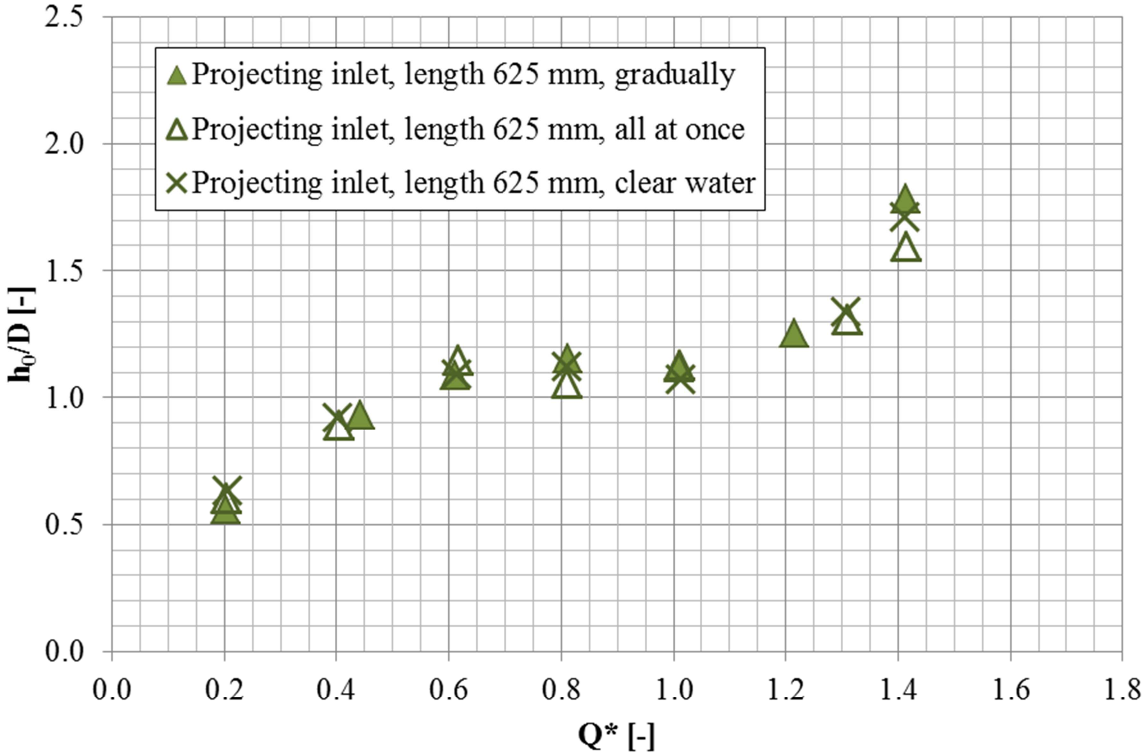


Figure B.39 Culvert capacity with projecting inlet under sediment transport – feeding effect with 625 mm basin length (based on the results of Gotvassli (2013))

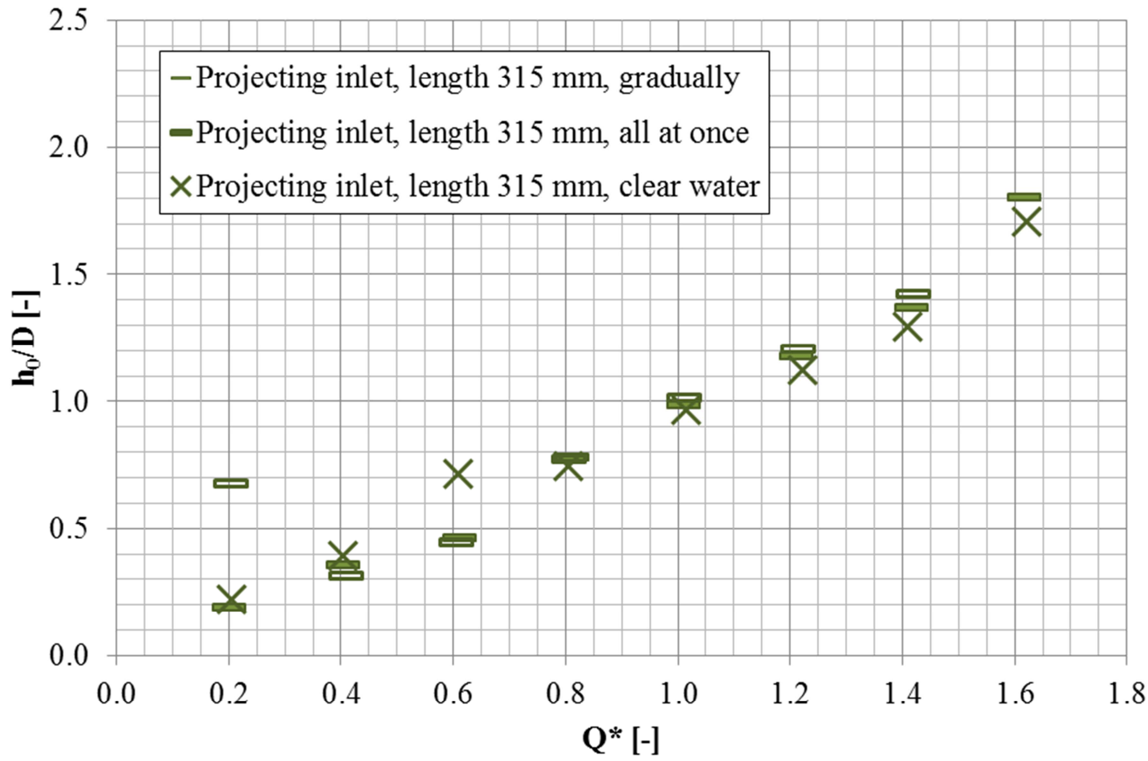


Figure B.40 Culvert capacity with projecting inlet under sediment transport – feeding effect with 315 mm basin length (based on the results of Gotvassli (2013))

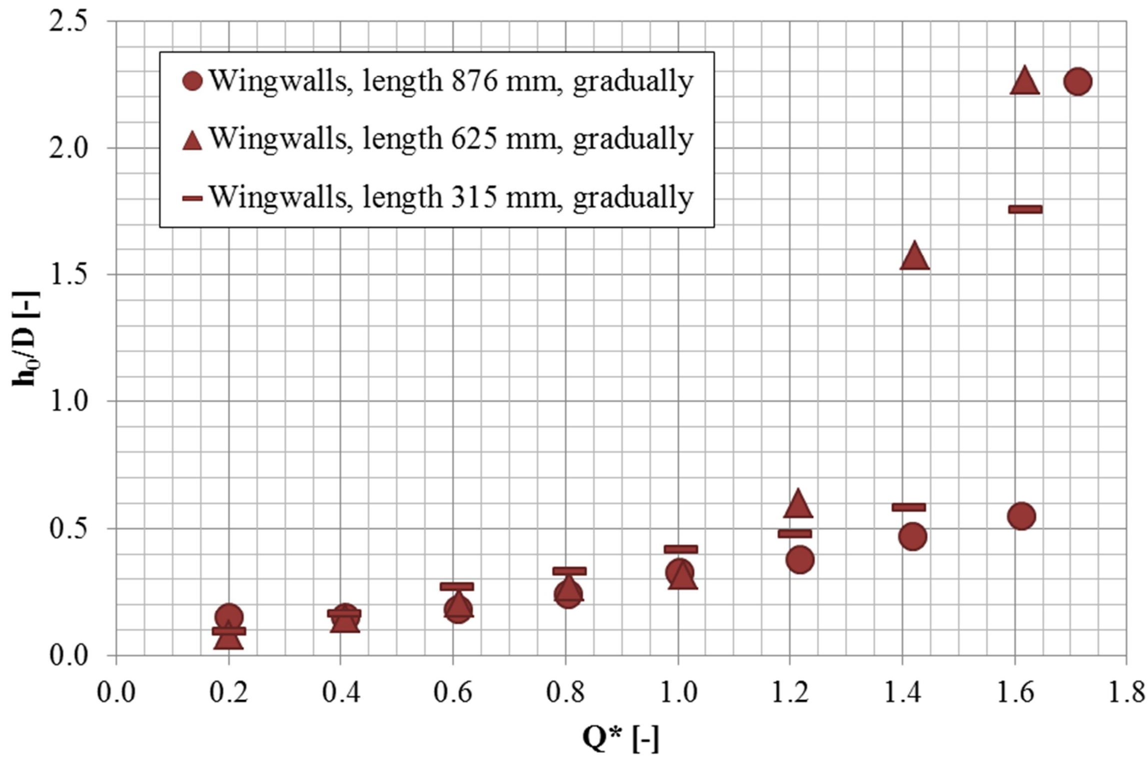


Figure B.41 Culvert capacity with wingwalls under sediment transport – length effect with gradually feeding (based on the results of Gotvassli (2013))

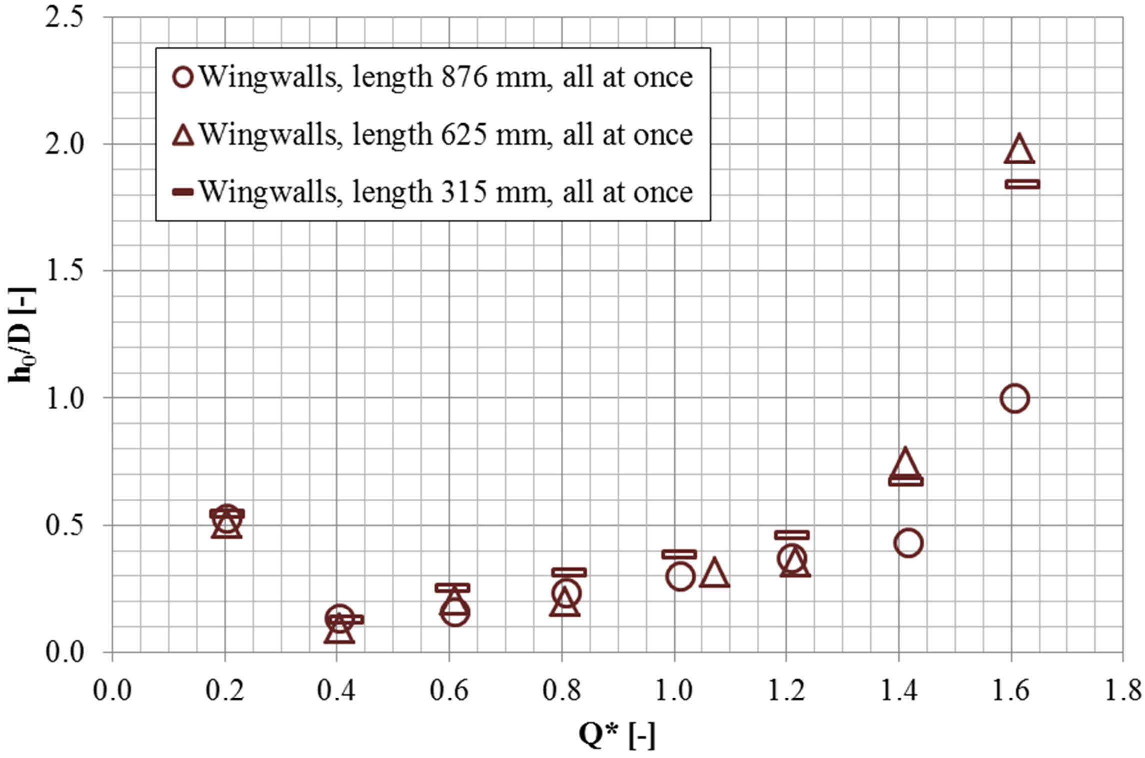


Figure B.42 Culvert capacity with wingwalls under sediment transport – length effect with all at once feeding (based on the results of Gotvassli (2013))

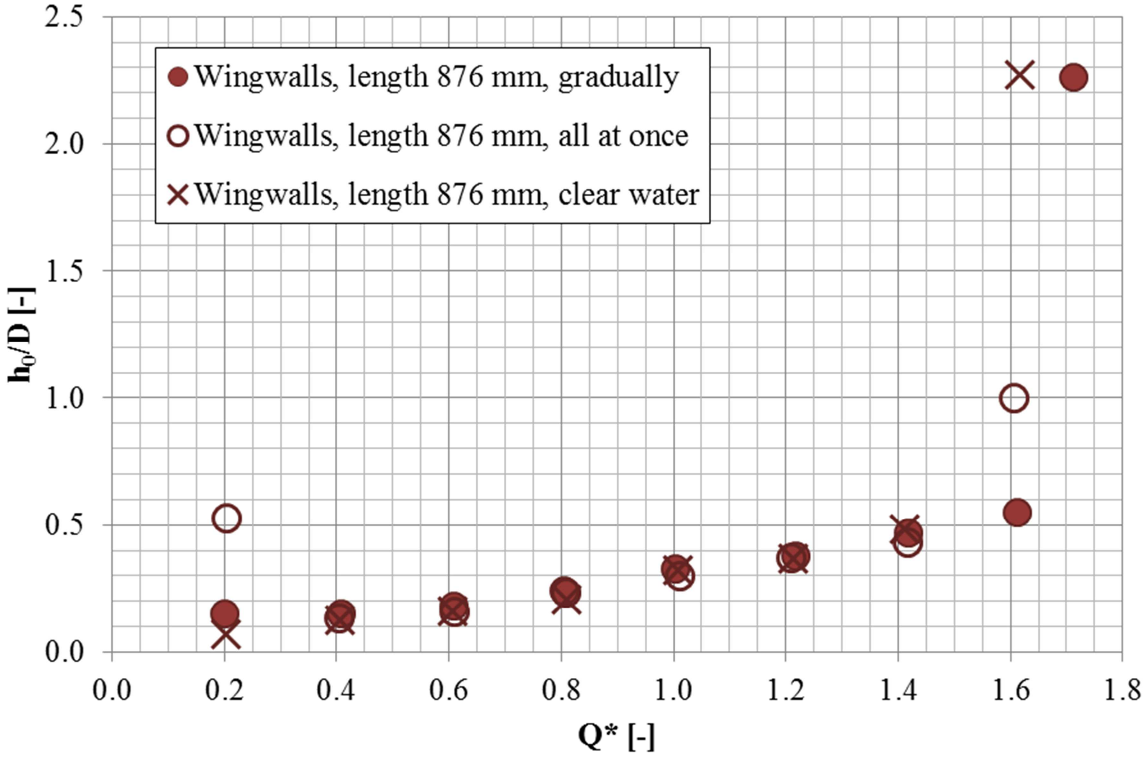


Figure B.43 Culvert capacity with wingwalls under sediment transport – feeding effect with 876 mm basin length (based on the results of Gotvassli (2013))

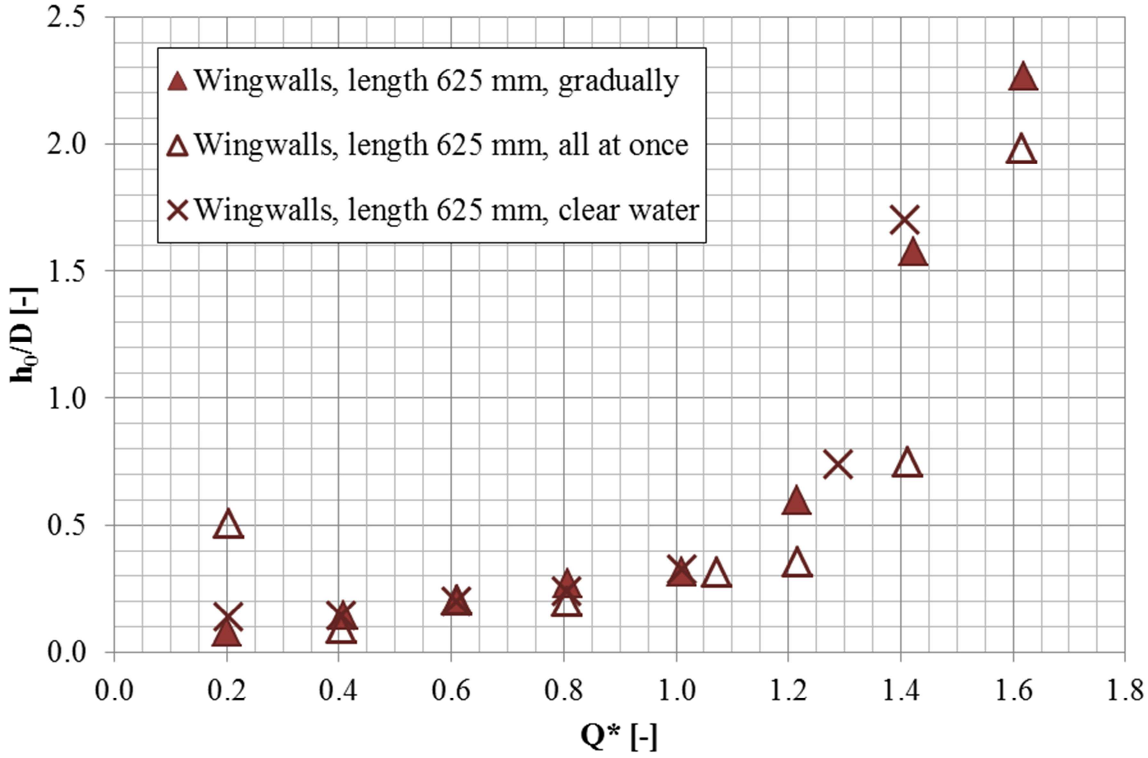


Figure B.44 Culvert capacity with wingwalls under sediment transport – feeding effect with 625 mm basin length (based on the results of Gotvassli (2013))

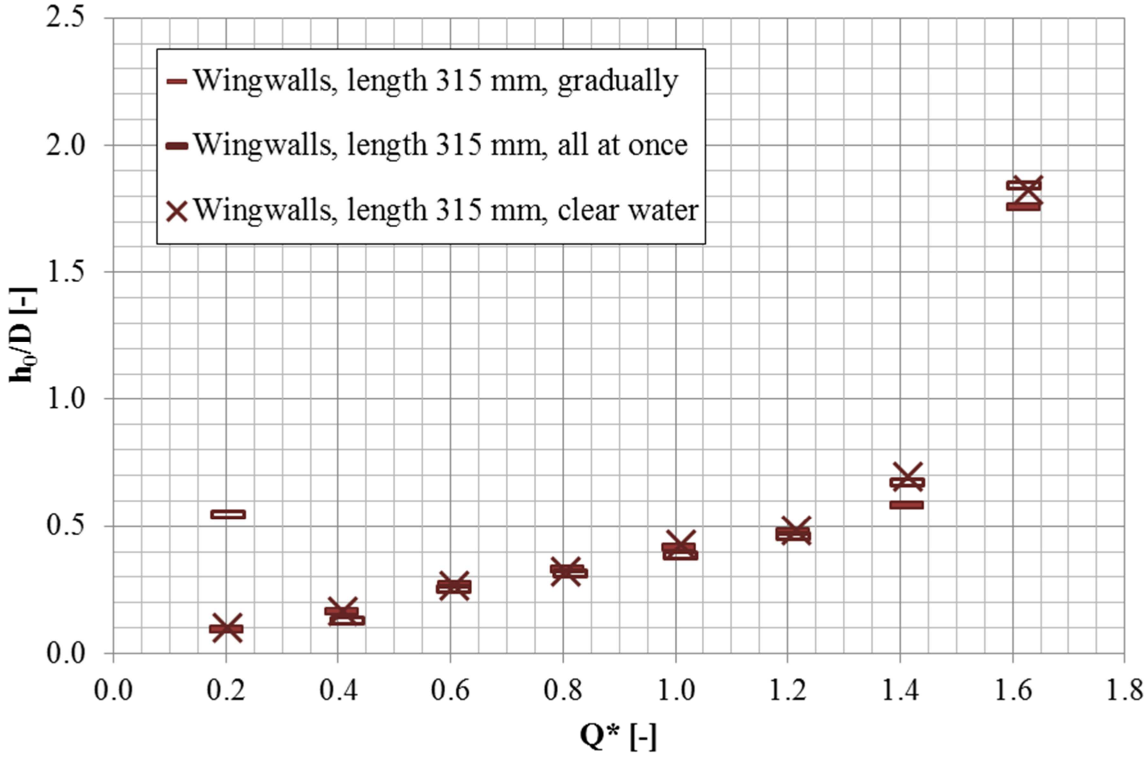


Figure B.45 Culvert capacity with wingwalls under sediment transport – feeding effect with 315 mm basin length (based on the results of Gotvassli (2013))

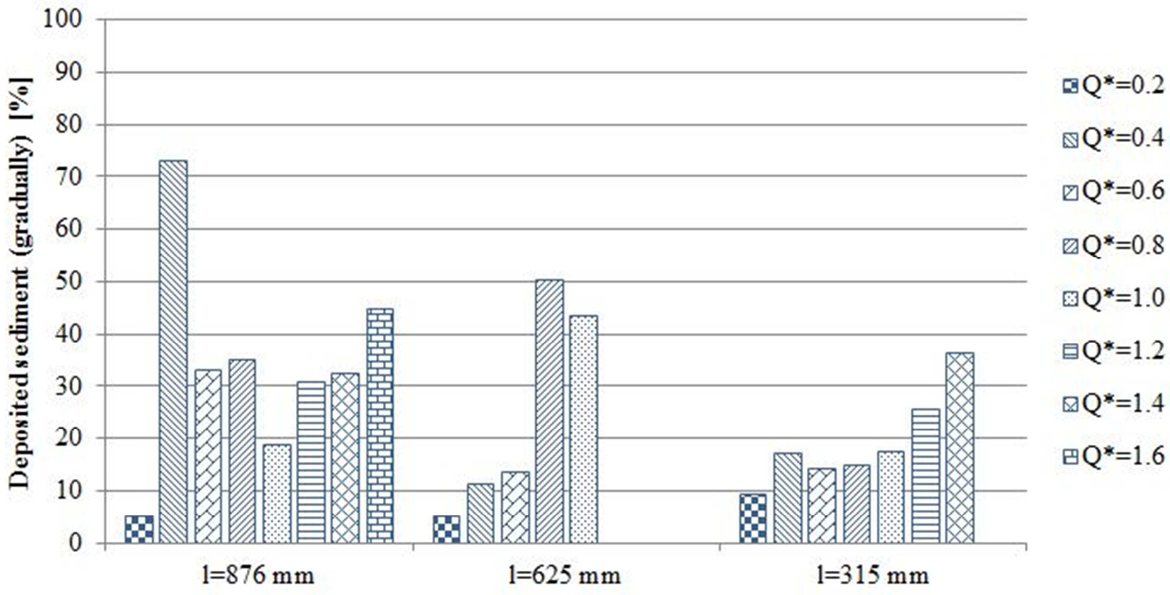


Figure B.46 Deposited sediment amount in case of cut inlet with gradually feeding – length effect (based on the results of Gotvassli (2013))

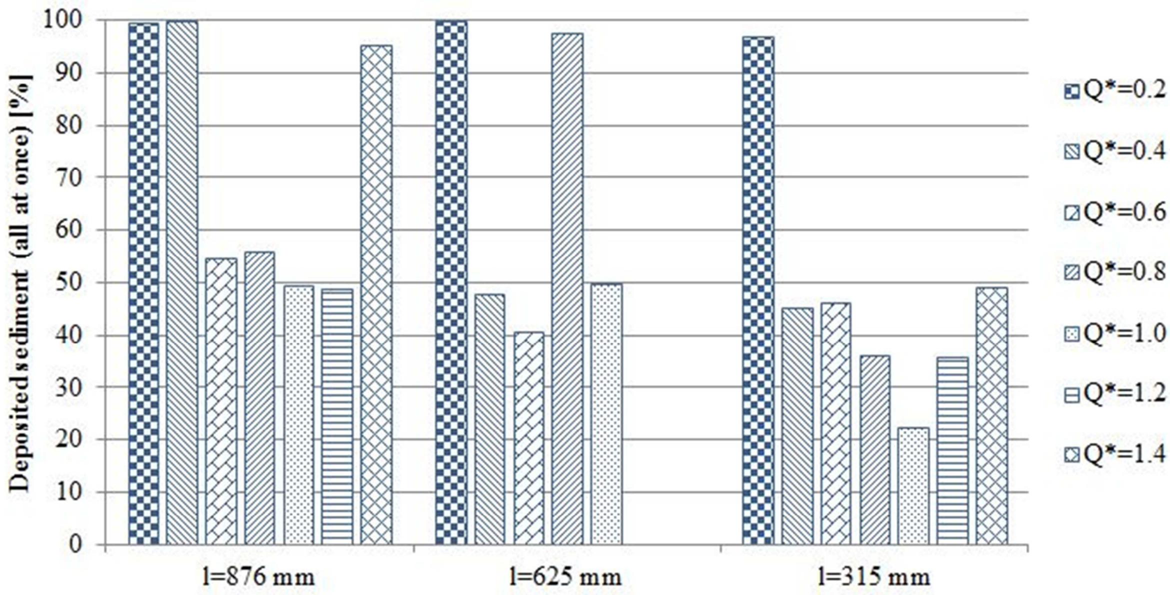


Figure B.47 Deposited sediment amount in case of cut inlet with all at once feeding – length effect (based on the results of Gotvassli (2013))

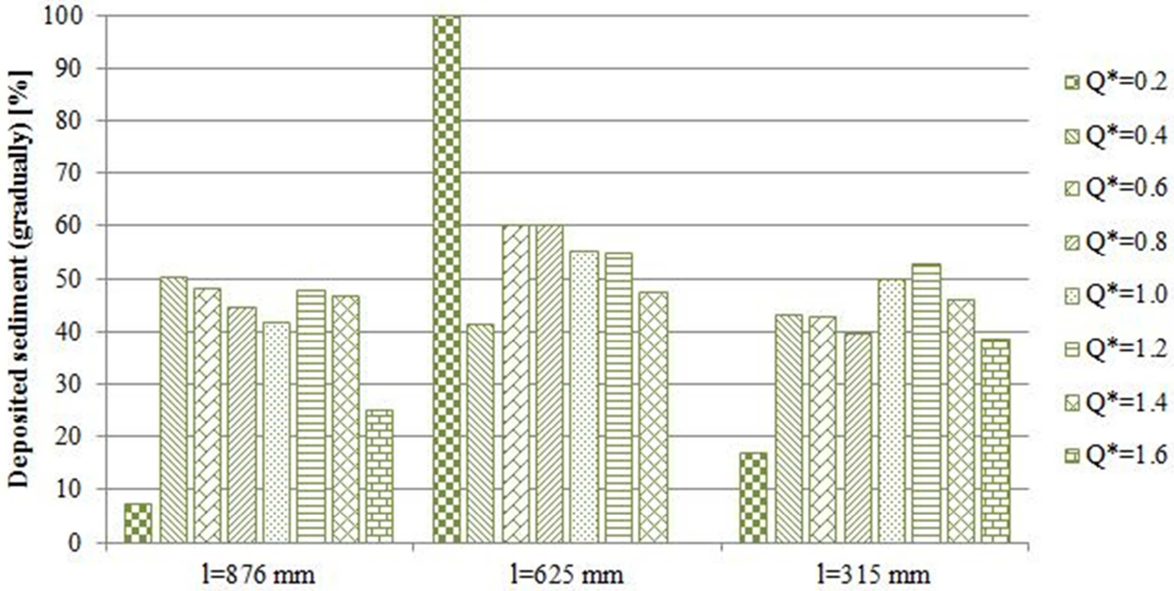


Figure B.48 Deposited sediment amount in case of projecting inlet with gradually feeding – length effect (based on the results of Gotvassli (2013))

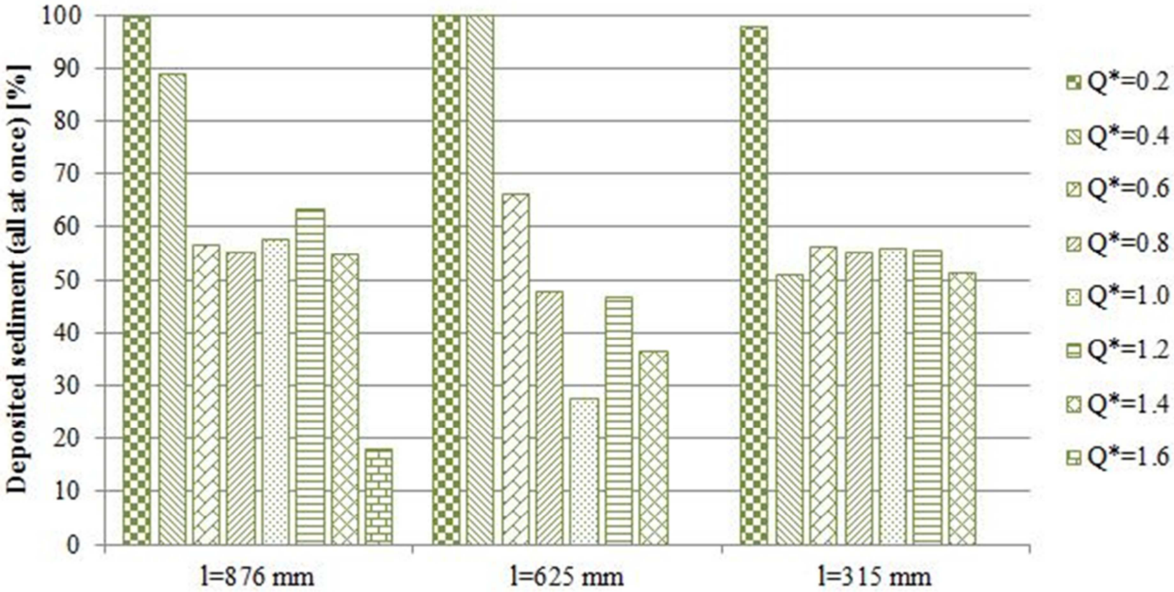


Figure B.49 Deposited sediment amount in case of projecting inlet with all at once feeding – length effect (based on the results of Gotvassli (2013))

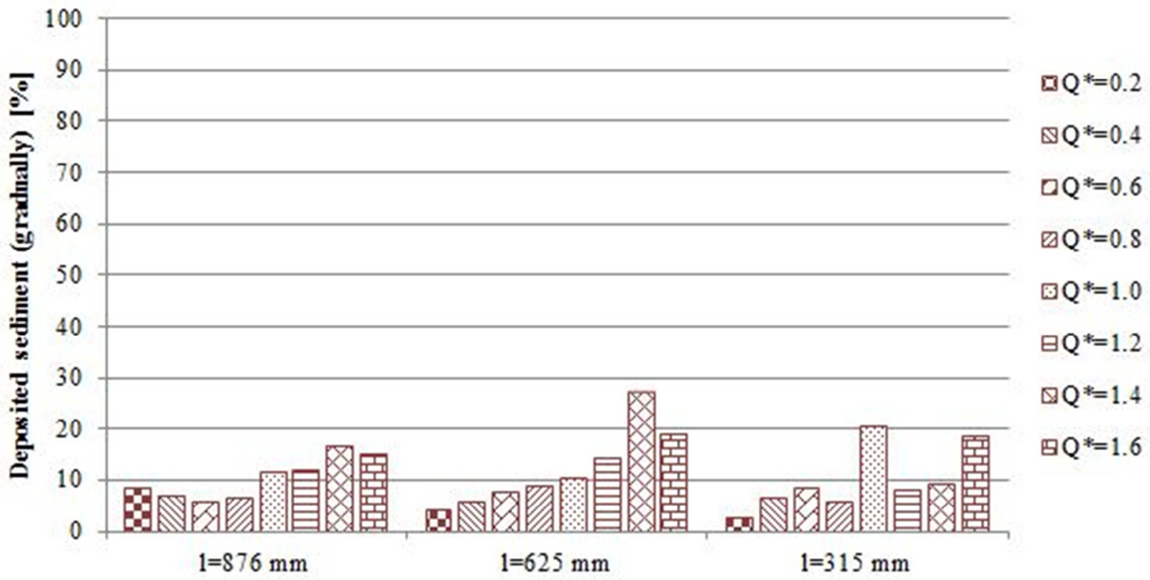


Figure B.50 Deposited sediment amount in case of wingwalls with gradually feeding – length effect (based on the results of Gotvassli (2013))

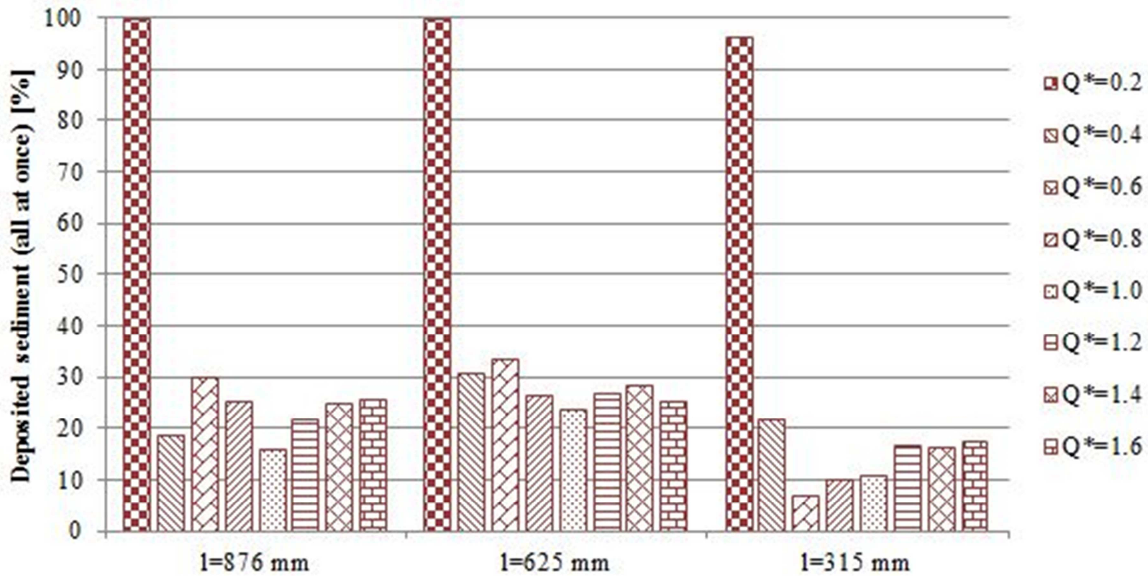


Figure B.51 Deposited sediment amount in case of wingwalls with all at once feeding – length effect (based on the results of Gotvassli (2013))

Basin width effect: Slope: 1:9, Basin length: 876 mm, with energy dissipation

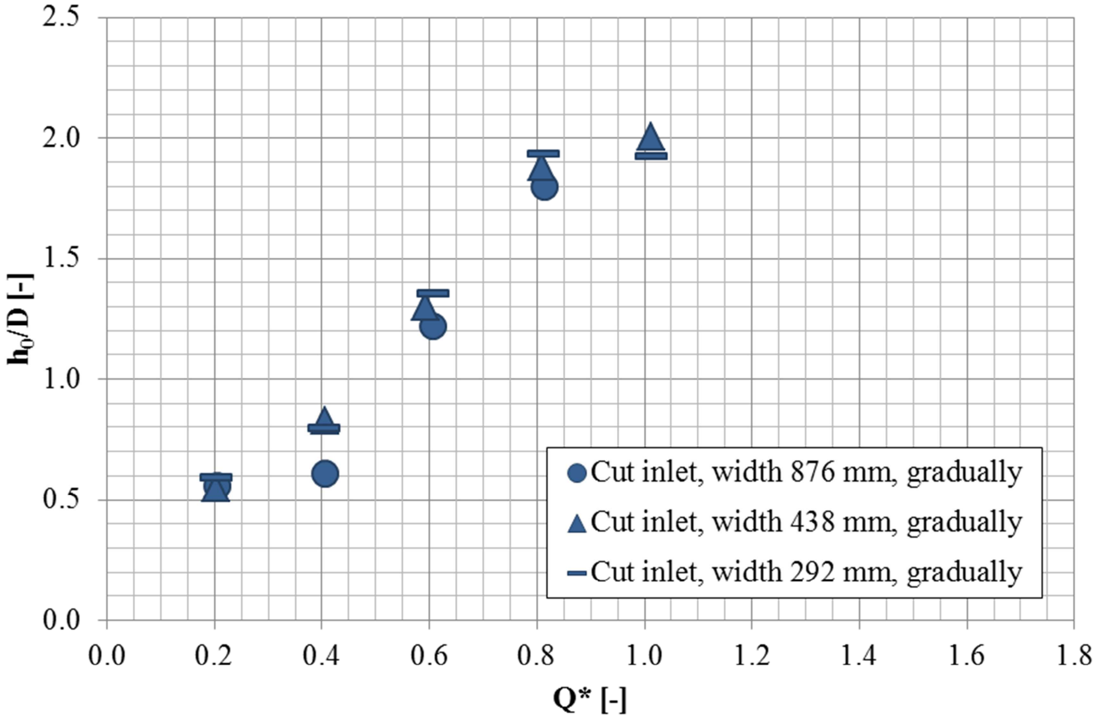


Figure B.52 Culvert capacity with cut inlet under sediment transport – width effect with gradually feeding (based on the results of Putri (2014))

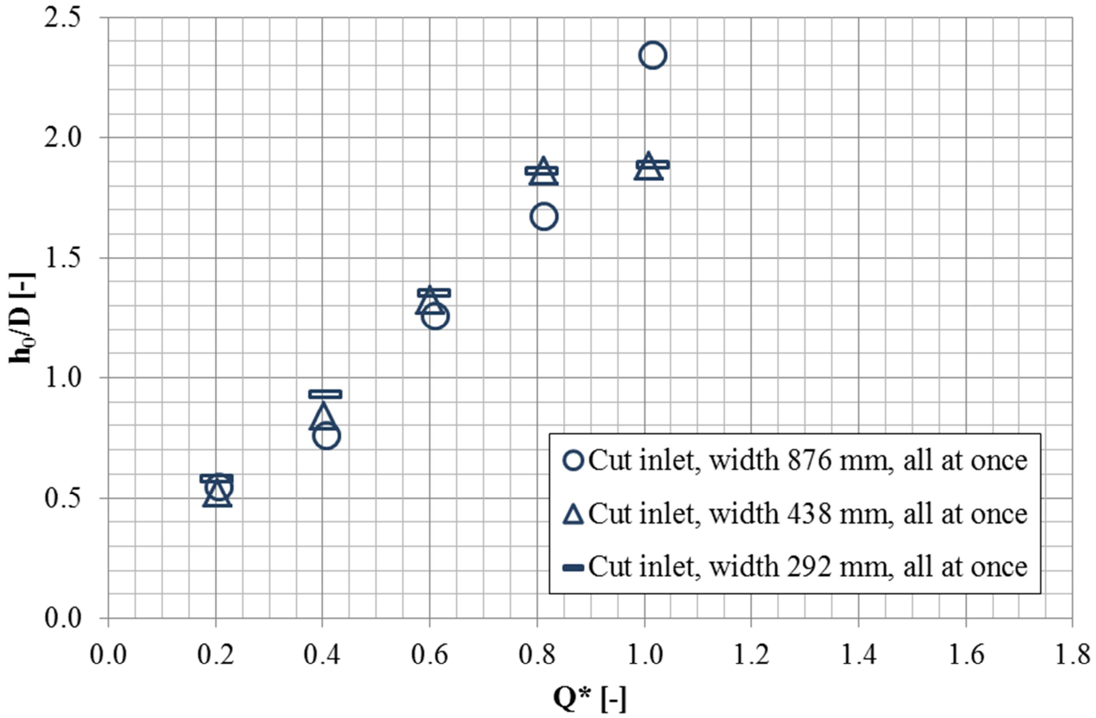


Figure B.53 Culvert capacity with cut inlet under sediment transport – width effect with all at once feeding (based on the results of Putri (2014))

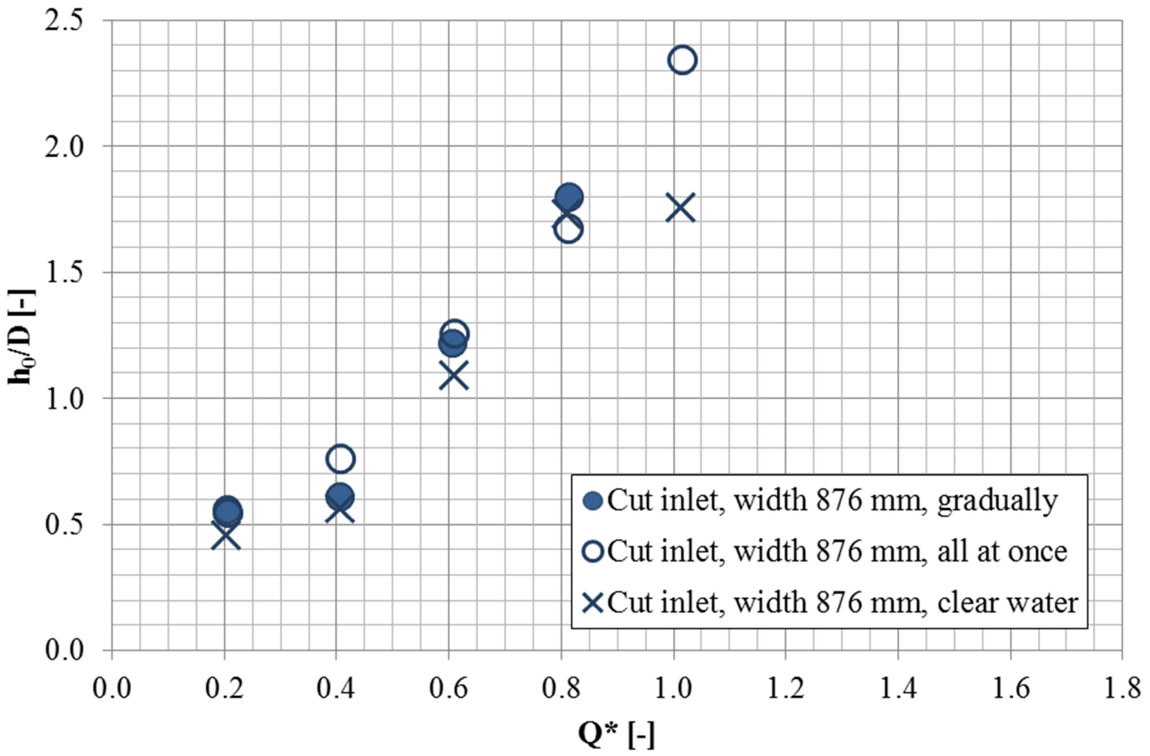


Figure B.54 Culvert capacity with cut inlet under sediment transport – feeding effect with 876 mm basin width (based on the results of Putri (2014))

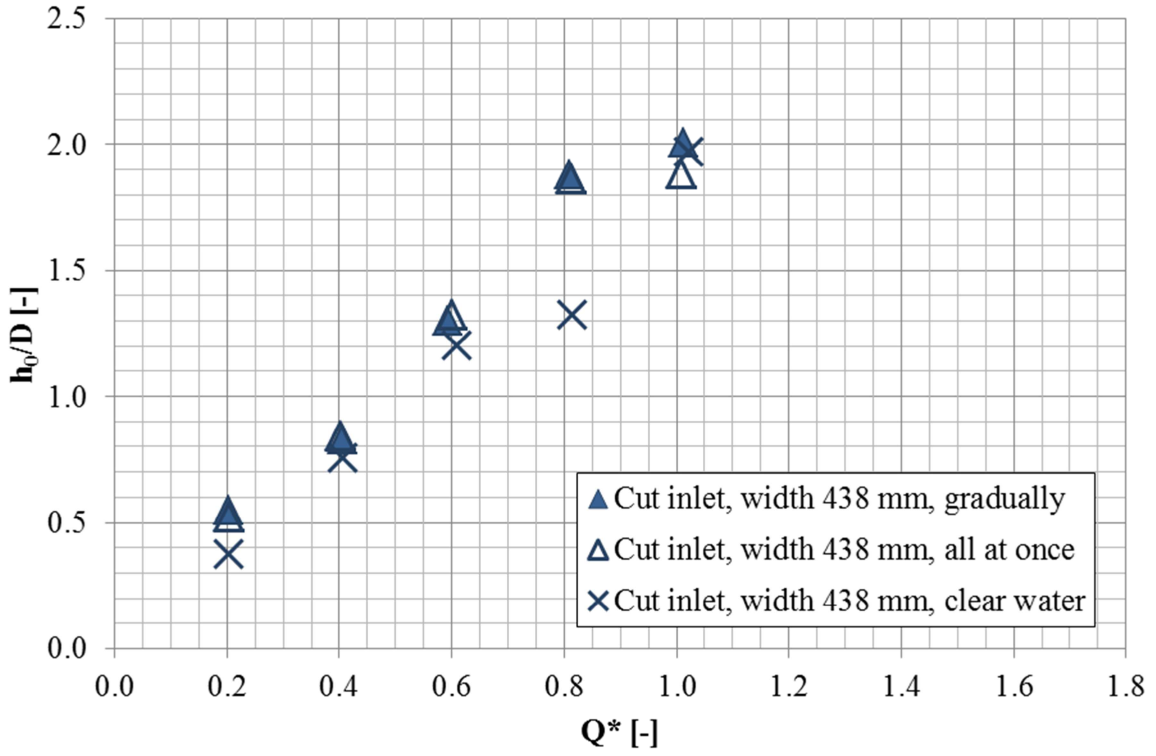


Figure B.55 Culvert capacity with cut inlet under sediment transport – feeding effect with 438 mm basin width (based on the results of Putri (2014))

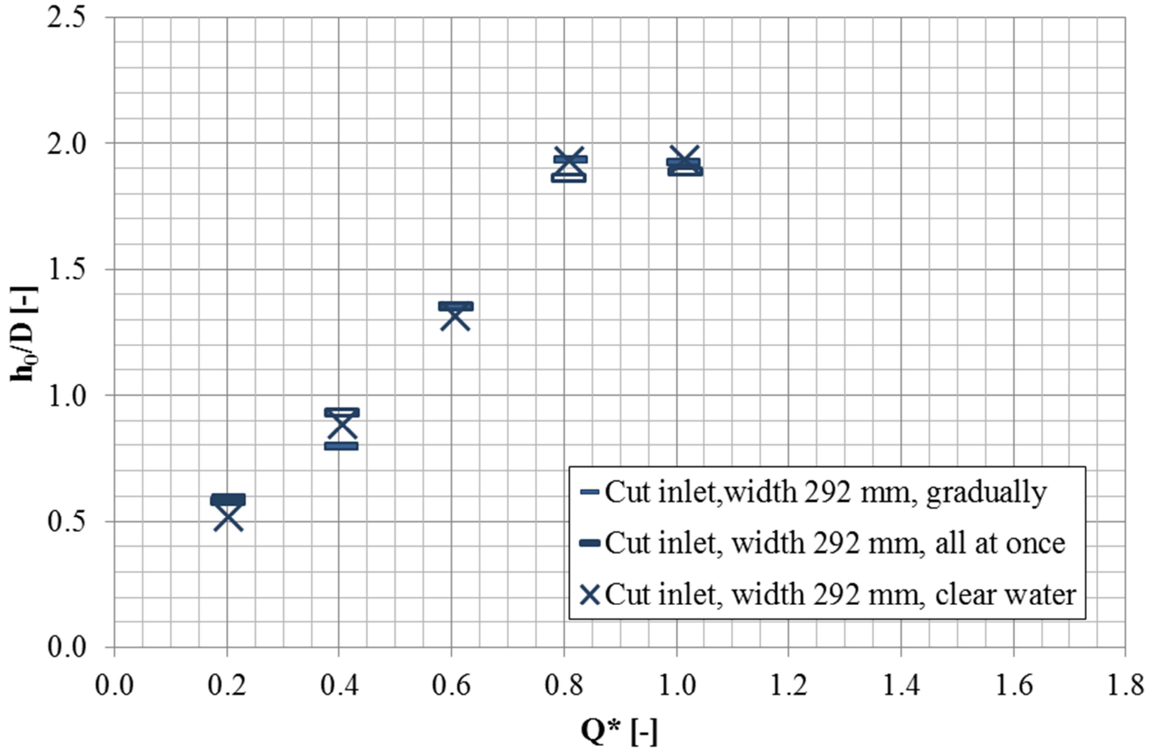


Figure B.56 Culvert capacity with cut inlet under sediment transport – feeding effect with 292 mm basin width (based on the results of Putri (2014))

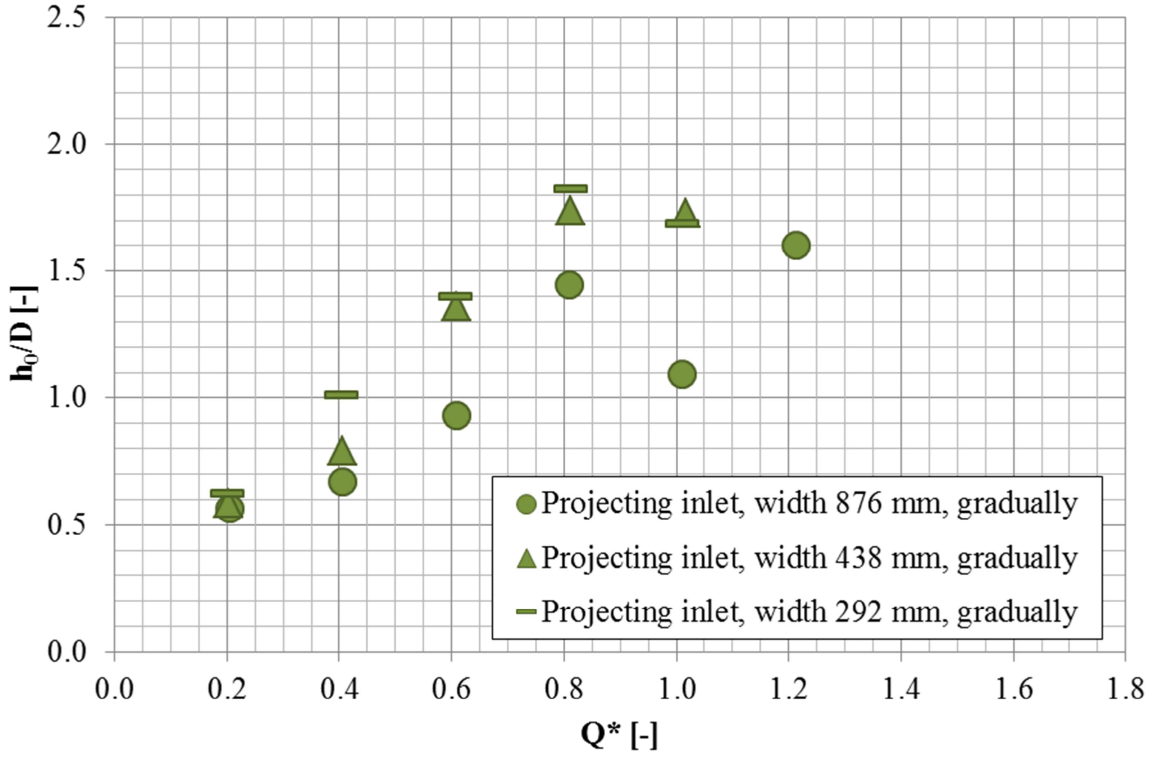


Figure B.57 Culvert capacity with projecting inlet under sediment transport – width effect with gradually feeding (based on the results of Putri (2014))

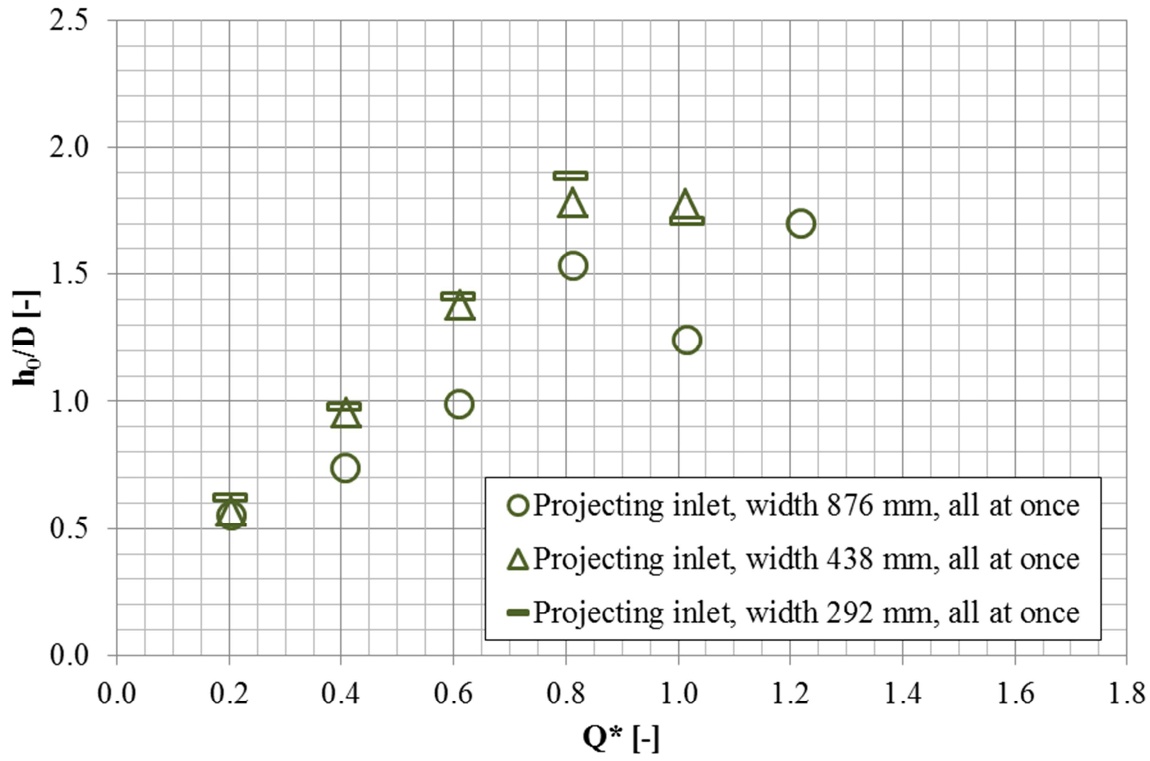


Figure B.58 Culvert capacity with projecting inlet under sediment transport – width effect with all at once feeding (based on the results of Putri (2014))

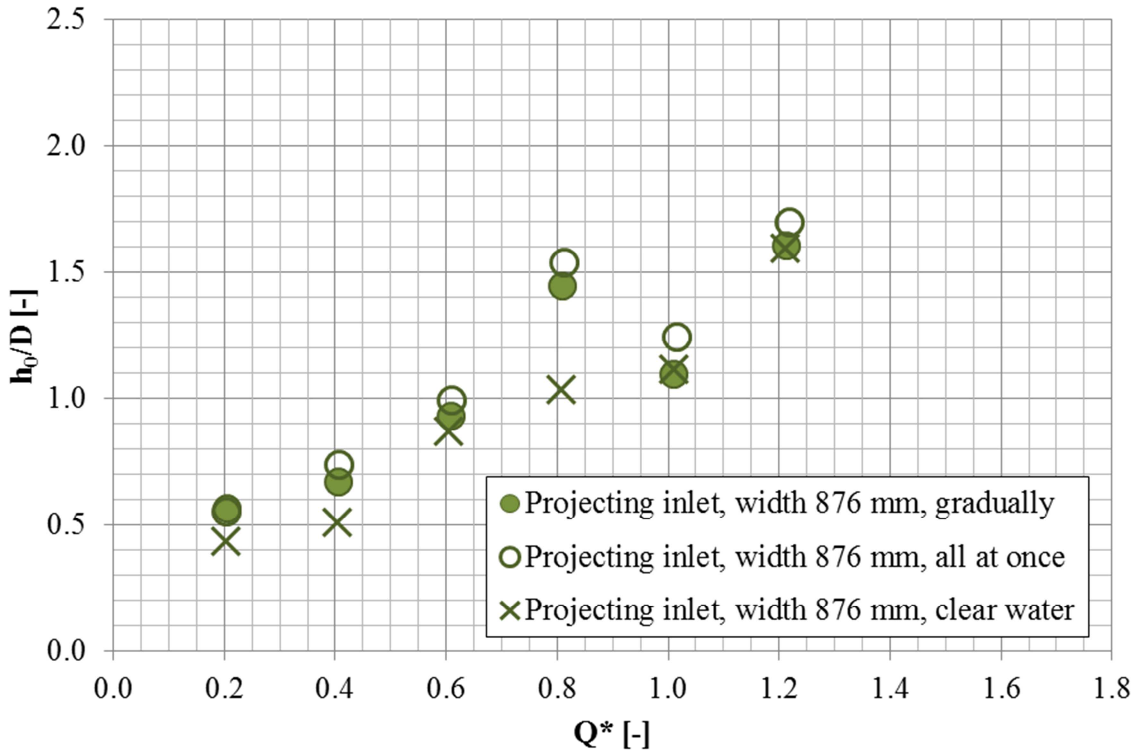


Figure B.59 Culvert capacity with projecting inlet under sediment transport – feeding effect with 876 mm basin width (based on the results of Putri (2014))

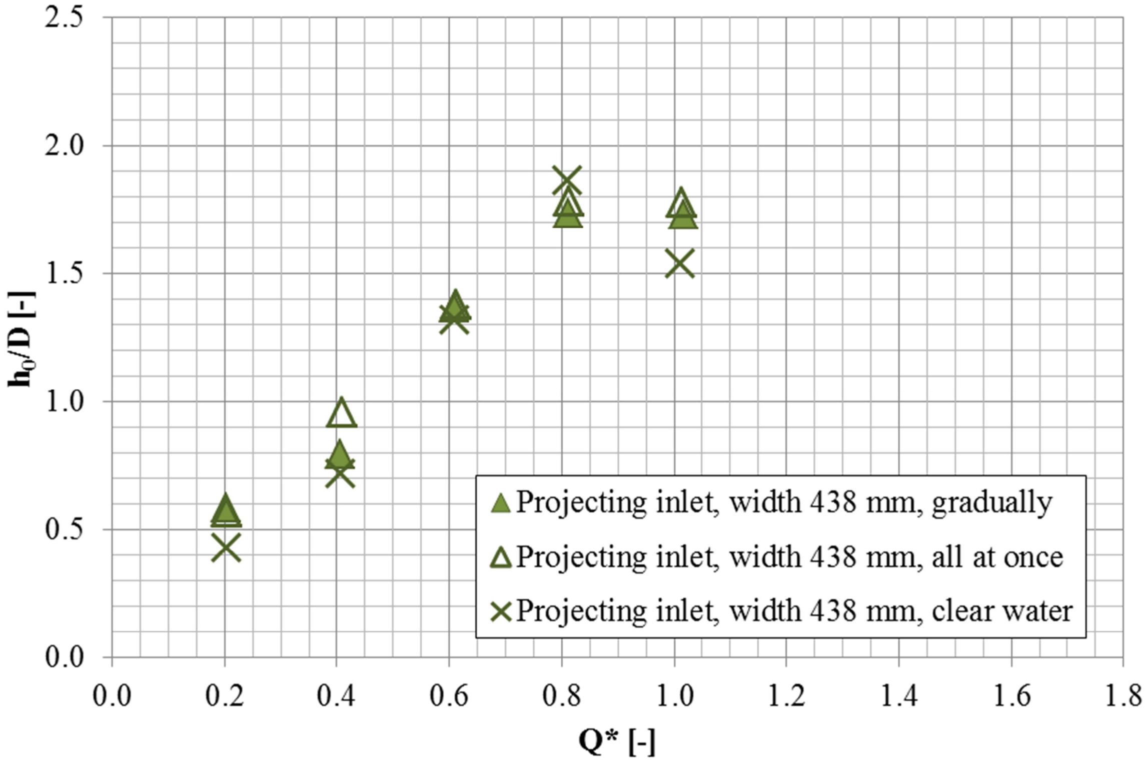


Figure B.60 Culvert capacity with projecting inlet under sediment transport – feeding effect with 438 mm basin width (based on the results of Putri (2014))

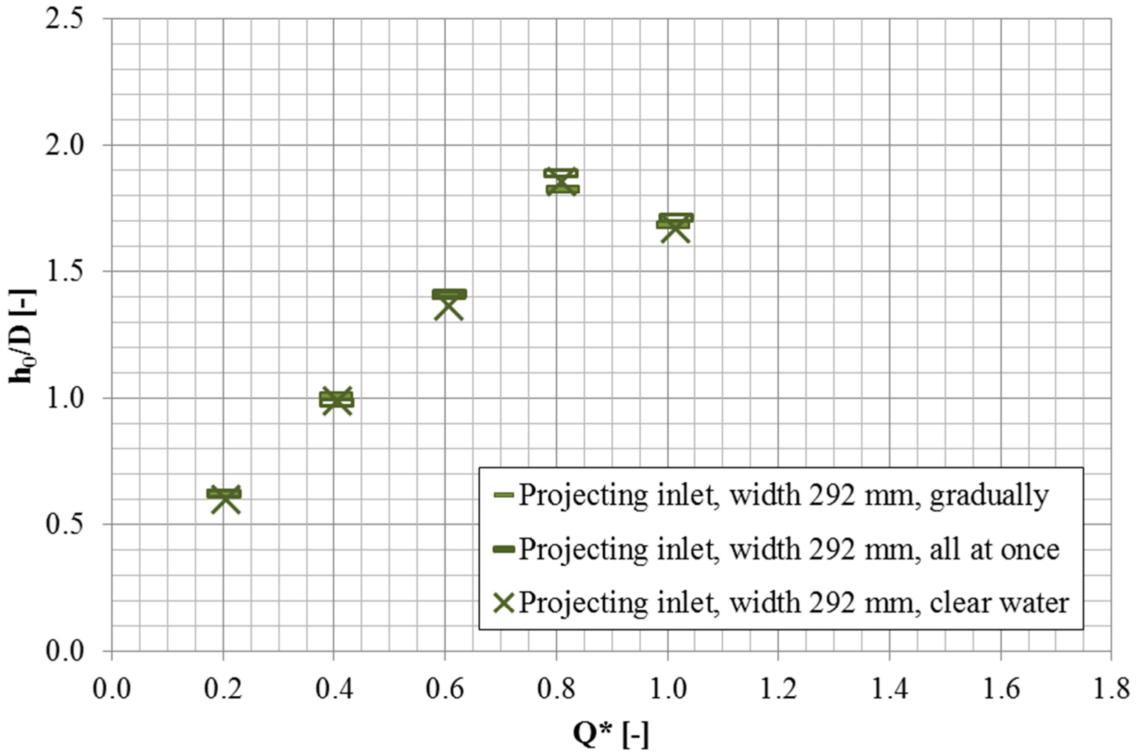


Figure B.61 Culvert capacity with projecting inlet under sediment transport – feeding effect with 292 mm basin width (based on the results of Putri (2014))

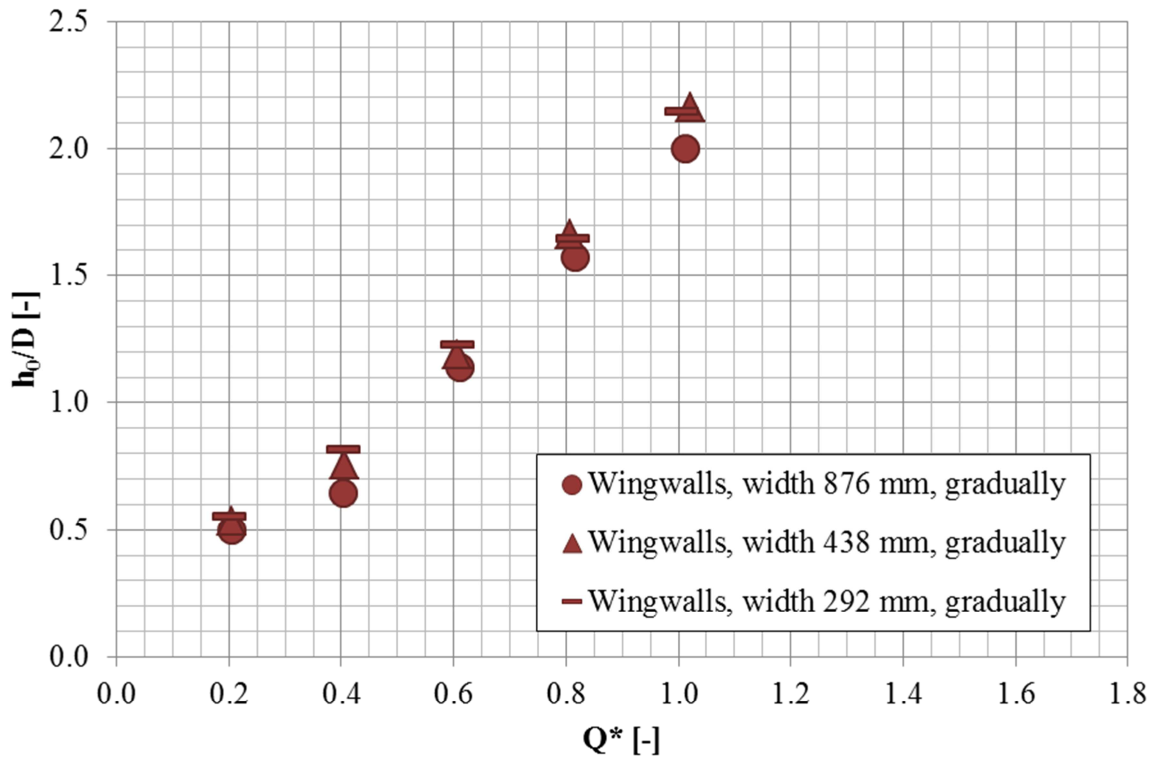


Figure B.62 Culvert capacity with wingwalls under sediment transport – width effect with gradually feeding (based on the results of Putri (2014))

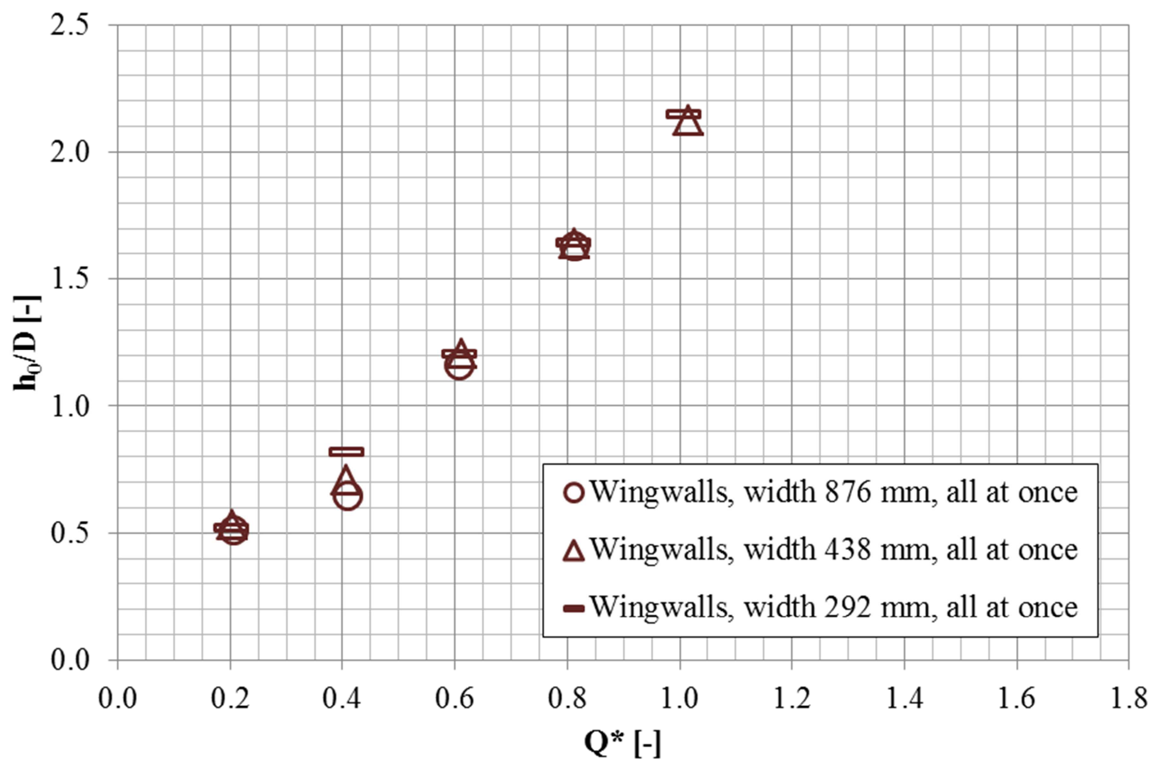


Figure B.63 Culvert capacity with wingwalls under sediment transport – width effect with all at once feeding (based on the results of Putri (2014))

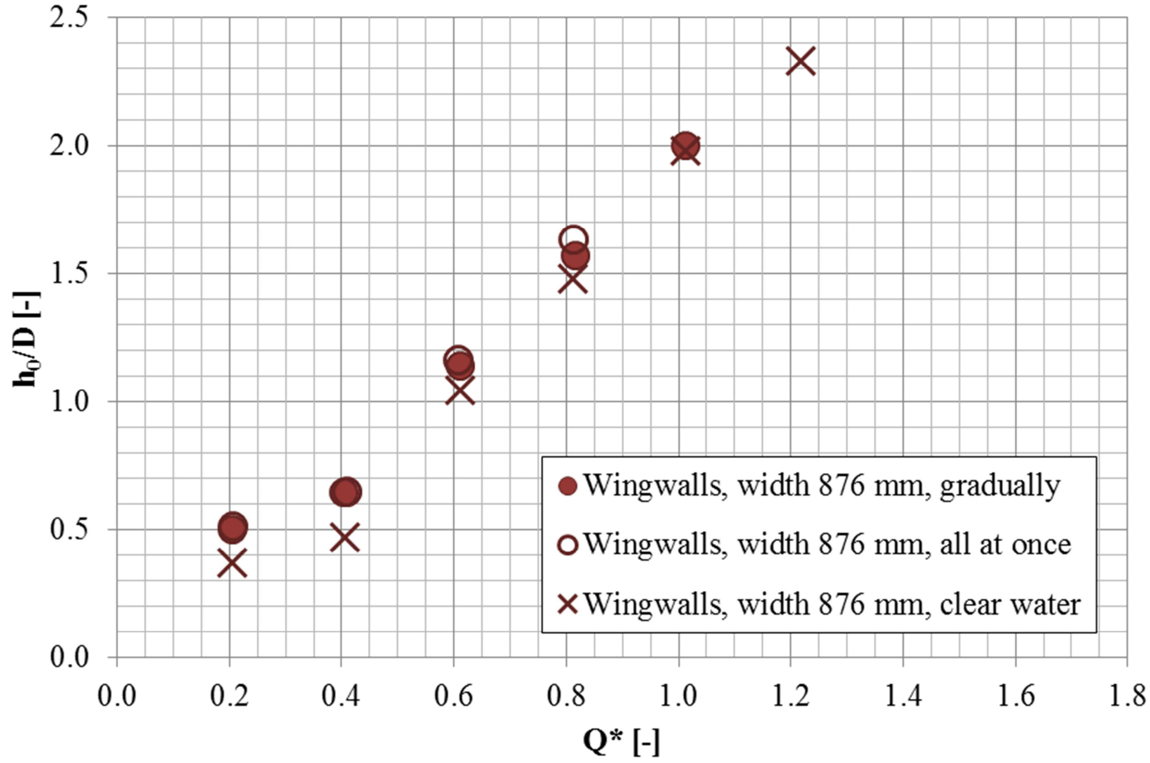


Figure B.64 Culvert capacity with wingwalls under sediment transport – feeding effect with 876 mm basin width (based on the results of Putri (2014))

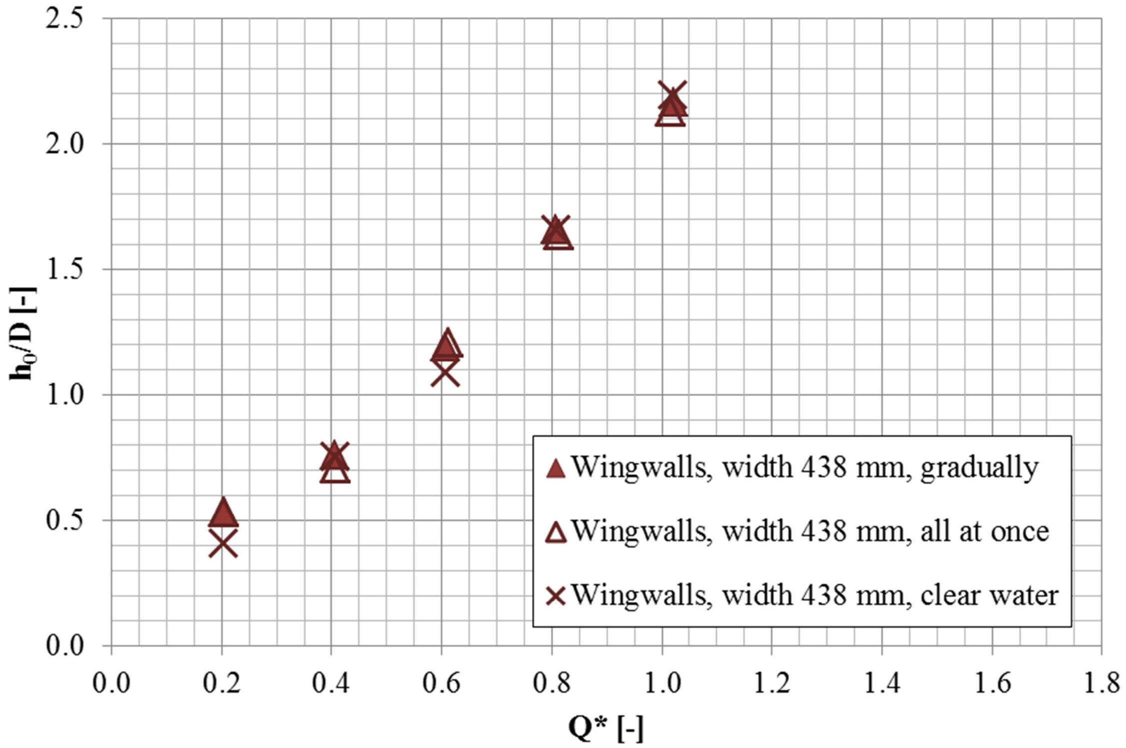


Figure B.65 Culvert capacity with wingwalls under sediment transport – feeding effect with 438 mm basin width (based on the results of Putri (2014))

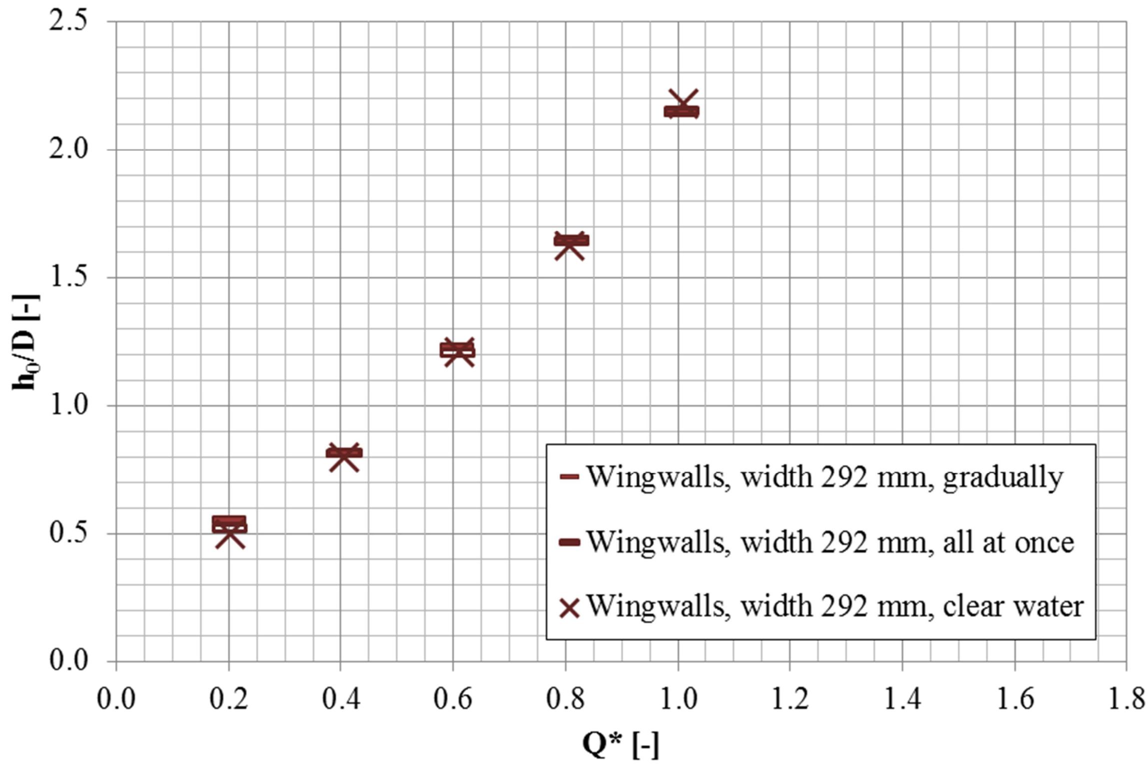


Figure B.66 Culvert capacity with wingwalls under sediment transport – feeding effect with 292 mm basin width (based on the results of Putri (2014))

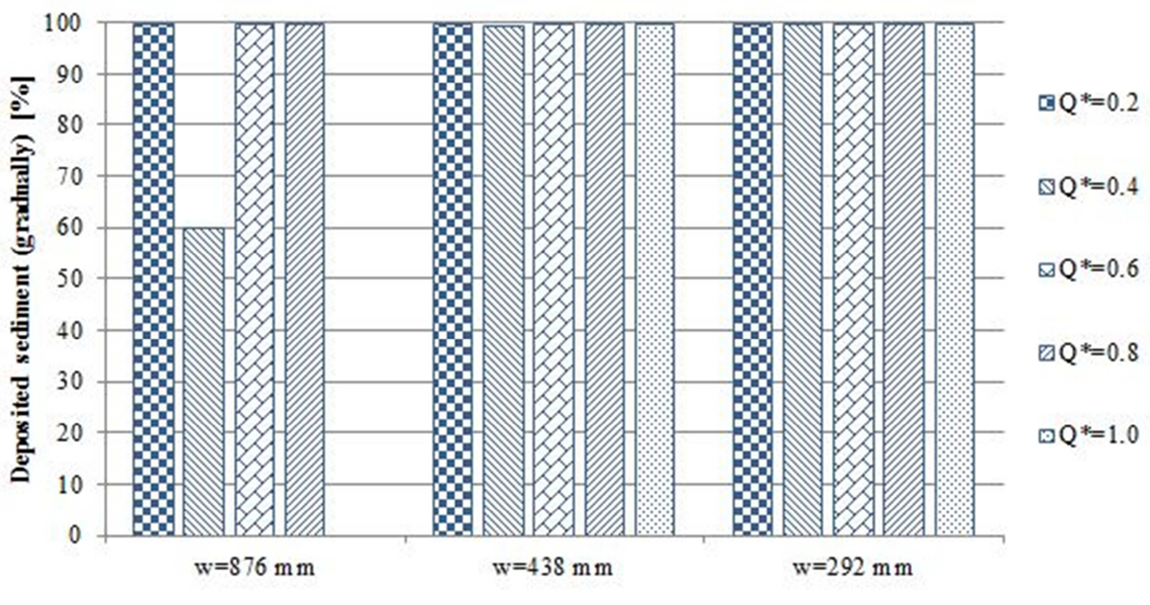


Figure B.67 Deposited sediment amount in case of cut inlet with gradually feeding – width effect (based on the results of Putri (2014))

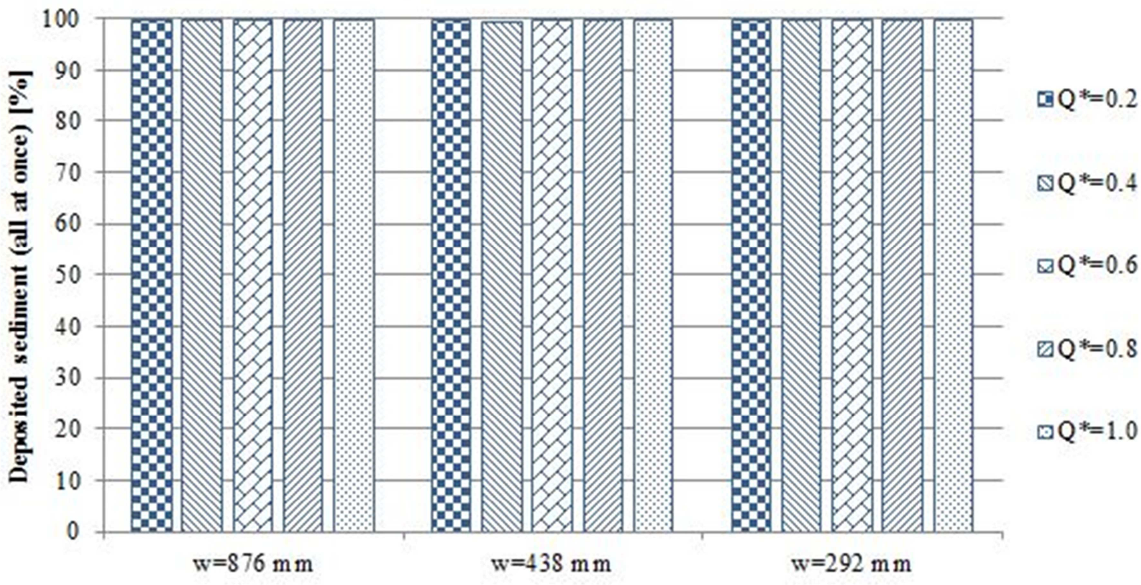


Figure B.68 Deposited sediment amount in case of cut inlet with all at once feeding – width effect (based on the results of Putri (2014))

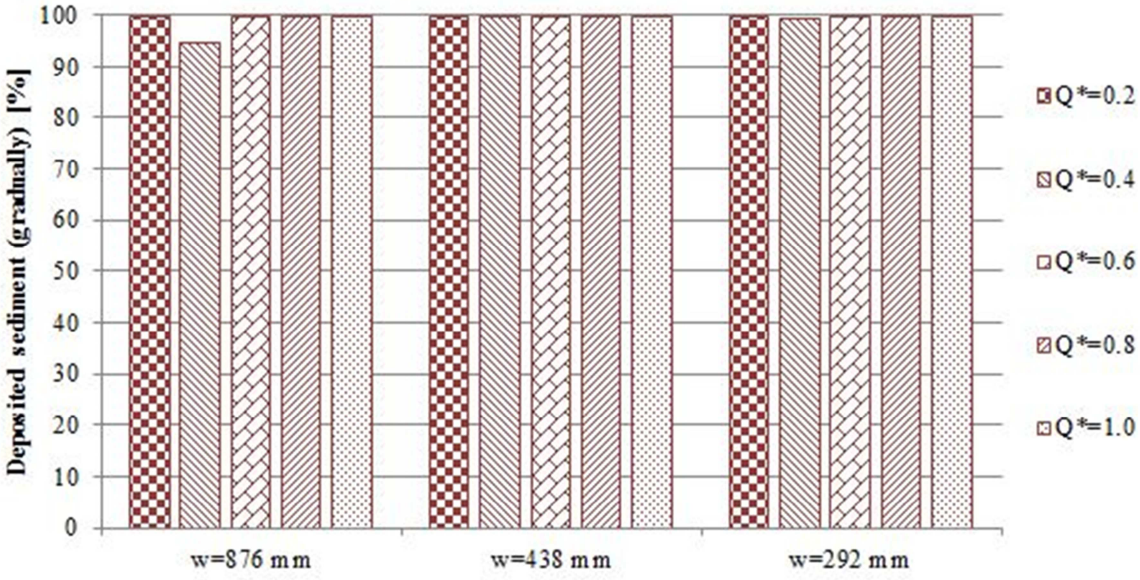


Figure B.69 Deposited sediment amount in case of wingwalls with gradually feeding – width effect (based on the results of Putri (2014))

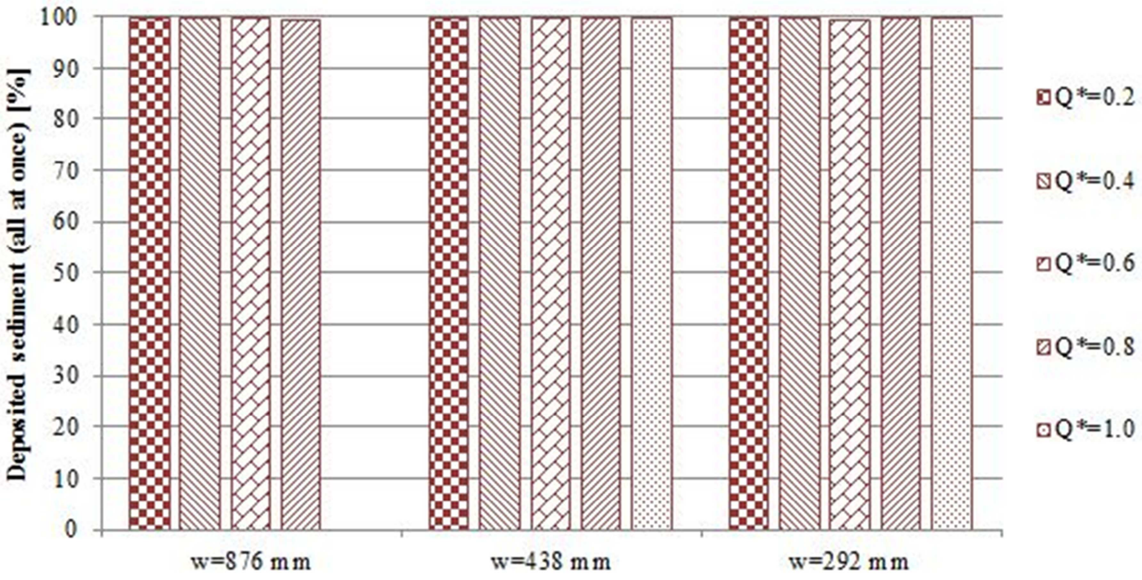


Figure B.70 Deposited sediment amount in case of wingwalls with all at once feeding – width effect (based on the results of Putri (2014))

Effect of reserve barrel: Slope: 1:9, Basin length: 876 mm, Basin width: 1100 mm, with energy dissipation

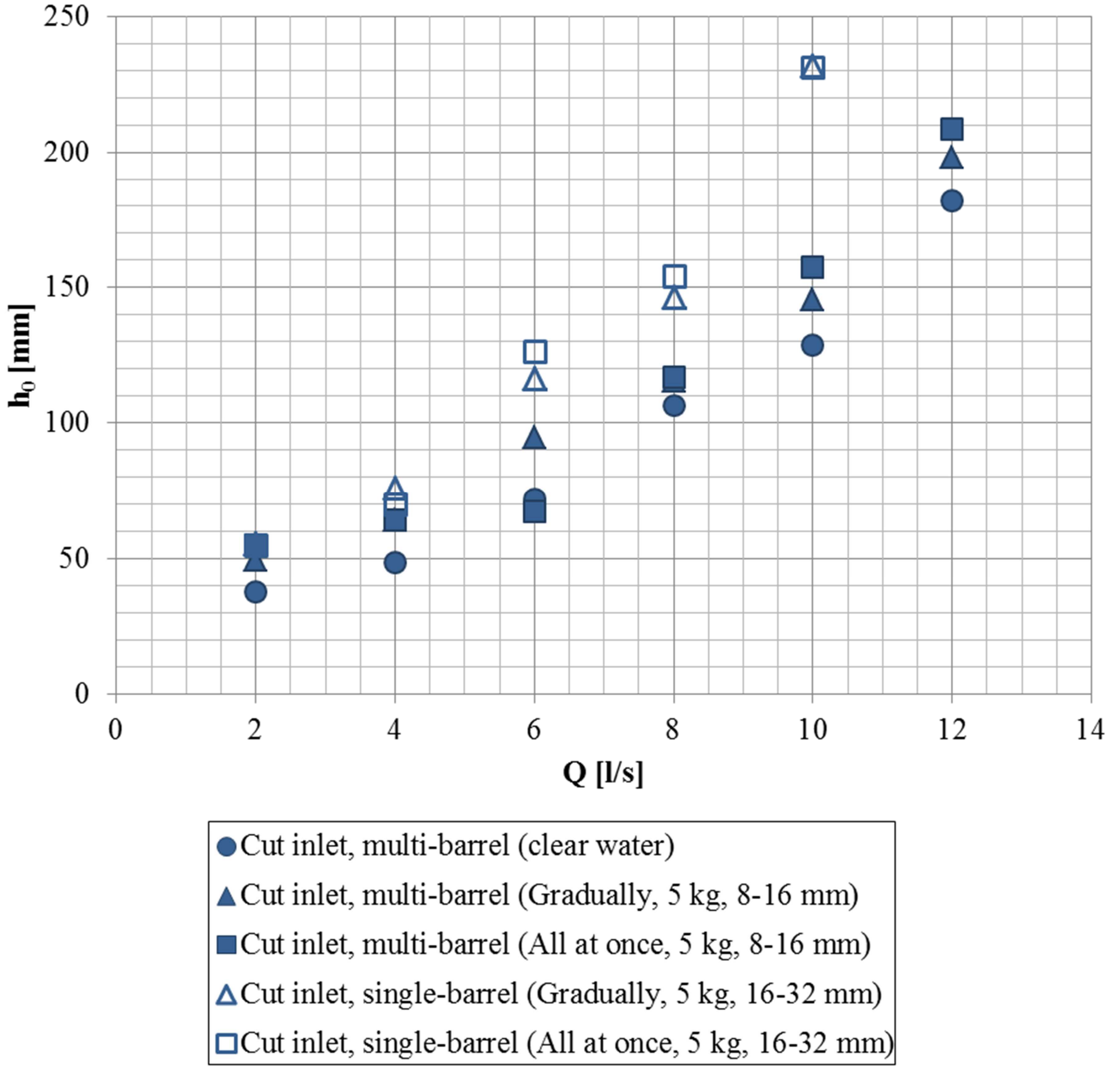


Figure B.71 Sediment effect in multi- and single barrel system with cut inlet (based on the results of Faqiri (2014))

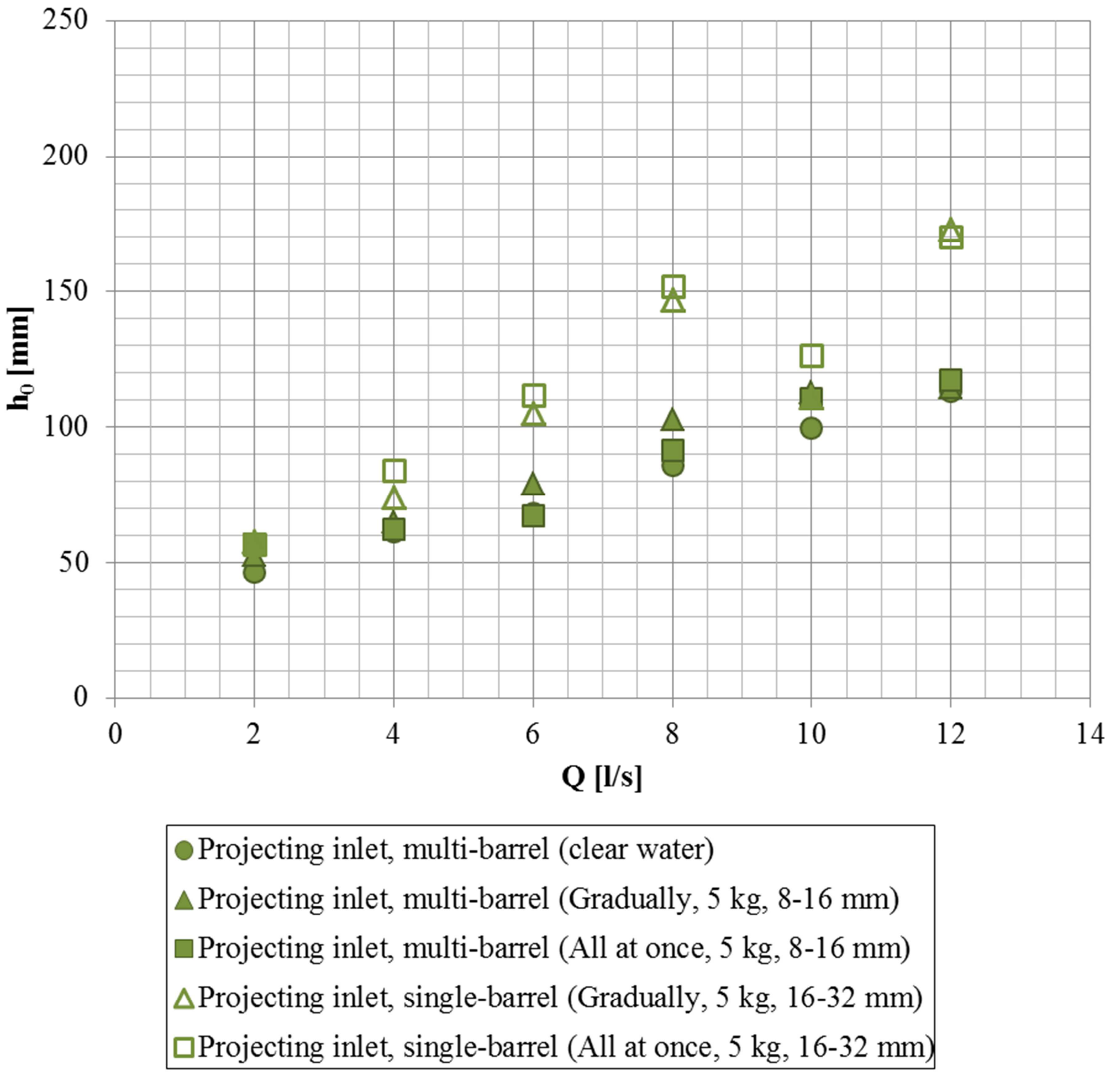


Figure B.72 Sediment effect in multi- and single barrel system with projecting inlet (based on the results of Faqiri (2014))

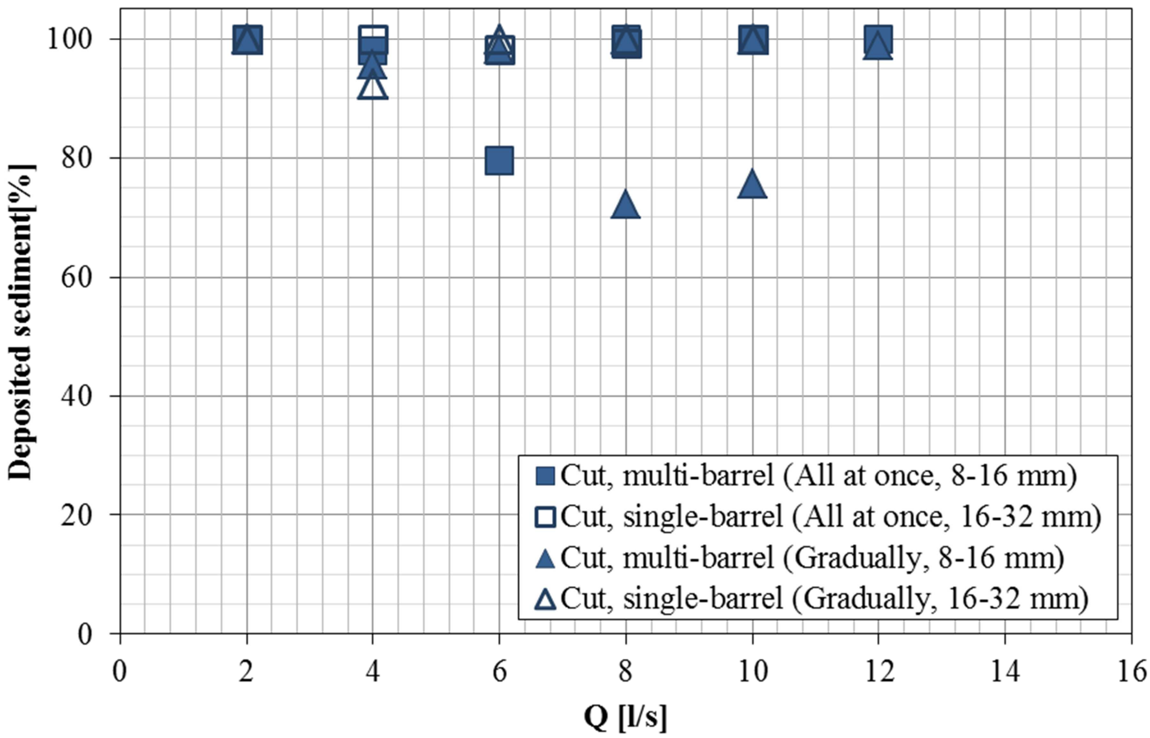


Figure B.73 Sediment deposition with multi- and single-barrel system in case of cut inlet (based on the results of Faqiri (2014))

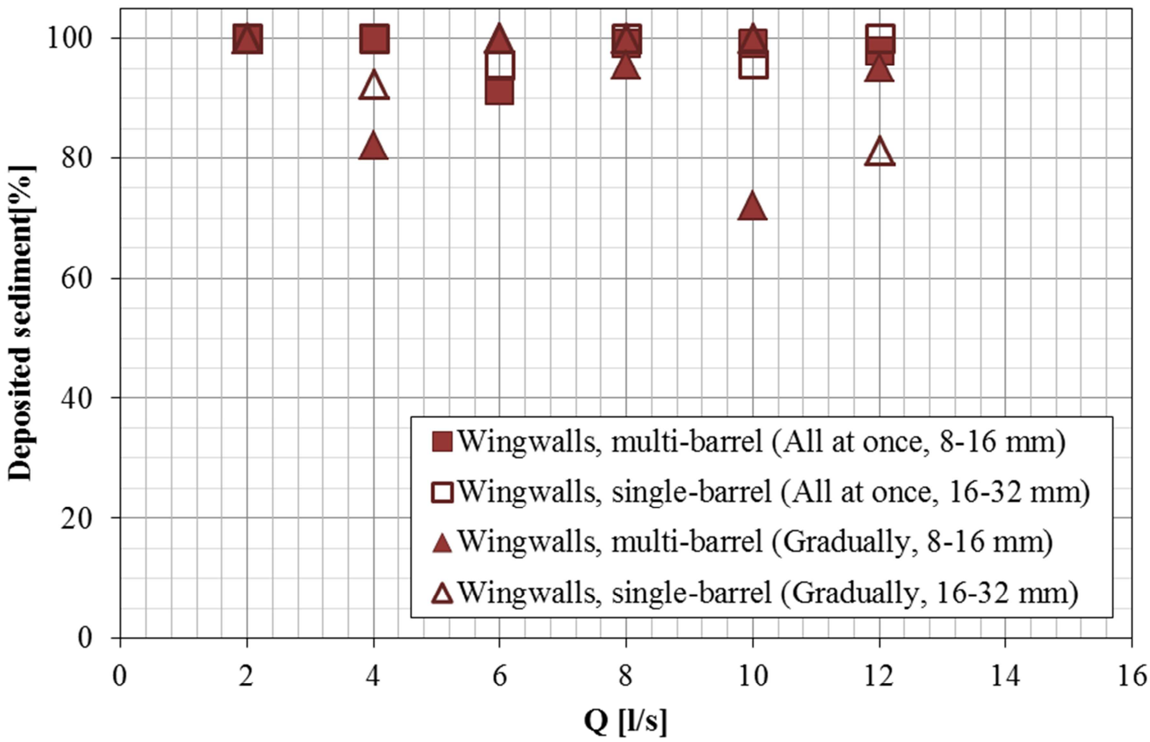


Figure B.74 Sediment deposition with multi- and single-barrel system in case of wingwalls (based on the results of Faqiri (2014))

Effect of trash racks and debris deflector: Slope: 1:9, Basin length: 876 mm, Basin width: 1100 mm, with energy dissipation

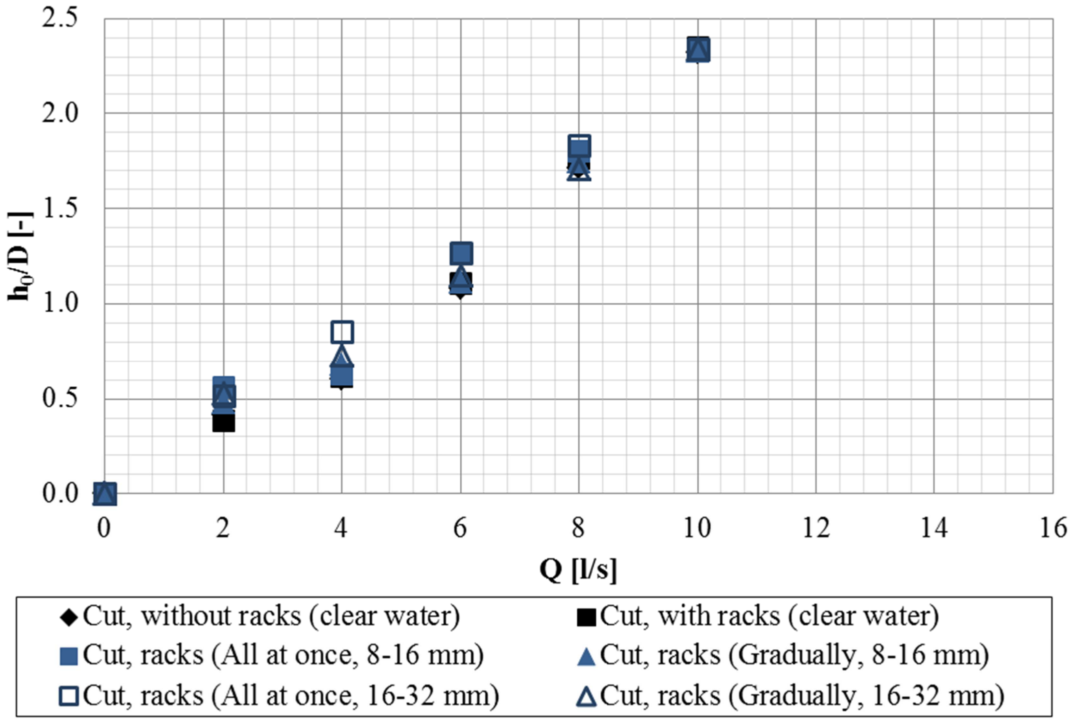


Figure B.75 Performance curves in case of cut inlet with trash racks (based on the results of Dirks (2014))

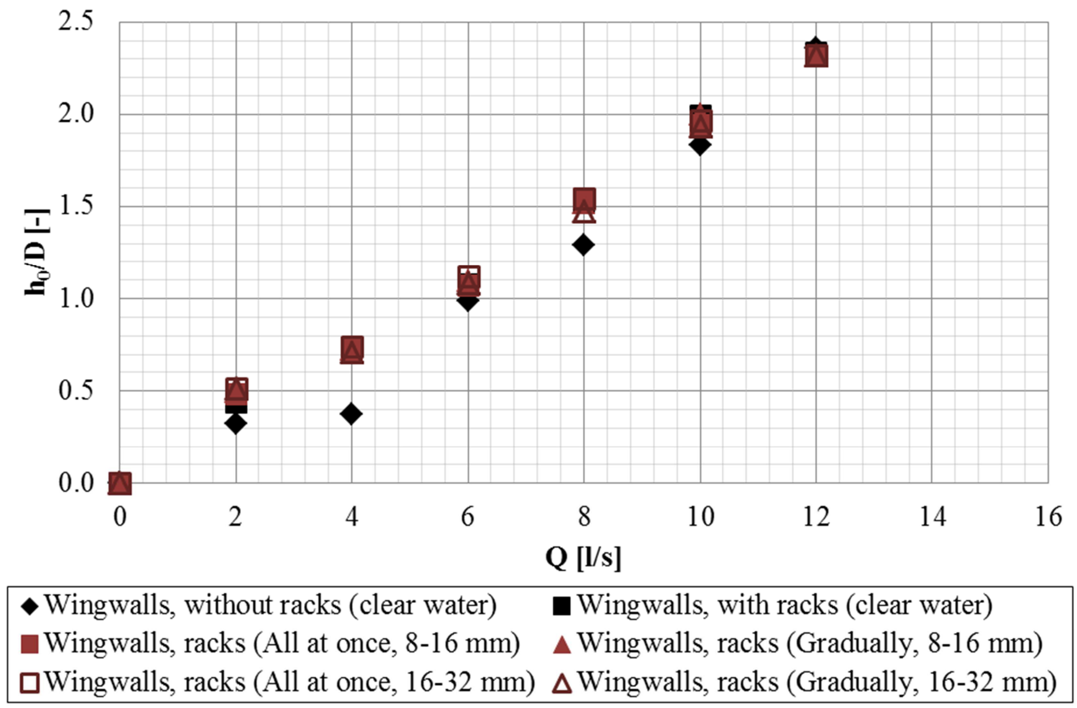


Figure B.76 Performance curves in case of wingwalls with trash racks (based on the results of Dirks (2014))

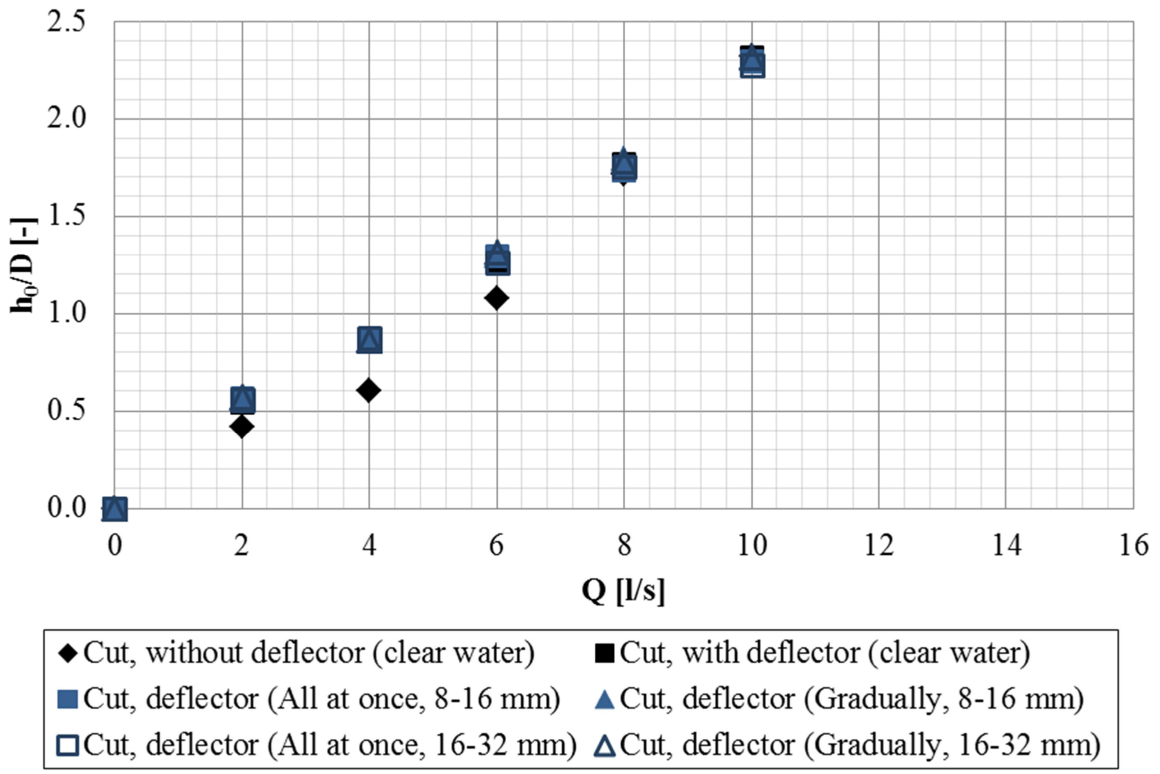


Figure B.77 Performance curves in case of cut inlet with debris deflectors (based on the results of Dirks (2014))

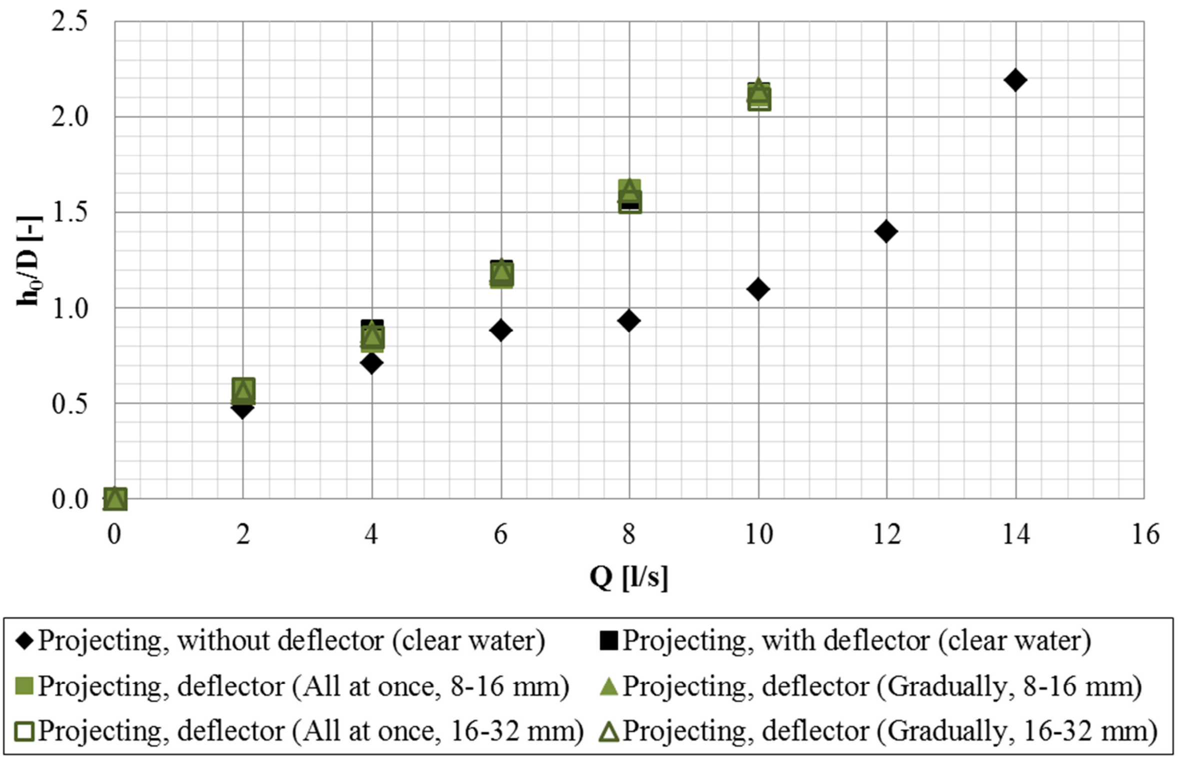


Figure B.78 Performance curves in case of projecting inlet with debris deflectors (based on the results of Dirks (2014))

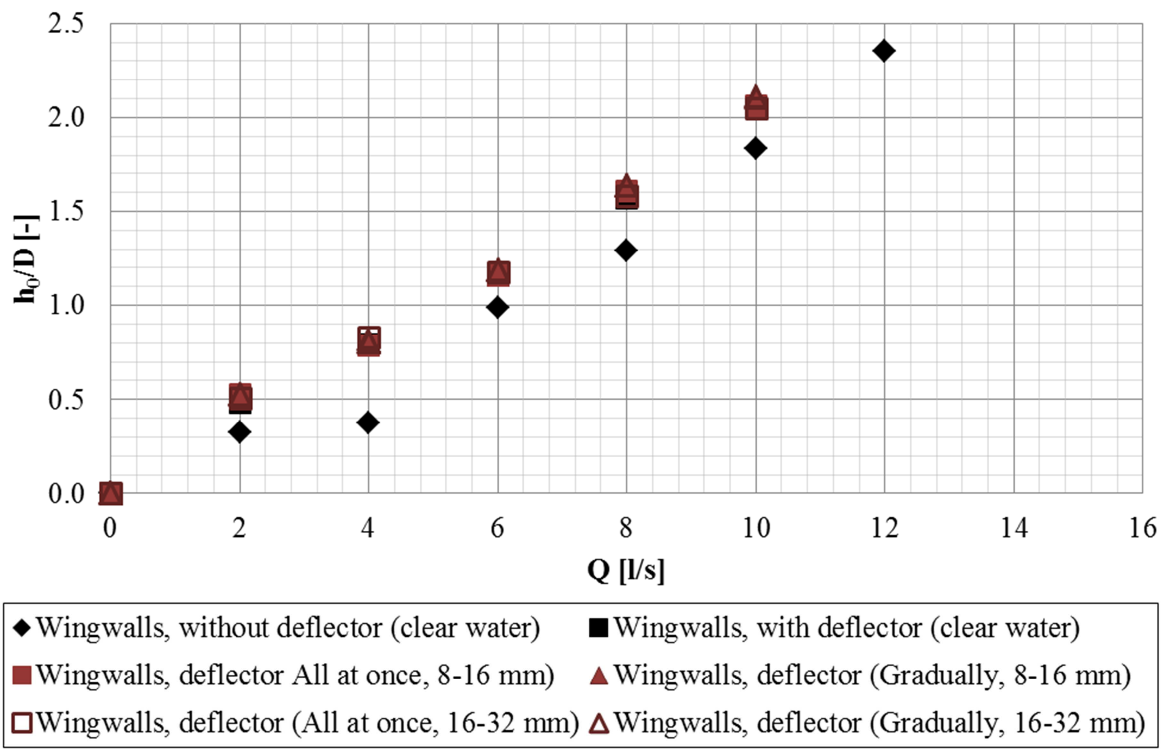


Figure B.79 Performance curves in case of wingwalls with debris deflectors (based on the results of Dirks (2014))

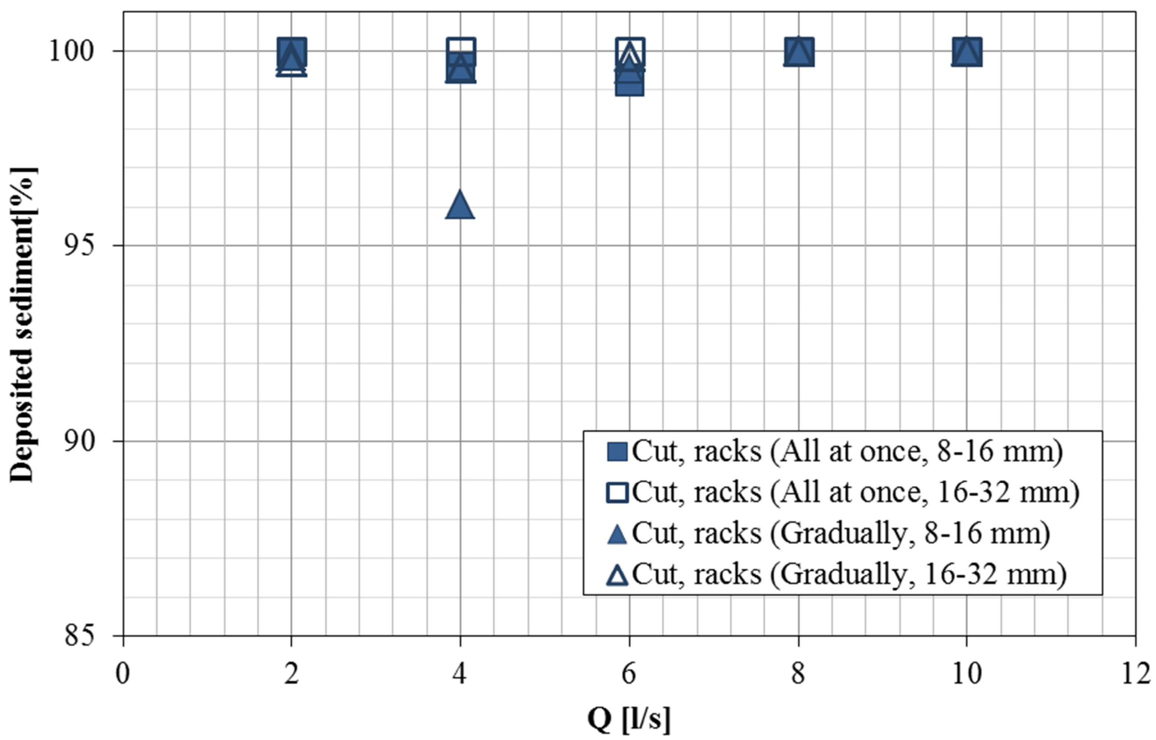


Figure B.80 B.81 Cut inlet with trash racks – sediment deposition (based on the results of Dirks (2014))

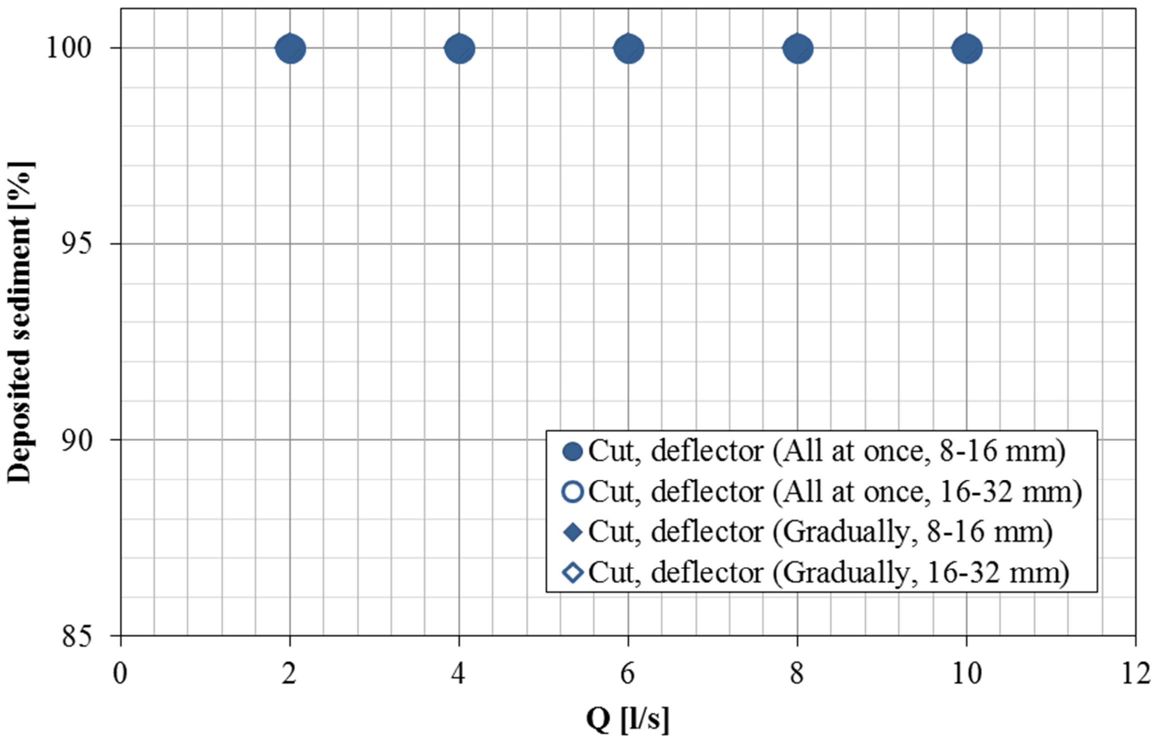


Figure B.82 Cut inlet with debris deflector– sediment deposition (based on the results of Dirks (2014))

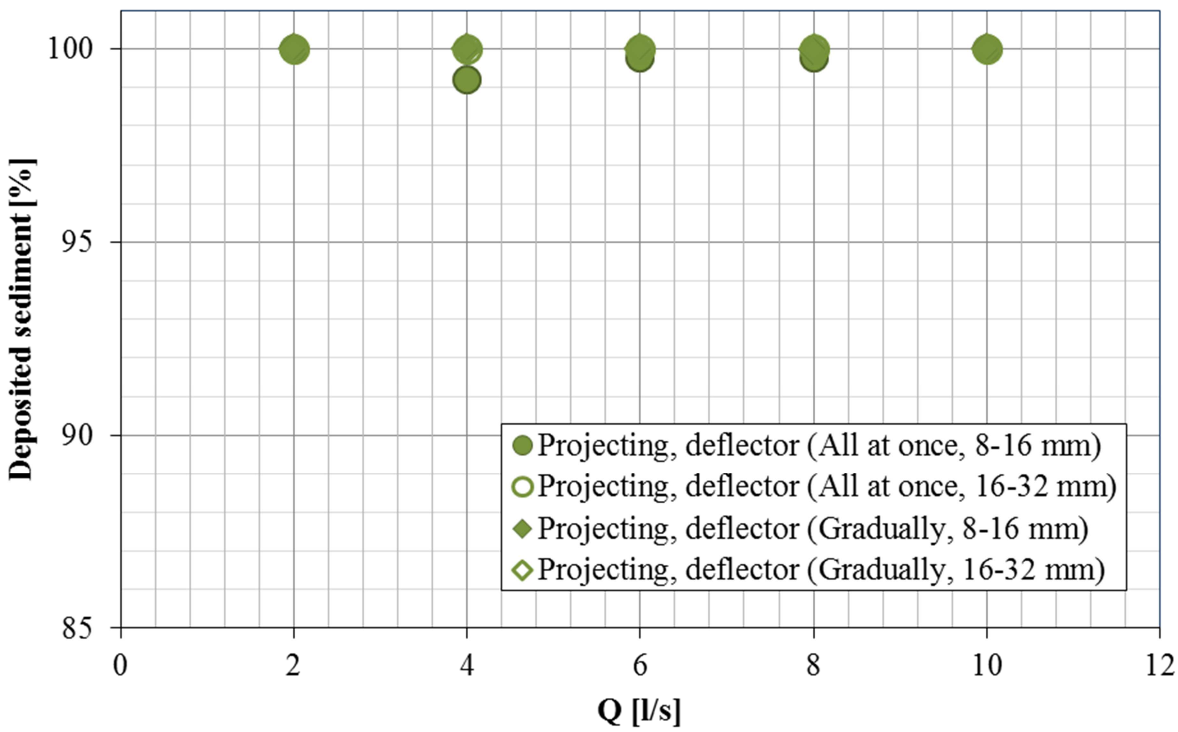


Figure B.83 Projecting inlet with debris deflector– sediment deposition (based on the results of Dirks (2014))

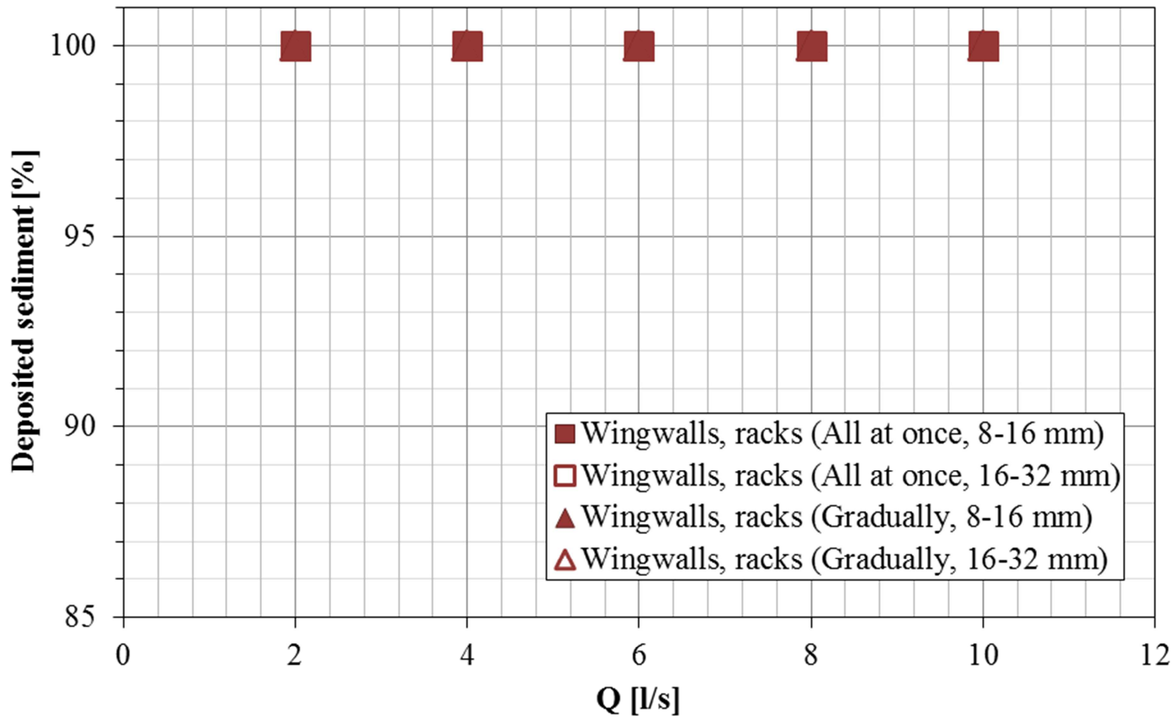


Figure B.84 Wingwalls with trash racks – sediment deposition (based on the results of Dirks (2014))

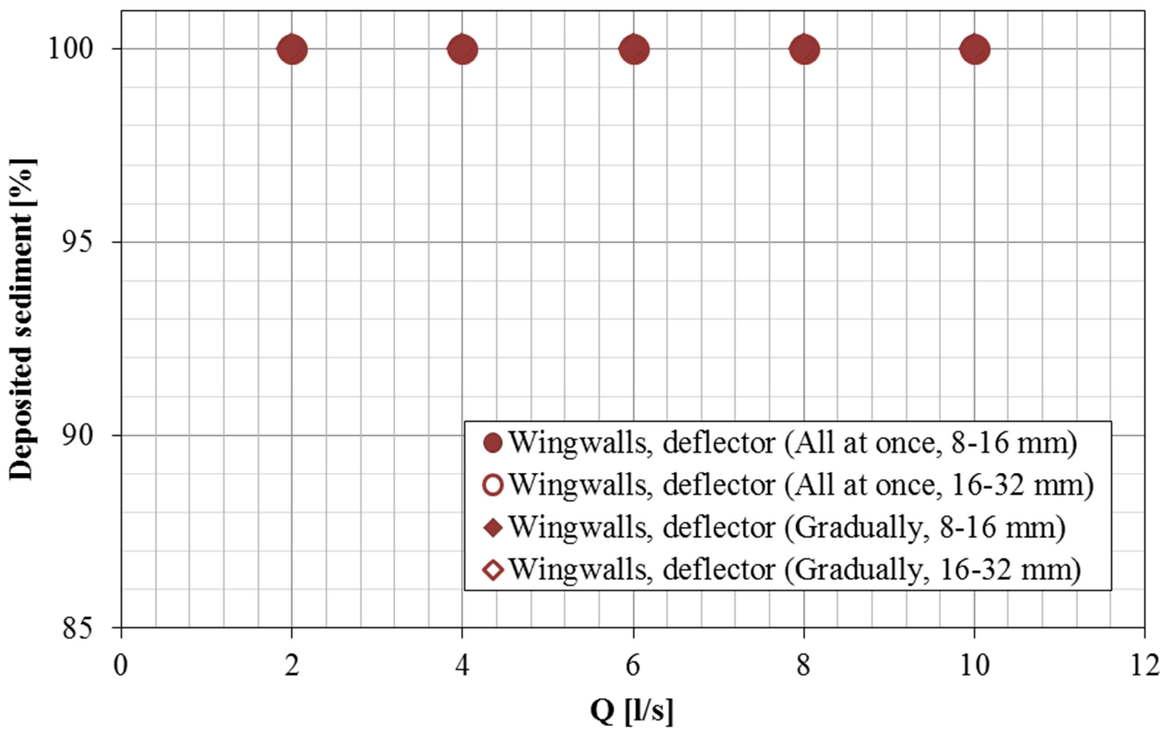


Figure B.85 Wingwalls with debris deflector – sediment deposition (based on the results of Dirks (2014))

Inlet shape effect

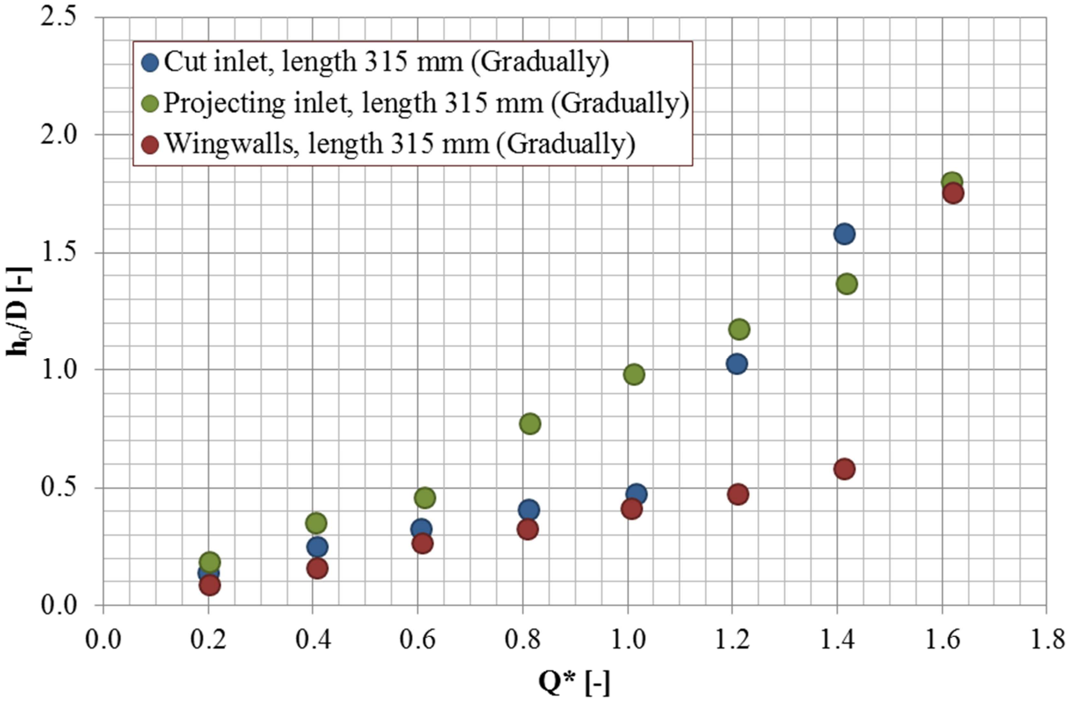


Figure B.86 Inlet shape effect – Slope 1:5 without energy dissipation, 315 mm basin length, 5 kg, 8-16 mm sized gradually fed sediment (based on the results of Gotvassli (2013))

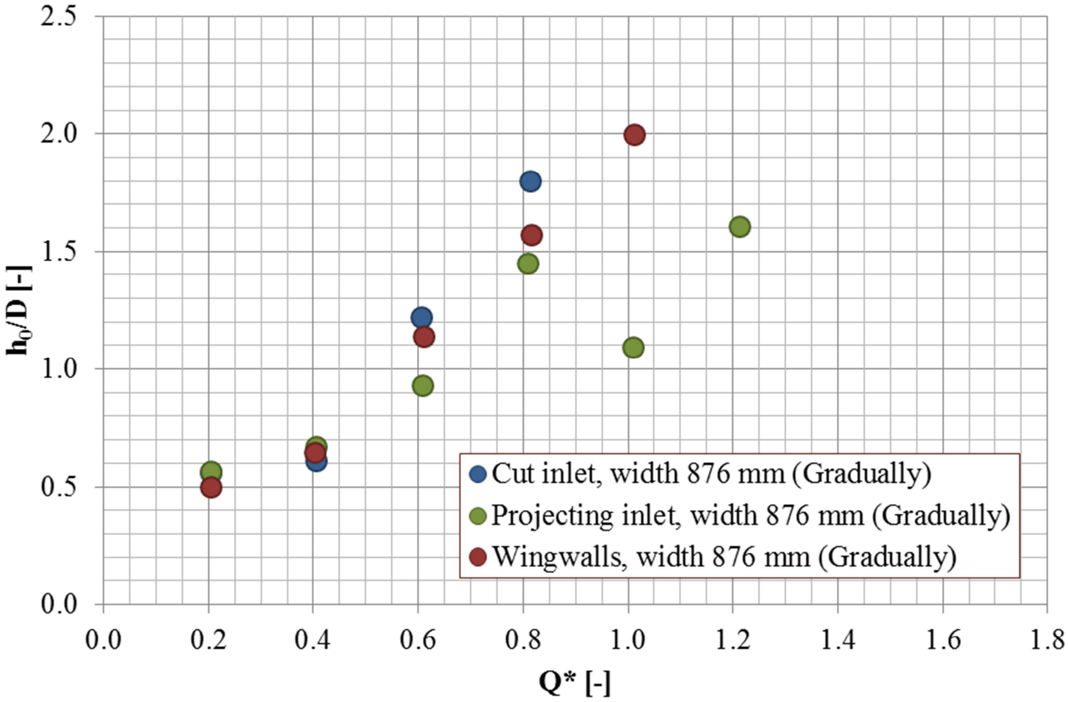


Figure B.87 Inlet shape effect – Slope 1:9 with energy dissipation, 876 mm basin width, 7 kg, 8-16 mm sized gradually fed sediment (based on the results of Putri (2014))

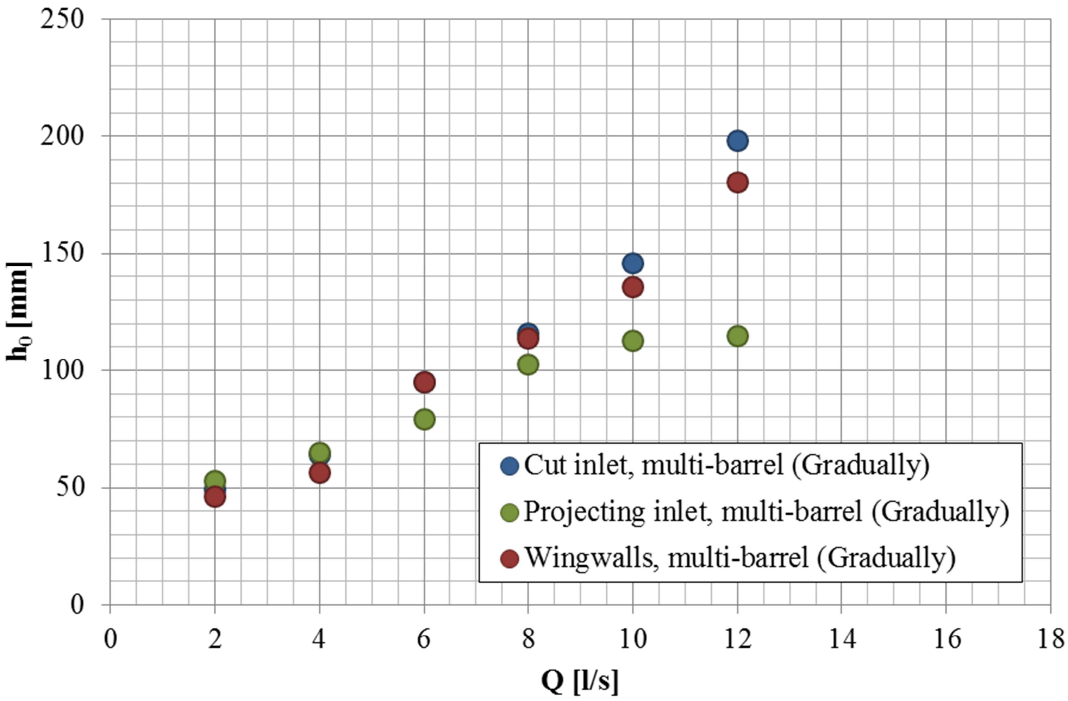


Figure B.88 Inlet shape effect - Slope 1:9 with energy dissipation, multi-barrel system, 5 kg, 8-16 mm sized gradually fed sediment (based on the results of Faqiri (2013))

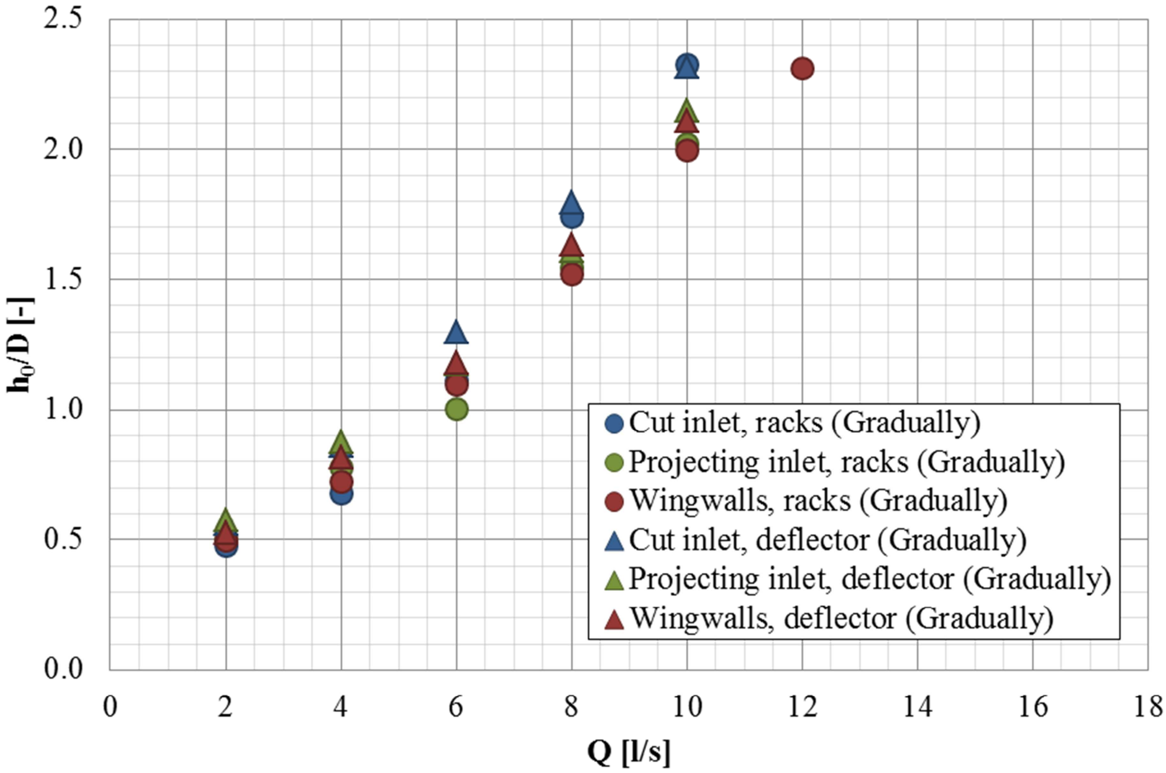


Figure B.89 Inlet shape effect - Slope 1:9 with energy dissipation, with sediment countermeasures, 5 kg, 8-16 mm sized gradually fed sediment (based on the results of Dirks (2013))