APPLICATION OF COLLARS AS A SCOUR COUNTERMEASURE FOR SPILL-THROUGH ABUTMENTS

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ABSTRACT

APPLICATION OF COLLARS AS A SCOUR COUNTERMEASURE FOR SPILL-THROUGH ABUTMENTS

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In the study the effect of collars on scour for spill-through abutments under clear-water conditions was investigated. Total of 70 experiments were conducted. Two abutments were placed on the opposite sides of a straight rectangular channel. Collars with different widths were placed at different depths around these abutments and reduction on scour was investigated for each case. Using different abutment lengths allowed investigation of collars at different contraction ratios and hence optimum collar configuration and depth was defined for abutments with various contraction ratios. It is concluded that collars are effective in reducing scour and protecting spill-through abutments against scour.

Keywords: Collar, Scour, Scour Countermeasure, Sediment Transport, Spill-through Abutments, Temporal Evolution of Scour.

ÖZ

EĞİMLİ YÜZEYLİ KÖPRÜ YAN AYAKLARINDA OYULMAYI ÖNLEYİCİ YATAY PLAKA UYGULAMASI

Yılmaz, Kutay
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Bu çalışmada, temiz su oyulması koşulları altında eğimli yüzeyli köprü yan ayakları etrafında oyulmayı önleyici yatay plaka uygulaması incelenmiştir. Çalışma kapsamında 70 deney yapılmıştır. Deneylerde, düz dikdörtgen bir kanalın karşılıklı iki yanına yerleştirilen köprü yan ayakları etrafında farklı derinliklerde yerleştirilmiş olan farklı genişliklerdeki yatay plakalarla oyulma miktarındaki azalma incelenmiştir. Ayrıca farklı uzunluklardaki köprü yan ayakları kullanılarak farklı daralma oranlarında oluşan koşullar da incelenmiştir. Bu şekilde oyulmayı azaltacak olan optimum yatay plaka konfigürasyonu ve ayak üzerindeki yeri farklı daralma oranları için belirlenmiştir. Plaka uygulamasının oyulmayı azaltmada ve köprü yan ayağını oyulmaya karşı korumada etkili bir yöntem olduğu sonucuna ulaşılmıştır.

Anahtar Kelimler: Yatay Plaka, Oyulma, Oyulma önlemi, Sediman, Köprü Yan Ayağı, Zamana Bağlı Oyulma Gelişimi.

To my family

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$A_{abutment}$	Abutment area on the horizontal plane
A_{total}	Total area of the abutment with collar
B_c	Collar width around the abutment
C	Cohesiveness
C_u	Uniformity coefficient
d_{50}	Median size of sediment
d_s	Local scour depth at the abutment at any time
$d_{s,max}$	Maximum scour depth at the abutment without collar
$d_{s\ max,c}$	Maximum scour depth at the abutment with collar
F_r	Froude number of flow
g	Gravitational acceleration
K_g	Approach channel geometry
K_s	Shape factor of abutment
L	Abutment length corresponding mid-depth of the flow
L_a	Shape factor of abutment
Q	Discharge of the flow
Re_*	Particle Reynolds number
S	Particle shape factor
S_0	Slope of the channel
S_e	Energy slope of flow
S_s	Specific gravity
t	Time
U	Mean approach flow velocity
U_*	Shear velocity of the approach flow
U_{*c}	The value of the U_* at the threshold of grain motion
U_c	The value of the U at the threshold of grain motion
U_f	Sediment fall velocity
W	Channel width
W_a	Abutment width
x	x axis in cartesian coordinate system
y'	y axis in cartesian coordinate system
y	Normal flow depth
y_c	Critical flow depth at the threshold of grain motion
Z_c	Collar level on the abutment with reference to bed level
B	Contraction ratio
θ	Ratio of total area of the abutment and collar to the abutment area

CHAPTER 1

INTRODUCTION

1.1 Background

Bridges are important part of the transport network. Lots of transportation network includes bridges so design, construction and maintenance of these structures are crucial. Flaw in design, construction or maintenance can results in loss of lives and economic damages.

Richardson et al. (1993) mentioned in his study that results of a study for Federal Highway Administration found out that 72% percent of bridge failures involved damaged abutments. Also Sutherland (1986) mentioned that 29 of 108 bridge failures in New Zealand related to abutment scour. In addition Macky (1990) mentioned that 70% of expenditures on bridges are due to abutment scour in New Zealand.

Wardhana and Hadipriono (2003) studied causes of bridge failures in U.S.A by considering bridge failure data obtained by Federal Highway Administration, NYDOT etc. between 1989 and 2000. According to the study causes of failures are divided into six major categories that include enabling (design, detailing, construction, maintenance and material related problems) and triggering (external related events) and hydraulic causes responsible for 53% of the failures.

Bridges constructed in channels which are filled with erodible material contract the flow in the waterway and cause scour. Continuous scouring around piers and abutments can end up with possible failure of the structure (Khwairakpam & Mazumdar, 2009). Scour may occur any time due to the flow conditions around abutments and piers as well as human related factors and hydrological events but its progress is fast during a flood event which can end up with sudden failure of the bridge.

There are lots of failures due to scour around the world. In April 2012 Çaycuma Bridge constructed in Filyos Creek, Zonguldak, Turkey, collapsed and a bus fell down to the river resulting in eleven people’s death. Moreover 4 people reported as missing and never found. Collapse of Çaycuma Bridge was investigated and main causes of collapse were determined as a scour around bridge foundation during excessive flood (Turkish Association for Bridge and Structural Engineering, 2014).

In 1987 Schoharie Creek Bridge collapsed and resulted in falling down of five cars in to the river and ten people’s death. Causes of failure were investigated by two teams WJE associates Inc. with Mueser Rutledge Consulting engineers and Thornto-Tomasetti P.C. Each team found similar results and concluded that cause of the failure is an extensive scour under pier three during flood (Storey & Delatte, ASCE).

Scour problem around bridges has been investigated for many years. Causes and mechanism of scour are sought by the researchers to develop countermeasure techniques. Due to the specific properties that each channel and bridge has, each scour problem can be evaluated as a unique case. Moreover, required countermeasure techniques have to be determined and applied for each bridge in order to prevent collapse of the structures as well as loss of lives.

1.2 Objectives

The main objective of this study is to investigate the effect of different sized collars on decreasing the maximum scour depth that is caused by local and contraction scour around spill-through abutments. Also temporal variation of scour around abutments was investigated. Experiments were conducted under clear-water conditions at a laboratory flume which has almost uniform sand.

1.3 Synopsis of the Thesis

In Chapter 2, review of the scour phenomena, parameters related to scour are covered as well as the mechanism behind the scouring process. Chapter 3 covers countermeasure methods against scour. In Chapter 4, experimental equipment and procedure described briefly. Results and findings of the experiments are presented in Chapter 5. In Chapter 6, conclusions which were drawn from the results of the experiments are summarized. For future studies, recommendations were made.

CHAPTER 2

SCOUR DEFINITON, TYPES AND MECHANISM

2.1 Introduction

Scour problem has been investigated by many researchers because scour around abutments and piers can cause damage to the hydraulic structures and can results in failure of the bridges with possible loss of life and economic damages. Therefore development and application of countermeasure techniques are important. However, before examining countermeasure techniques it is important to understand scour, scour mechanism and factors effecting scour in order to develop and apply necessary scour countermeasure.

2.2 Scour

2.2.1 Scour Definition

Scour is a special type of erosion which is defined as removal of erodible material by dynamic movement of water. Therefore, river beds around piers or abutments are lowered because of erosive movement of water which can end up with a failure of hydraulic structures. Amount of lowering of the river bed after commencement of the scour is defined as a scour depth (Melville & Coleman, 2000). Flowing water past a pier or abutment may scoop bed material out in the channel bed which are known as scour holes (Deng & Cai, 2010). Figure 2-1 show scour hole around bridge. It can be seen from the Figure 2-1 that scour hole is formed as a result of lowering of original riverbed.

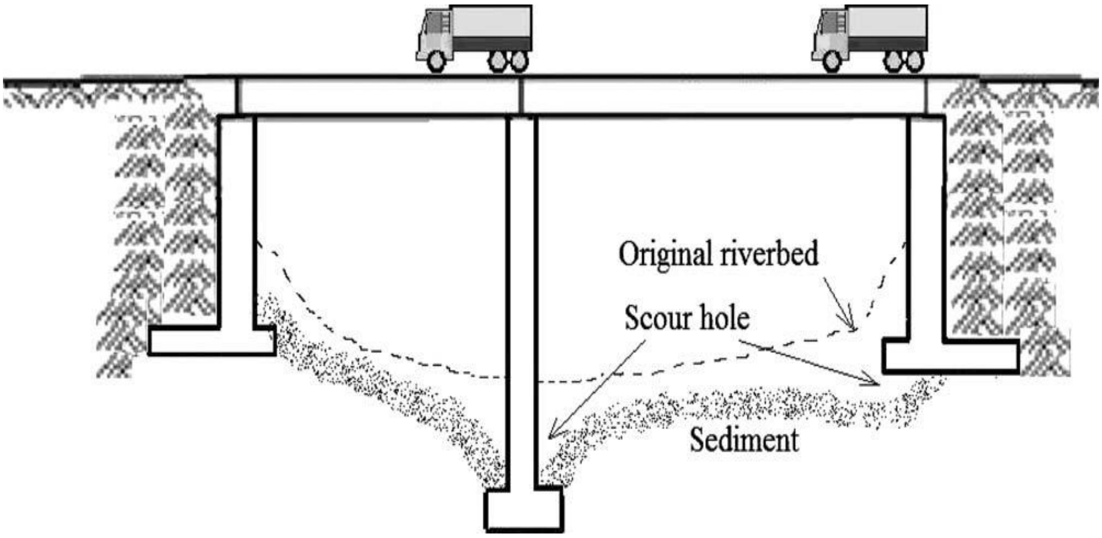


Figure 2-1: Scour hole around bridge (Deng & Cai, 2010).

2.2.2 Types of Scour

Scour can be classified into three types which are;

- General scour
- Contraction scour
- Local scour

General Scour is defined as the lowering of streambed by time which is independent of existence of hydraulic structures such as bridges, piers and abutments. It can occur either in a short term or long term and two of them are distinguished by time passed for scour development.

Short term general scour is caused by single or consecutive floods (Melville & Coleman, 2000).

Long term general scour also defined as the lowering of streambed by natural causes and man-made activities occurs in longer time scale than short term general scour. Moreover it is related to the progressive degradation and lateral bank erosion.

Progressive degradation means lowering of streambed by hydrometeorological, geomorphological changes or human related factors. On the other hand, lateral bank erosion can be defined as the undermining of a bank due to stream (Melville & Coleman, 2000).

Contraction scour is directly related to the existence of the hydraulic structures such as abutments, piers, bridges etc. When flow is approaching to these structures, streamlines adjoin due to the contraction that is caused by them. Flow within the bridge openings is accelerated as a result of the decrease in the cross sectional area. Passing the contracted region, flow is decelerated. This acceleration triggers the scour at the contracted section (Melville & Coleman, 2000).

Local Scour is defined as removal of the erodible material from around the abutments, piers and embankments. It is caused by the interaction of hydraulic structures with flow which results in the scour formation around abutments, piers etc. (Melville & Coleman, 2000).

Richardson and Davis (2001) noted that there are two conditions for contraction and local scour which are clear-water scour and live-bed scour. Scour is named as clear-water scour if bed material is not moved by the flow at the upstream or bed material in the upstream is transported in suspension through the scour hole around abutment or pier. On the other hand, scour is named as live-bed scour if bed material is transported from upstream to the crossing

2.3 Scour Mechanism

Scour mechanism around bridge piers has been investigated for several years and mechanism behind the pier scour is well understood by the studies of Melville (1974) and Ettema (1980) (Li et al. 2006). Studies of Wong (1982), Kandasamy (1985, 1989) and Dongol (1994) show that mechanism behind the abutment scour is similar to the pier scour mechanism. Therefore, basic mechanism causing scour is the formation of vortices. Horseshoe vortex caused due to the pile up of water on the upstream of the abutment and causes the flow to accelerate around frontal part of the abutment. Occurrence of vortex causes the removal of bed material around the abutment. Amount of sediment carried out around the abutment by the vortices are higher than the amount of sediment carried towards the abutment so that scour hole is formed. However, as the depth of scour increases, strength of the horseshoe vortex decreases. Vortex patterns are determined by dye injection at the experiment conducted by various researchers such as Liu (1961) and Gill (1970).

Koken and Constantinescu (2006) studied the physics behind the scour process. They concluded that vortex is very strong at the upstream between abutment and bed jet flow while at the downstream it disappears.

Hagerty and Parola (1992) reported that seepage can be an additional force contributing to scour. Pressure difference caused by flow separation formed seepage into and out of the abutment foundation so that seepage forces carry sediments out of the bed when seepage occurs beside the abutment. Figure 2-2 shows the parameters that cause scouring of bed material.

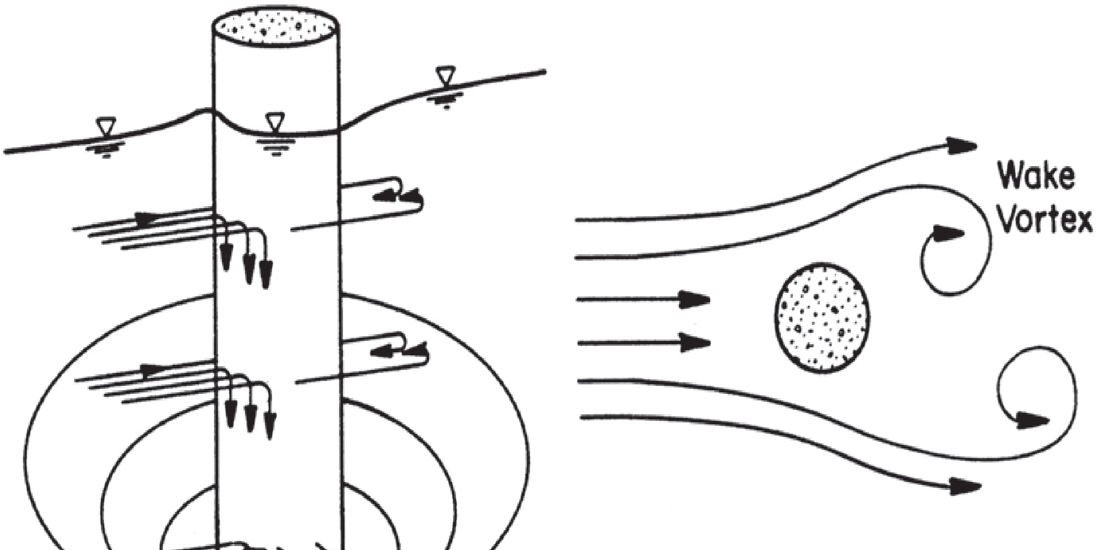


Figure 2-2 : Scour formation around pier (Richardson & Davis, 2001).

2.4 Parameters Related to Scour

Scour is a complex phenomenon and is affected by the parameters related to the properties of fluid, flow, channel, abutment and material. These parameters and related properties which are also given in Table 2-1 are classified as follows;

1. Parameters related to properties of the channel geometry; slope, width and cross sectional shape.
2. Parameters related to properties of the abutment such as; shape, size, orientation, projected length of the abutment.
3. Parameters related to properties of the sediment such as; angle of repose, median size and grain size distribution.
4. Parameters related to properties of the fluid such as; temperature, density, viscosity, gravitational acceleration.
5. Parameters related to properties of the flow such as; mean velocity, depth of flow, shear velocity.
6. Also time passed during scour event is important in the process.

Table 2-1 : Parameters Influencing Local Scour at Abutments (Li, Kuhnle & Barkdoll, 2006).

Variable Name	Symbol	Attribution
Length of Abutment	L_a	Abutment
Angle of Attack	α	
Shape of Abutment	K_s	
Normal Flow Depth	y	Flow
Mean Approach Velocity	U	
Gravitational Acceleration	g	
Energy Slope of Flow	S_e	
Width of Channel	W	Channel
Slope of Channel	S_0	
Geometry of Channel	K_g	
Median Size	d_{50}	Bed Material
Specific Gravity	S_s	
Standard Deviation	σ_g	
Fall Velocity	u_f	
Particle Shape Factor	S	
Angle of Repose	ϕ	
Cohesiveness	C	
Dimensionless Critical Shear Stress	τ	
Particle Reynolds Number	Re_*	
Density	ρ	Fluid
Dynamic Viscosity	μ	
Temperature	T	
Time	t	Time

To improve the effectiveness of countermeasures against scour, various parameters related to scour should be investigated. Therefore; important parameters related to the abutment scour are explained in details below.

2.4.1 Flow Velocity and Flow Intensity

Barbhuiya et al. (2004) noted that the flow velocity is included in the formula that is used to approximately determine the maximum scour depth. In the formula flow velocity is used either as a part of Froude number, Fr, or shear velocity, U_*. According to Garde et al. (1961) use of Froude number Fr for the calculation of maximum scour depth is sufficient to represent the effect of flow velocity on scour depth. On the other hand, according to Richardson et al. (1991) an increase in the flow velocity ends up with deeper depths in the scour hole.

Flow intensity can be expressed either as a ratio of shear velocity U_* to critical shear velocity U_{*c} or ratio of approach velocity U to critical velocity U_c. Li et al. (2006) noted that shear velocity ratio represents the strength of the down flow or scouring potential of the vortex structures. However, velocity ratio is used as flow intensity due to the difficulties in determining shear velocity.

Dongol (1994) found that there is almost linear correlation between scour depth and flow velocity until the threshold of live-bed condition. After flow transforms into live-bed condition, the scour depth changes depending on the bed regime of approach channel. Studies of Gill (1972), Kandasamy (1989) and Dongol (1994) show similar results which indicate increasing trend between scour depth and flow velocity.

Clear-water scour takes place when approaching flow velocity, U, is smaller than the critical velocity, U_c which is required for entrainment of the bed material ($U/U_c \leq 1$). On the other hand, live-bed scour takes place if $U/U_c \geq 1$. Under clear-water condition ($U/U_c \leq 1$), the maximum scour depth occurs at the threshold of live-bed condition which means $U=U_c$. After passing threshold condition, which means at live-bed condition, that is $U \geq U_c$ the scour depth initially decreases with increasing velocity after reaching minimum it increases to a second maximum. (Barbhuiya & Dey, 2004)

Melville (1992) noted that after passing the flat bed condition, the scour depth decreases with increasing velocity due to the antidunes formation.

2.4.2 Flow Depth

Experimental studies conducted by Wong (1982), Tey (1984), Kwan (1988), Kandasamy (1989) and Dongol (1994) show that for constant shear velocity ratio U_*/U_{*c} the scour depth at an abutment increases with an increasing flow depth at a decreasing rate until effect of flow depth becomes negligible. This trend does not depend on live-bed scour condition or clear-water scour condition (Barbhuiya and Dey, 2004).

According to Dey & Barbhuiya (2004a) scour depth increases significantly with increasing flow depth for shallow depths, on the other hand, the scour depth is independent of flow depth for higher flow depths.

Richardson and Davis (2001) noted that an increase in the flow depth can increase the maximum scour depth by a ratio of 1.1 to 2.15 depending on the shape of the abutment.

2.4.3 Abutment Length and Contraction Ratio

Abutment length is an important parameter that has an effect on scour around abutments. Effect of abutment length was investigated by Laursen (1962), Garde (1961), Gill (1970), Zaghloul (1983), Kwan (1984), Kandasamy (1989), Melville (1992) and Dongol (1994). Different dimensionless parameters such as contraction ratio, opening ratio that is inverse of contraction ratio and abutment length to flow depth ratio are used to evaluate the effect of abutment length on scour (Li, Kuhnle & Barkdoll, 2006). Husain, Quraishi and Ibrahim (1998) concluded that scour depth increases with a decreasing contraction ratio if other parameters are kept constant. Study of Dongol (1994) shows that increment in scour depth is negligible for $L_a/y \geq 60$ and scour depth remains unchanged for $L_a/y \geq 100$ where L_a is the abutment length and y is the flow depth. Study of Kayatürk (2005) shows that for a constant Froude number, the maximum scour depth increases with an increasing abutment length.

2.4.4 Abutment Shape

Abutment shape plays an important role on the scour depth. If the shape of an abutment is more like a blunt body, then turbulent vortices are stronger which results in a larger scour depth. On the other hand, abutments with streamlined shapes cause relatively smaller scour depths. Laboratory experiments of Liu et al. (1961), Garde et al. (1961) and Wong (1982) show that vertical wall abutments form larger scour depths then spill-through and wing wall abutments (Barbhuiya and Dey, 2004).

Melville (1992) proposed a shape factor K_s to express the effects of abutments with different shapes on the scour. A vertical plate is taken as a reference which means shape factor of a vertical plate is one. In addition, length of spill-through abutments is taken as the corresponding length at mid depth of the flow. Shape factors of different shapes are given in Table 2-2. Moreover, longer abutment length, L_a, causes shape factor, K_s to diminish so adjusted shape factor K_{s*} proposed by Melville for nondimensional abutment length, L_a/y, greater than 10. (Li, Kuhnle & Barkdoll, 2006)

Table 2-2: Shape Factors (Melville, 1995).

Abutment Shape	Shape Factor K_s
Vertical Plate or Narrow Vertical Wall	1.00
Vertical Wall Abutment with Semicircular end	0.75
45 Wing Wall	0.75
Spill-Through (H:V):	
0.5:1	0.60
1:1	0.50
1.5:1	0.45

2.4.5 Abutment Skewness

Abutments are generally straight and normally oriented to the flow directions on the rivers. However, due to the road conditions or channel geometry the abutment axis may have different angles with the flow direction. The angle between the abutment and the flow directions is defined as abutment skewness as illustrated in Figure 2-3. Also it is referred as angle of attack and independent of whether live-bed conditions or clear-water conditions are present (Barbhuiya and Dey, 2004).

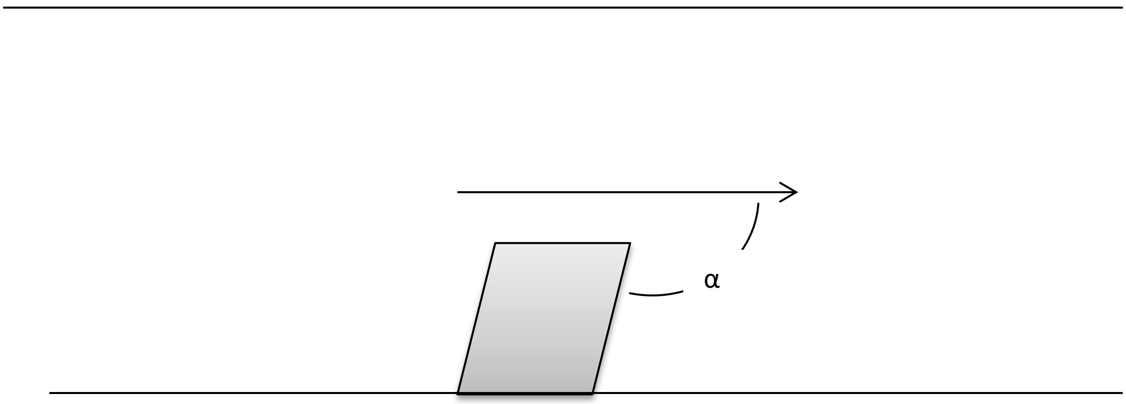


Figure 2-3: Abutment skewness.

Previous studies show that if an abutment is aligned towards upstream where $\alpha \leq 90$ scour is increased (Barbhuiya and Dey, 2004). Melville (1992) developed an abutment alignment factor, K_α which is shown in Table 2-3 for different angles and concluded that alignment factor K_α increases with increasing angle α. Also abutment alignment factor depends on abutment length. Therefore, alignment factor can be applied to the abutment with nondimensional lengths of $L_a/y \geq 3$. For short abutments having nondimensional length of $L_a/y \leq 1$ alignment factor is negligible. So in order to adjust abutment skewness for different lengths Mellville (1992) proposed an update for the alignment factor changing with nondimensional abutment length La/y.

Table 2-3: Alignment Factor for Different Angles (Melville & Coleman, 2000).

α (deg)	30	45	60	90	120	135	150
K_α	0.90	0.95	0.98	1.00	1.05	1.07	1.08

2.4.6 Sediment Gradation

Sediment gradation is defined as a geometric standard deviation of the sediment particle distribution and denoted as σ_g. It is considered as a measure of uniformity (Barbhuiya & Dey, 2004).

According to report by Li et al. (2006) effect of sediment gradation on scour vary depending on whether the live-bed scour or clear-water scour conditions are present. It is reported that scour is smaller for nonuniform sediments than uniform sediments if other conditions are the same so the scour depth decreases significantly with increasing σ_g.

According to studies which were conducted by Dongol (1994) increasing σ_g causes thicker armor layer which prevents the movement of sediments. Therefore, the scour depth decreases. Moreover, effect of sediment gradation on scour is more significant at low velocities.

2.4.7 Sediment Size

In the early studies effect of sediment size on scour is controversial but later studies for clear-water scour condition show that scour depth increases with increasing sediment size for fine sediments. On the other hand, scour depth decreases with increasing sediment size for coarse sediments (Li et al., 2006).

Li et al. (2006) noted that Dongol (1994) studied the effect of sediment size on scour by using sediment size relative to abutment length L_a/d_{50} where d_{50} is the median sediment size and L_a is the abutment length and classified the parameter by 4 groups which are;

- L_a/d_{50} >100: Fine sediment
- 40< L_a/d_{50} <100: Intermediate sediment
- 10< L_a/d_{50} <40: Coarse sediment
- L_a/d_{50} <10: Very coarse sediment

Dongol (1994) also found that scour depth decreases when sediment gets coarser, in other words, if d_{50} decreases between $10 < L_a/d_{50} < 40$. There is no effect of sediment size on scour for $L_a/d_{50} < 10$.

2.4.8 Time

Protection of bridge foundation from scour is crucial and the necessary protection can be provided by knowing the maximum scour depth. On the other hand, knowing the temporal variations in scour depth and the time required to reach the equilibrium scour conditions are also important in protection of bridge foundations (Li, Kuhnle & Barkdoll, 2006).

Li et al. (2006) mentioned that scour depth increases dramatically with time before reaching to the equilibrium condition. Moreover, according to Cunha (1975), time required for equilibrium scour conditions is longer for clear-water conditions compared to live-bed conditions.

Hoffmans and Verheij (1997) defined four phases for abutment scour as: an initial phase, development phase, stabilization phase and equilibrium phase. They also added that long abutment lengths require exponential expression. Study of Ballio and Orsi (2001) match up with Hoffmans and Verheij’s (1997) result which suggest the use of exponential expression for scour depth development with time (Coleman, Lauchlan & Melville, 2003).

Cardoso and Bettess (1999) defined two phases in scour as a principle phase and an equilibrium phase for compound channels.

Santos and Cardoso (2001) studied the parameters that affect the temporal evolution of scour. As a result they found that scouring time depends on flow intensity and relative abutment size and independent of relative sediment size (Coleman, Lauchlan & Melville, 2003).

CHAPTER 3

SCOUR COUNTERMEASURES

3.1 Introduction

Undermining of bridge piers or abutments due to scour can cause collapse of the bridge which may result in possible deaths, high costs of repair and disruption of transportation. Extensive studies over scour around piers and abutments helped researchers to understand the scour mechanism and causes of scour so that countermeasure techniques can be developed (Deng & Cai, 2010).

Hydraulic countermeasures against scour can be divided into two categories. These are:

- River training countermeasures or flow altering countermeasures
- Armoring countermeasures

Main principle of armoring is to protect erodible material by providing additional layer. On the other hand, flow altering countermeasures protect erodible material by changing hydraulic properties of the flow. Riprap is the most commonly used armoring countermeasure. Cable-tied blocks, geobags, concrete aprons are other armoring countermeasures techniques. On the other hand collars, spur dikes and parallel walls are the flow altering countermeasures (Deng & Cai, 2010). Table 3-1 represents the advantages and disadvantages as well as basic principles of countermeasures.

Table 3-1: Armoring vs. Flow Altering Countermeasures (Deng & Cai, 2010).

	Armoring Countermeasures	Flow-altering Countermeasures
Principle	Protect the bed materials underneath the armoring layer from being scoured away	Alter the flow alignment or break up vortices and therefore reduce the scour effect
Advantages	Most commonly used type; easy to use; works well in most situations	Different designs can be selected for different site conditions to achieve satisfactory results
Problems	Winnowing of sands through the armor; difficult to keep the armor in place; constrict the channel and cause additional contraction scour	Special design may be needed for particular site conditions; significant cost and construction of new structures may be needed

Most common types of both armoring and flow altering counter measures are explained in the following parts.

3.2 Riprap

Melville et al. (2006) noted that Riprap is the most commonly used type of armoring countermeasures. Riprap as a scour countermeasure was studied by Simon and Lewis (1971), Macky (1986), Pagan-Ortiz (1991). Riprap is formed by loose and coarse elements of natural stone which are heavy and placed on the bed material to provide armoring layer. Resistance of bed covered by riprap increases due to the weight and withstands higher velocities and turbulences. Typically riprap is applied to slopes of embankments to protect sediment. Also a riprap apron construction near the toe of the embankment slope is recommended as an alternative. Therefore scour depth is reduced due to the coverage of scour area by a riprap apron (Barkdoll, Ettema & Melville, 2007). Table 3-2 shows the advantages and disadvantages of riprap application.

Application of riprap on spill-through abutments does not reduce the depth of scour but deflect the scour hole away from around the abutment. Moreover, scour hole is deflected away and reduced in size with increasing abutment toe protection if scour hole formed in flood channel. On the other hand if scour hole is close to the main channel bank, the size of the scour hole can increases with increasing abutment toe protection (Melville et al., 2006). Application of riprap apron around abutment in laboratory can be seen in Figure 3-1.

Table 3-2: Advantages and Disadvantages of Riprap (Barkdoll, Ettema & Melville, 2007).

Advantages of Riprap	Disadvantages of Riprap
Natural appearance that can be enhanced by vegetation	Limited availability and relatively high cost in some areas
Flexibility	Environmental restrictions on use
Tendency to be self- healing	variations in quality
Extensive experience and design guidance to support its use	Difficulties of transport and placement in some locations
Ease of repair of local failures	
Relative ease of construction	

Figure 3-1: Riprap application before and after scour (Barkdoll, Ettema & Melville, 2007).

3.2 Cable Tied Blocks

Cable tied blocks (CTB) compose of concrete blocks or slabs connected with steel, copper or synthetic cables. One concrete block itself can be unstable and cannot resist the flow but connected concrete blocks can resist much higher velocities and prevent movement of bed material and therefore scouring where it is applied (Barkdoll, Ettema & Melville, 2007). According to Melville et al. (2007) primary advantages of CTBs can be listed as;

- Ease of construction
- Minimal damage to river channel
- Lower weight per unit area covered than riprap

Barkdoll (2007) reported that studies about use of Cable Tied Blocks as scour countermeasures are limited and mostly used in pier scour cases. McCorquodale (1993), Parker (1998), Eve (1999) studied effects of CTBs on pier scour while Hoe (2001) studied the effect of CTBs on abutment scour. Hoe (2001) conducted experiments to observe effect of CTBs to protect spill-through abutments from scour. After 24 hours of experiment conducted under clear-water conditions slope remained stable despite the significant scour. CTB application to abutment in laboratory can be seen in Figure 3-2.

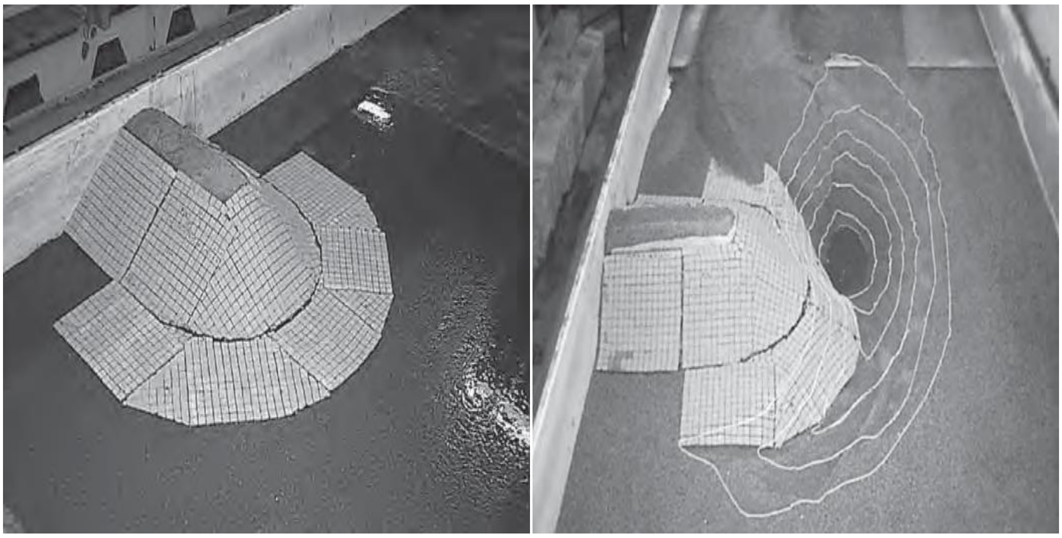


Figure 3-2: Cable tied blocks application before and after scour (Barkdoll, Ettema & Melville, 2007).

3.3 Geobags

Geobags are geo-syntheic containers and typically used as a scour countermeasure in coastal engineering. Geobags can be filled with sediments, soils or concrete and can be formed in different sizes. Use of geobags as an abutment scour countermeasure is not common. Sand filled geobags as an abutment countermeasure is more protective than riprap because geobags are not winnowed as ripraps. Also size and weight of geobags can be easily arranged to resist scour effects (Barkdoll, Ettema & Melville, 2007).

Study of Korkut (2007) showed that it is not possible to prevent local scour completely by using apron of geobags but use of geobags is an alternative for of riprap as an abutment scour countermeasure. In addition connection of geobags is recommended in order to prevent failure. Figure 3-3 shows the geobags application to abutment in laboratory.

Figure 3-3: Geobags application before and after scour (Barkdoll, Ettema & Melville, 2007).

3.4 Spur Dikes

Spur dikes are structures that are projecting from bank to channel which are common river training structures that are used to improve navigation, for flood control and to protect erodible banks (Copeland, 1983). Concrete, earth, rock, steel or timber can be used as a material in spur dike construction. Also they can be designed to submerge all the time as well as submerged in the flood events (Barkdoll, Ettema & Melville, 2007).

Existence of spur dikes around abutment reduces the scour around abutment by changing flow direction. As it can be seen from the Figure 3-4 spur dikes are placed perpendicular to flow at different locations such as upstream or downstream of the abutment and prevent floodplain flow to collide the face of the abutment so that scour around abutment can be reduced. Although wake vortices can be formed due to the existence of spur dikes effect of these vortices can be minimized by selecting the proper configuration of the spur dikes around abutment (Barkdoll, Ettema & Melville, 2007).

Spur dikes as an abutment scour countermeasure is studied by Li et al. (2005). They located spur dikes to different positions around the abutment to achieve higher reduction in scour. Moreover, they found that single spur dike at the upstream of the abutment where scour is most likely to occur is not sufficient enough to reduce scouring. Three spur dikes that is configured as one at the each corner of the abutment and one at the upstream of the abutment or one at the abutment corner , one at each upstream and downstream of the abutment found as best configuration to prevent abutment scour. Also rock materials instead of rigid materials were recommended.

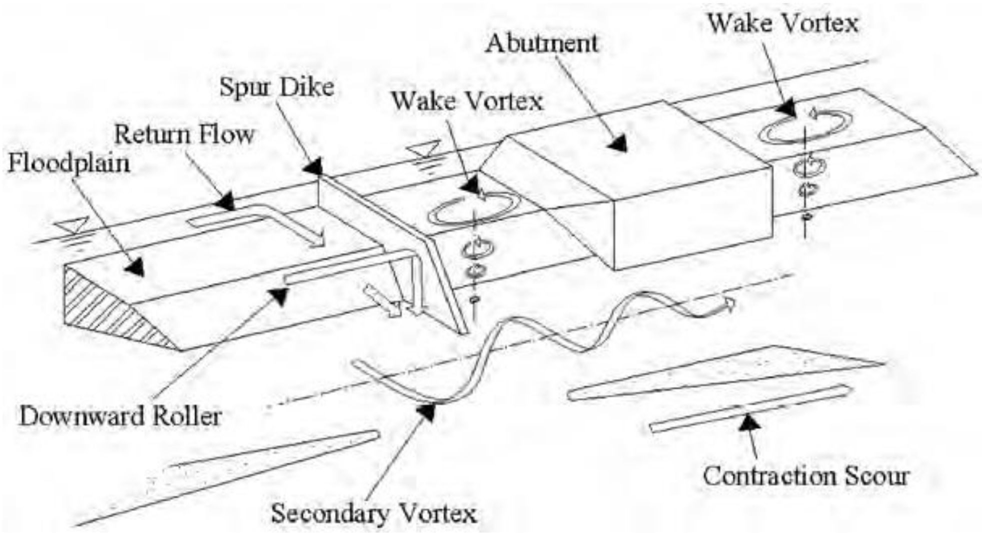


Figure 3-4: Flow patterns with spur dike application (Barkdoll, Ettema & Melville, 2007).

3.5 Parallel Walls

As the name implied parallel walls are the walls attached to the upstream corner of the abutment parallel to the flow. Parallel walls change the flow direction as shown in Figure 3-5. Basic principle behind the parallel walls is that down-flow which affects upstream of the abutment corner is pushed away from the abutment. For compound channels in addition to pushing away the down-flow, parallel walls form slow-moving zones that reduce the embankment scour caused by return flow from flood plain (Barkdoll, Ettema & Melville, 2007).

Parallel walls as an abutment scour countermeasure was studied by Li et al. (2006) and it is noted that parallel walls can be used as an abutment scour countermeasure and in order to obtain an acceptable reduction length of the wall should be 1.6 times greater than abutment length. It was also stated that usage of rock walls instead of solid walls is more efficient in terms of cost and stability.

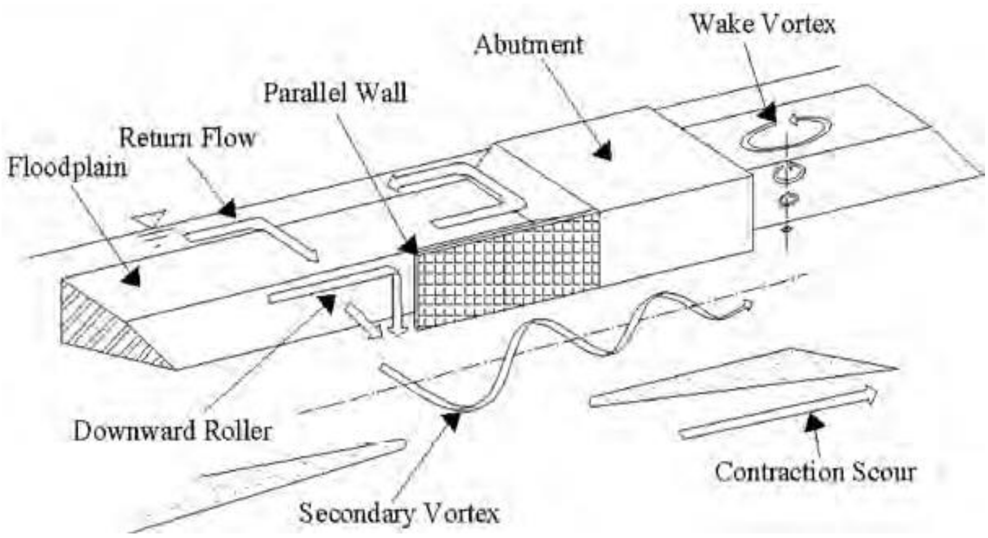


Figure 3-5: Flow patterns with parallel wall application (Barkdoll, Ettema & Melville, 2007).

3.6 Abutment Collar

National Cooperative Highway Research Program report noted that collars as a scour countermeasure around piers have been studied by Kapoor and Keana (1994), Kumar et al. (1999) and Borghie et al. (2004). It is found that collars reduce the scour by preventing the formation of secondary vortices and blocking the downflow as it can be seen from Figure 3-6.

Study of Li et al. (2005) shows that collars are effective for scour prevention because they prevent the contact of bed material with the turbulent flow and vortex system. In addition with an increasing collar width scour depth decreases. Extension of collar to the downstream of an abutment cause scour hole to form farther downstream. Recommended minimum collar width is 0.23 times greater than the length of the abutment (Li et al., 2005). Gogus and Dogan (2010) concluded that scour reduction depends on size and vertical position of the collar. Scour depth decreases with an increasing collar size. However, performance of the collar decreases with increasing abutment length. Study of Kayatürk (2005) show that collar application to abutment slows down the development of the scour. In addition increasing collar width causes reduction in maximum scour depth.

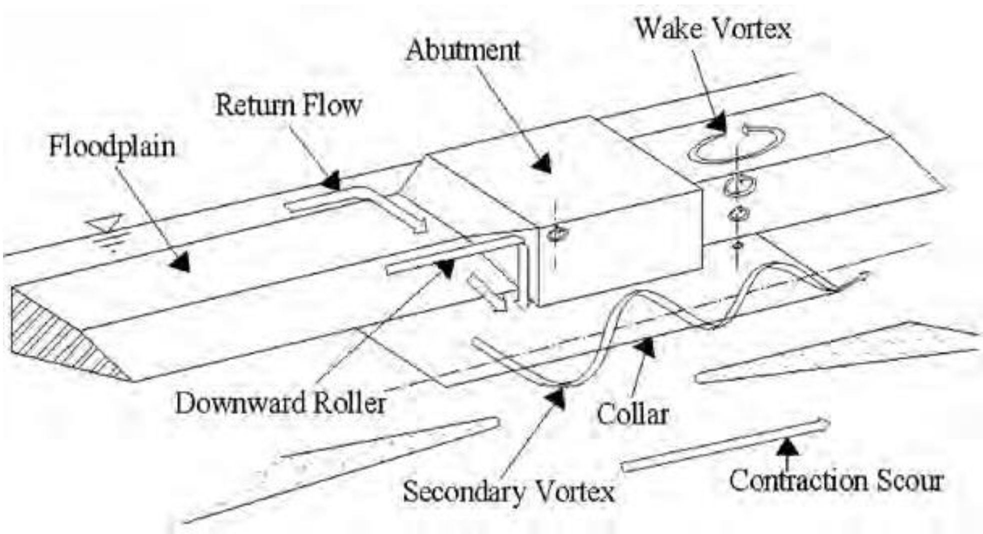


Figure 3-6: Flow patterns with collar application (Barkdoll, Ettema & Melville, 2007).

CHAPTER 4

EXPERIMENTAL SETUP

4.1 Introduction

Experiments in the study were conducted at a labaratory flume in the Hydromechanics Labaratory of the Civil Engineering Department at Middle East Technical University, Ankara. Information about the experiments, labarotary flume, sediment charecteristics, and measurement techniques can be found in this chapter.

4.2 Laboratory Flume

Experiments were conducted at a flume which has lenght of 29 m, width of 1.5 m and height of 0.5 m. Flume has a sediment storage section at the 13.5 m downstream of the flume entrance and storage section has a length of 6 m and depth of 0.5 m. Figure 4-1 shows the sediment storage part and downstream of the flume. As shown in Figure 4-1 the bottom and side walls of the flume were concrete, on the other hand, the side walls of the sediment storage is made of glass. Water is pumped to a constant head tank and released from the tank to the flume by gravity to provide constant flow. At the upstream entrance of the flume there exist a rectangular weir to measure the discharge and at the downstream of the flume there exist a control gate to adjust water level in the flume. All of the experiments are conducted at a constant water elevation of 13.5 cm. Due to the clear water conditions the average velocity of the flow, U, is selected as 0.9 times of the critical velocity, U_c, so that the average velocity is U=0.335 m/s where the discharge is Q=67 l/s.

Figure 4-1: Downstream and sediment storage part of the flume after the experiment. (Arrow shows the flow direction)

4.3 Abutment Model

Two spill through abutments with sharp corners were used in the all experiments which were placed oppositely at the sediment storage section of the flume as shown in Figure 4-2 . Abutments were constructed from plexiglass with a bottom width of 25.6 cm and upper width of 10 cm. Length of the abutment, L_a is changed from 12.8 cm to 37.8 cm with increments of 5 cm. Moreover; collars constructed by pilexiglass with different widths of, B_c; 5 cm, 7.5 cm and 10 cm were applied to abutments at elevations of, Z_c 0 cm, -3.40 cm and -6.75 cm to investigate the effect of collars on scour. Figure 4-2 shows the shematic representation of abutment model and collars. Figure 4-3 shows the top, side and frontal view of the shortest abutment model.

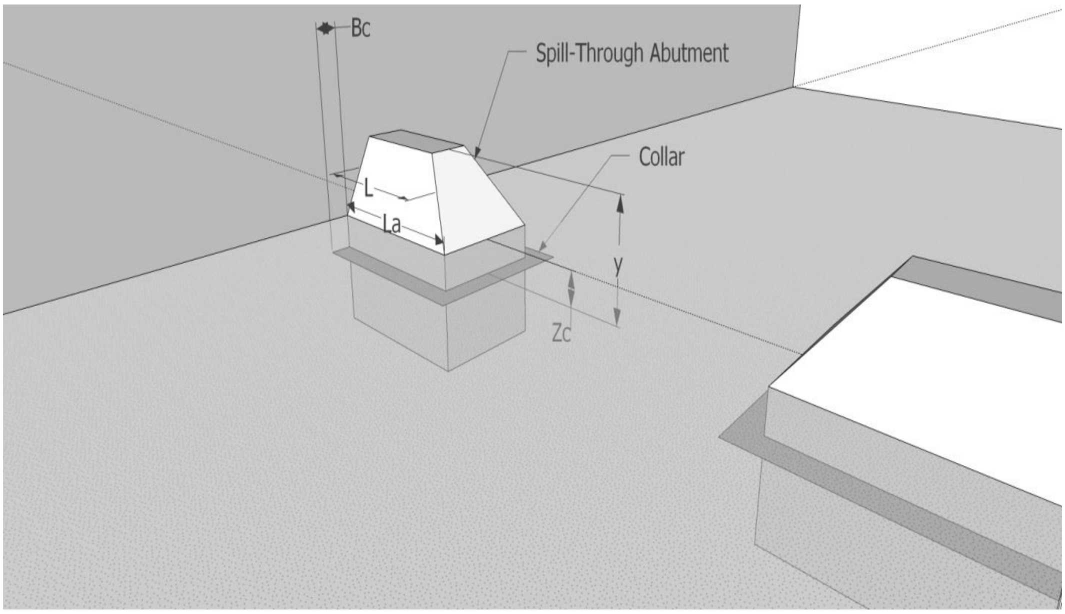


Figure 4-2: Representation of the abutment model and collar in the channel.

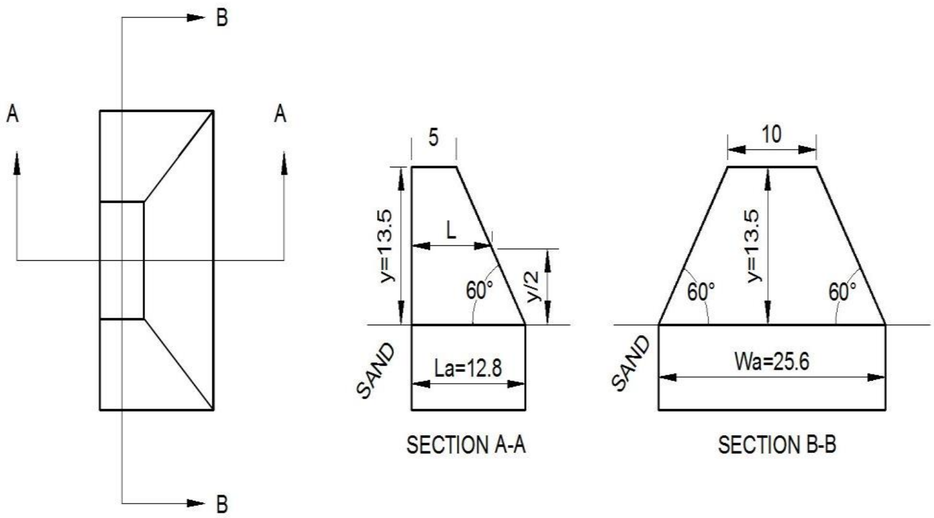


Figure 4-3: Abutment model for shortest length.

In addition to the experiments that have conducted with two spill-through abutments (multiple abutment configuration), additional experiments were conducted by placing single abutment (single abutment configuration) into the channel. An example of the experiments with single abutment model can be seen in Figure 4-4.

Figure 4-4: Experimental setup with a single abutment configuration.

4.4 Sediment Characteristics

Bed material used in the sediment storage part of the flume was selected as uniform sand with a median grain size of d_{50}=1.5 mm, geometric standard deviation of particle size distribution is σ=1.29 with a uniformity coefficient of, C_u=1.7. Bed material can be seen in Figure 4-5.

Figure 4-5: Aerial view of sediments around the abutment.

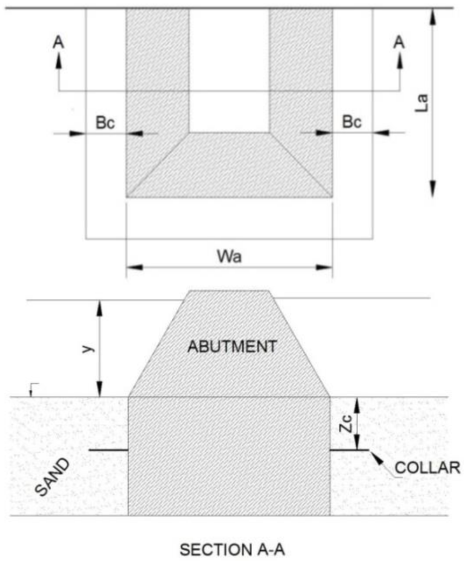
4.5 Flow Characteristics

Experiments were conducted at clear-water conditions such that the mean velocity ratio, $U/U_c<1$. U/U_c ratio is selected as 0.9 in the experiments in order not to move bed material. The water depth that corresponds to $U/U_c=0.9$ at a discharge of Q=67.8 t/s is determined as y=13.5 cm. Water depth of 13.5 cm was adjusted by using the control gate at the downstream of the flume. At this flow depth the average velocity, U, of the flow in the channel is 0.335 m/s.

4.6 Measurement and Instrumentation

Discharge is measured by using a sharp crested rectangular weir which is placed at the upstream of the flume. After starting the pump, water is pumped from a storage basin to constant elevation tank. The valve which is placed between the constant elevation-tank and flume is opened gradually to prevent sudden movement of the bed material so that water reaches to channel by gravity. After valve is fully opened and reaching the dicharge of 67.8 l/s, the experiment was started that will last for a duration of 4 hours. After the experiment has finished, the maximum scour depth around the abutment was measured by a point-gauge and also the position of maximum scour hole was determined. Experimental conditions are presented in Table 4-1.

Table 4-1: Range of the Experiments.

Abutment and collar configuration		L_a (cm)	B_c (cm)	Z_c (cm)	y (cm)
	Set 1	37.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	
	Set 2	32.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	
	Set 3	27.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	
	Set 4	22.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	
	Set 5	17.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	
	Set 6	12.80	5.00	0.00	13.50
			7.50	-3.40	
			10.00	-6.75	

In addition to point-gauge measurements, the temporal variation pattern of the bed material around the abutment was measured at two different sections by using Sea Tek 5 Mhz ulstrasonic batymmetry measurement device as shown in the Figure 4-6. This device works under water where it sends sound waves to the channel bottom to locate the vertical position of the bed.

Figure 4-6: Temporal evolution experiment.

SeaTek devices are used both in field and laboratory for recording of seabed profiles and 3-D bed profiles. Figure 4-7 shows the SeaTek device with transducers connected to it. Total numbers of 32 transducers were mounted on the continuous array that is made of stainless steel. The transducer spacing was 2.5 cm from center to center. Device record the data with 32 transducers at a rate of 5 Hz.

Figure 4-7: SeaTek ultrasonic bathymetry measurement device.

CHAPTER 5

RESULTS OF THE EXPERIMENTS

5.1 Introduction

In the present study, collars are applied to spill-through abutments as a scour countermeasure in order to investigate the effects of collars on local scour as well as contraction scour. All the experiments were done under clear-water conditions and in all cases collars are applied. In order to assess the effectiveness of collars for multiple abutment configuration, the result of scour experiments without collars are required. Therefore the maximum scour depth values without collar application were obtained from the study of Yildiz (2014).

5.2 Dimensional Analysis

Scour is a complex phenomenon that is affected by lots of parameters such as properties of fluid, properties of flow, properties of channel geometry, properties of sediment and time. So the functional representation of maximum scour depth with collar application can be written as;

$$(d_s)_{c,max} = f\{U, U_c, \theta, y, S_0, g, W, L_a, W_a, \rho, \rho_s, \mu, \sigma_g, d_{50}, t, \beta, K_s, B_c, Z_c\} \qquad \text{Equation 5.1}$$

where U is the average approach velocity of the flow, y is the approaching flow depth, S_0 is the bed slope of the channel, g is the gravitational acceleration, W is the channel width, L_a is the abutment length, W_a is the abutment width, ρ is the density of water, ρ_s is the density of sediment, μ is the dynamic viscosity of the water, d_{50} is the median size of the sediment, t is time, β is the channel contraction ratio and K_s is the abutment shape factor.

The following dimensionless parameters are obtained by the Buckingham's pi theorem;

$$\frac{(d_s)_{c,max}}{y} = f\left\{\frac{U}{\sqrt{gy}}, \frac{U}{U_c} S_0, \frac{W}{y}, \frac{L_a}{y}, \frac{W_a}{y}, \frac{\rho_s}{\rho}, \frac{\mu}{Uy}, \sigma_g, \frac{d_{50}}{y\rho U}, \beta, K_s, \frac{B_c}{y}, \frac{Z_c}{y}, \theta\right\} \qquad \text{Equation 5.2}$$

In this study the experiments were conducted with the constant sediment site, flow intensity, channel slope, abutment width, and test duration so equation 5.2 can be reduced to;

$$\frac{(d_s)_{c,max}}{y} = f\left\{\beta, \frac{Z_c}{y}, \frac{L_a}{B_c}, \theta\right\} \qquad \text{Equation 5.3}$$

5.3 Experimental Results

In the study, six sets of experiments with multiple abutment configuration that correspond to a total number of 54 were conducted for a duration of 4 hours where the maximum scour depth was measured by a point-gauge and additional 8 experiments were conducted with and without collar for single abutment configuration to investigate the effect of contraction on local scour as well as the effect of collars on scour. In addition to that a total of 8 experiments were conducted to evaluate the temporal evaluation of scour by taking continuous measurements using SeaTek device. In all experiments water level was kept constant at 13.5 cm that is denoted by y and discharge was constant at 67.8 l/s and denoted by Q. Collars with different widths placed at 3 different elevations are used in all of the sets. In the first set of the experiments abutments with a length of 37.8 cm is used. Collars with widths of 5 cm, 7.5 cm and 10 cm are placed at sand surface, 3.40 cm and 6.75 cm below the sand surface where collar width is denoted by B_c and elevations of collar is denoted by Z_c. In the following 6 sets of experiments the same collar widths and same collar elevations were used but lengths of the abutments are decreased by 5 cm increments for each following set. By changing the abutment length L_a, the flow is contracted with different contraction ratios (β=2L/W) and by keeping the other parameters constant in the experiments the effect of the contraction ratio on scour was evaluated.

In Table 5-1, abutment length L_a, contraction ratio β, collar width B_c and collar elevation Z_c as well as the maximum scour depths with and without collars are presented. L is defined by Melville (1997) as effective length of the abutment which corresponds to a length at the middle depth of the flow. Contraction ratio β is calculated by using L.

Table 5-1: Experimental Conditions for Multiple Abutment Configurations.

Set No	Experiment No	La (cm)	L (cm)	Bc (cm)	Zc (cm)	y (cm)	β(2L/W)	La/Bc	Zc/y
Set-1	1	37.80	33.90	5.00	0.00	13.50	0.45	7.56	0.00
	2	37.80	33.90	5.00	-3.40	13.50	0.45	7.56	-0.25
	3	37.80	33.90	5.00	-6.75	13.50	0.45	7.56	-0.50
	4	37.80	33.90	7.50	0.00	13.50	0.45	5.04	0.00
	5	37.80	33.90	7.50	-3.40	13.50	0.45	5.04	-0.25
	6	37.80	33.90	7.50	-6.75	13.50	0.45	5.04	-0.50
	7	37.80	33.90	10.00	0.00	13.50	0.45	3.78	0.00
	8	37.80	33.90	10.00	-3.40	13.50	0.45	3.78	-0.25
	9	37.80	33.90	10.00	-6.75	13.50	0.45	3.78	-0.50
Set-2	10	32.80	28.90	5.00	0.00	13.50	0.39	6.56	0.00
	11	32.80	28.90	5.00	-3.40	13.50	0.39	6.56	-0.25
	12	32.80	28.90	5.00	-6.75	13.50	0.39	6.56	-0.50
	13	32.80	28.90	7.50	0.00	13.50	0.39	4.37	0.00
	14	32.80	28.90	7.50	-3.40	13.50	0.39	4.37	-0.25
	15	32.80	28.90	7.50	-6.75	13.50	0.39	4.37	-0.50
	16	32.80	28.90	10.00	0.00	13.50	0.39	3.28	0.00
	17	32.80	28.90	10.00	-3.40	13.50	0.39	3.28	-0.25
	18	32.80	28.90	10.00	-6.75	13.50	0.39	3.28	-0.50
Set-3	19	27.80	23.90	5.00	0.00	13.50	0.32	5.56	0.00
	20	27.80	23.90	5.00	-3.40	13.50	0.32	5.56	-0.25
	21	27.80	23.90	5.00	-6.75	13.50	0.32	5.56	-0.50
	22	27.80	23.90	7.50	0.00	13.50	0.32	3.71	0.00
	23	27.80	23.90	7.50	-3.40	13.50	0.32	3.71	-0.25
	24	27.80	23.90	7.50	-6.75	13.50	0.32	3.71	-0.50
	25	27.80	23.90	10.00	0.00	13.50	0.32	2.78	0.00
	26	27.80	23.90	10.00	-3.40	13.50	0.32	2.78	-0.25
	27	27.80	23.90	10.00	-6.75	13.50	0.32	2.78	-0.50
Set-4	28	22.80	18.90	5.00	0.00	13.50	0.25	4.56	0.00
	29	22.80	18.90	5.00	-3.40	13.50	0.25	4.56	-0.25
	30	22.80	18.90	5.00	-6.75	13.50	0.25	4.56	-0.50
	31	22.80	18.90	7.50	0.00	13.50	0.25	3.04	0.00
	32	22.80	18.90	7.50	-3.40	13.50	0.25	3.04	-0.25
	33	22.80	18.90	7.50	-6.75	13.50	0.25	3.04	-0.50
	34	22.80	18.90	10.00	0.00	13.50	0.25	2.28	0.00
	35	22.80	18.90	10.00	-3.40	13.50	0.25	2.28	-0.25
	36	22.80	18.90	10.00	-6.75	13.50	0.25	2.28	-0.50
Set-5	37	17.80	13.90	5.00	0.00	13.50	0.19	3.56	0.00
	38	17.80	13.90	5.00	-3.40	13.50	0.19	3.56	-0.25
	39	17.80	13.90	5.00	-6.75	13.50	0.19	3.56	-0.50
	40	17.80	13.90	7.50	0.00	13.50	0.19	2.37	0.00
	41	17.80	13.90	7.50	-3.40	13.50	0.19	2.37	-0.25
	42	17.80	13.90	7.50	-6.75	13.50	0.19	2.37	-0.50
	43	17.80	13.90	10.00	0.00	13.50	0.19	1.78	0.00
	44	17.80	13.90	10.00	-3.40	13.50	0.19	1.78	-0.25
	45	17.80	13.90	10.00	-6.75	13.50	0.19	1.78	-0.50
Set-6	46	12.80	8.90	5.00	0.00	13.50	0.12	2.56	0.00
	47	12.80	8.90	5.00	-3.40	13.50	0.12	2.56	-0.25
	48	12.80	8.90	5.00	-6.75	13.50	0.12	2.56	-0.50
	49	12.80	8.90	7.50	0.00	13.50	0.12	1.71	0.00
	50	12.80	8.90	7.50	-3.40	13.50	0.12	1.71	-0.25
	51	12.80	8.90	7.50	-6.75	13.50	0.12	1.71	-0.50
	52	12.80	8.90	10.00	0.00	13.50	0.12	1.28	0.00
	53	12.80	8.90	10.00	-3.40	13.50	0.12	1.28	-0.25
	54	12.80	8.90	10.00	-6.75	13.50	0.12	1.28	-0.50

5.3.1 Evaluation of Set-1

In Set-1 nine experiments were conducted with an abutment length of 37.8 cm. Effective length of the abutments is denoted by L and equal to 33.9 cm. the collars with widths of 5 cm, 7.5 cm and 10 cm were applied at the dimensionless elevations of Z_c/y=0, -0.25 and -0.5. In all the experiments the maximum scour depth was observed at the upstream corner of the abutments. Compared to Yildiz's study (2014) whose experiments are conducted without collars, all of the collar applications in this set reduce the maximum scour depth. For the collar of 5 cm width, the maximum reduction is observed as 8.7% at Z_c/y=-0.5. For collars of 7.5 cm and 10 cm width the maximum reduction on the maximum scour depth is observed as by 20.6% and 25.9% respectively at Z_c/y=-0.5.

5.3.2 Evaluation of Set-2

In Set-2 nine experiments were conducted with an abutment length of 32.8 cm. The effective length, L was determined as 28.9 cm. Figure-5-1 shows the scour pattern around the abutment and as it can be seen from Figure 5-1 the maximum scour depth was observed at the upstream corner of the abutments and collar applications at Z_c=-0.5 gave the maximum reduction. Collars with widths of 5 cm, 7.5 cm and 10 cm reduced the scour by 24.7%, 27.5% and 45.2% respectively.

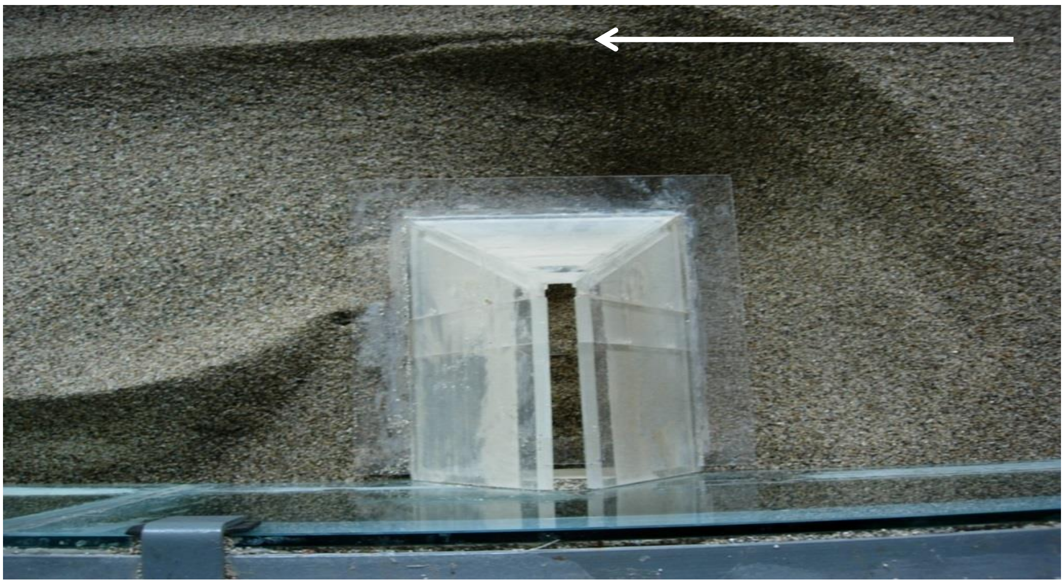


Figure 5-1: Scour hole with a collar of 5cm at Z_c =0.

5.3.3 Evaluation of Set-3

In Set-3, nine experiments were conducted by using the abutments with a length of 27.8 cm. The effective lengths of the abutments are determined as 23.9 cm. Again the maximum scour was formed at the upstream corner of the abutments as it can be seen from Figure 5-2. Collar with a width of 5 cm gives the maximum reduction at Z_c/y=-0.5. In addition collar with a width of 7.5 cm reduce the maximum scour depth at all elevations and maximum reduction in maximum scour depth was observed at Z_c/y =-0.5 as a 34.5%. Moreover; collar with a width of 10 cm reduced the maximum scour depth at all elevations. Maximum reduction was observed at the Z_c/y =-0.25 cm and at Z_c/y =-0.5 as a %42.6.

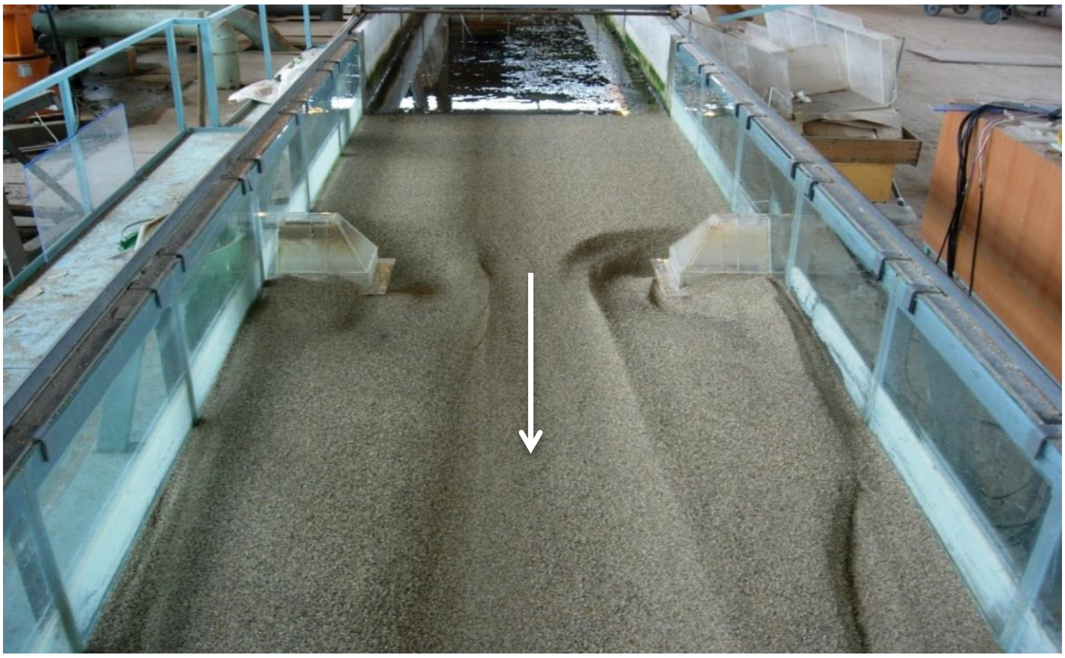


Figure 5-2: View of scour hole around abutment with a collar of 5 cm at Z_c=-0.5.

5.3.4 Evaluation of Set-4

In Set-4 nine experiments were conducted by applying collars with widths of 5 cm, 7.5 cm and 10 cm at Z_c/y =0, -0.25 and -0.5 where effective length of the abutment calculated as 18.9 cm. For the collar of 5 cm maximum reduction is observed as 16.6% at Z_c/y=-0.5. For collars of 7.5 cm and 10 cm maximum reduction on scour is observed at Z_c/y=-0.5 and reduce the maximum scour depth by 44.9% and 47.5% respectively.

5.3.5 Evaluation of Set-5

In Set-5 nine experiments were conducted by using abutment length of 17.8 cm that corresponds to effective length of L=13.9 cm. Collar of 5 cm provides maximum reduction at $Z_c/y=-0.5$ as 32.4% while collar of 7.5 cm provides maximum reduction in maximum scour depth at sand surface, $Z_c/y=0$ as 53.4%. Collar with a width of 10 cm provides maximum reduction in maximum scour depth at $Z_c/y=-0.5$ as 43.9 %.

5.3.6 Evaluation of Set-6

Nine experiments were conducted in Set-6 using abutments with an effective length of 13.9 cm. Collar with a width of 5 cm at $Z_c/y = -0.25$ reduced the maximum scour depth by 49.1 % while at $Z_c/y = -0.5$ it increased the maximum scour depth by 4.6%. Application of collar of 7.5 cm provides maximum reduction by 72% at sand surface, $Z_c/y = 0$ while it caused a deeper scour depth at $Z_c/y = -0.5$. Application of collar of 10 cm at $Z_c/y = -0.25$ provides maximum reduction of 60.7% while application of the collar at $Z_c/y = -0.5$ causes deeper scour.

5.4 Analysis of the Results

Reduction on scour depth depends on collar width, collar location, abutment length, water depth etc. Previous studies with different abutment lengths, flow depths, and different shaped abutments gave different results. Daşkın (2011) studied the effect of collars on local scour around semi-circular end abutments in her M.S study at METU. Her investigation was made under clear-water conditions where $U/U_c=0.9$ and test duration was 3 hours. She concluded that collars are effective in reducing scour depth around semi-circular end abutments and reduction in maximum scour depth reached 64% in some cases. Moreover, she found that scour depth decreases with increasing collar size. Similarly, Tekin (2012) studied the effect of collars on reducing maximum scour depth around semi-circular end abutments in her M.S study at METU. She used different flow intensities such as $U/U_c=0.8$ and $U/U_c=0.7$ under clear-water conditions and test duration was selected as 3 hours. She found out that 50% reduction in maximum scour depth can be possible by applying collar and she concluded that collars are effective in reducing maximum scour depth around semi-circular end abutments.

Figure 5-3 shows the percent reductions in the maximum scour depths compared to maximum scour depth without collar application for different dimensionless abutment lengths, L_a/B_c. Almost all the experiments with collar application results in smaller maximum scour depths compared to the experiments without collar application which shows the effectiveness of the collar plates in reducing maximum scour depth. The reduction in the maximum scour depths reaches 72% in some cases. Higher reduction in the maximum scour depth was observed in the study compared to the previous studies by Daşkın (2011) and Tekin (2012). Different abutment shape, flow depth, flow intensity, duration and contraction ratio cause different reductions in the maximum scour depth. For contraction ratios greater than 0.25, the reduction in the maximum scour depth increases as the collars are placed at deeper elevations. In addition, the reduction in maximum scour depth increases with increasing collar size. Therefore, the maximum reduction in the scour depth can be obtained by placing collar with largest width B_c at $Z_c/y=-0.5$ if the contraction ratio $2L/W \geq 0.25$. On the other hand, the maximum reduction in the scour depth can be observed at $Z_c/y=0$, -0.25 and -0.5 if $2L/W<0.25$. The highest reduction is observed at $Z_c/y=0.25$ with a collar of 7.5 cm width.

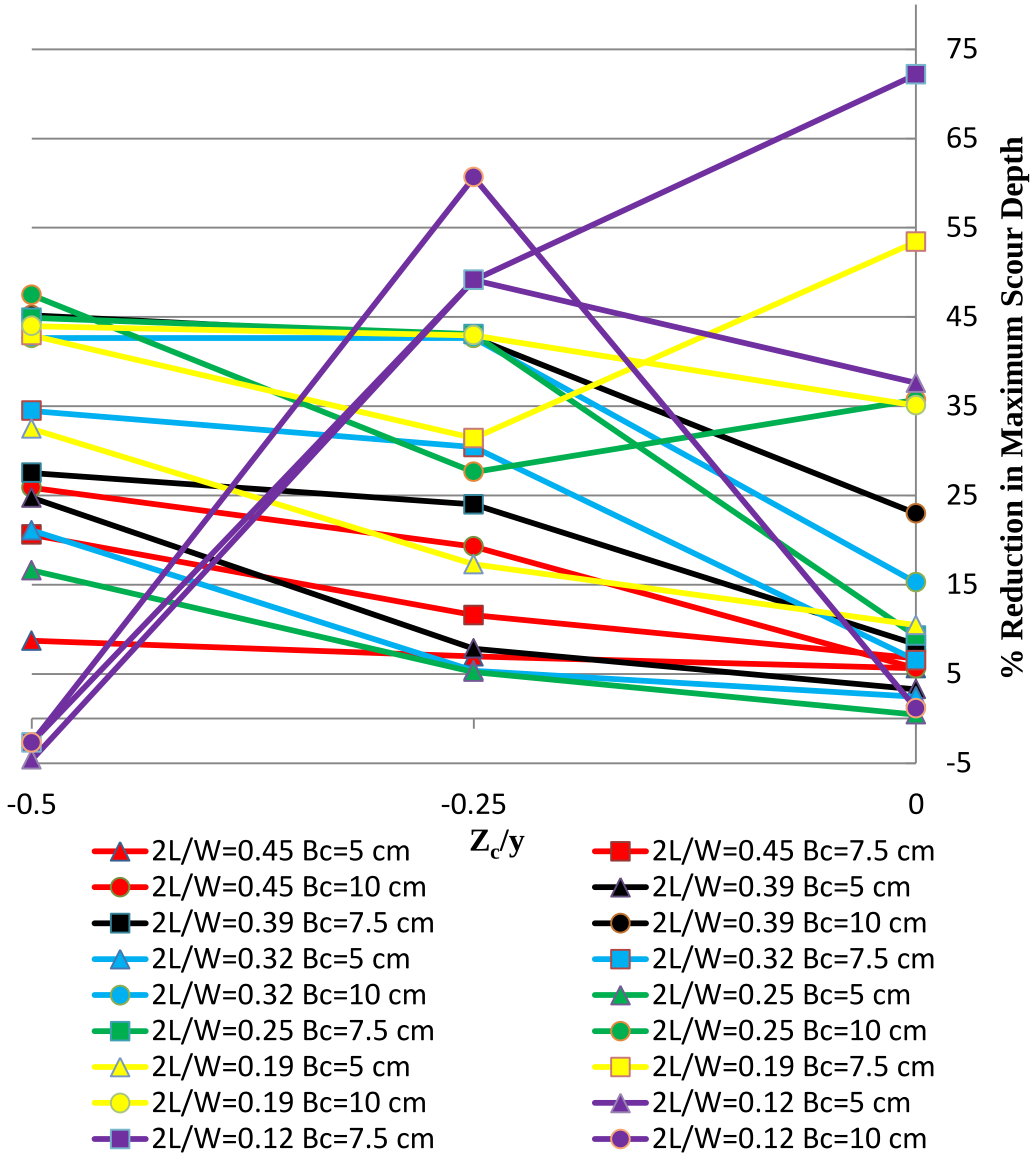


Figure 5-3: Effect of collar size and elevation on the maximum scour depth for abutments with different lengths.

θ is defined as the ratio of the total area that corresponds to the area with collar to area of the abutment without collar attached. It is calculated by using abutment length L_a and represents effect of area of the abutment and collar on scour and denoted as;

$$\theta = \frac{A\ total}{A\ abutment} \qquad \text{Equation 5.4}$$

Figure 5-4 shows the variations of the maximum scour depth which is obtained using the optimum collar configuration (which minimizes the scour depth), $((d_s)_{max,c}/y)_{opt}$, with respect to θ as a function of contraction ratio β. As it can be seen from Figure 5-4 there is a decreasing trend in $((d_s)_{max,c}/y)_{opt}$ with increasing θ for the contraction ratio 2L/W≥0.25. Therefore, as the collar area increases, the maximum scour depth decreases for contraction ratio equal or greater than 0.25. If the abutment size and collar width are known the best location of the collar for maximum reduction as well as the corresponding scour depth can be determined for a given contraction ratio.

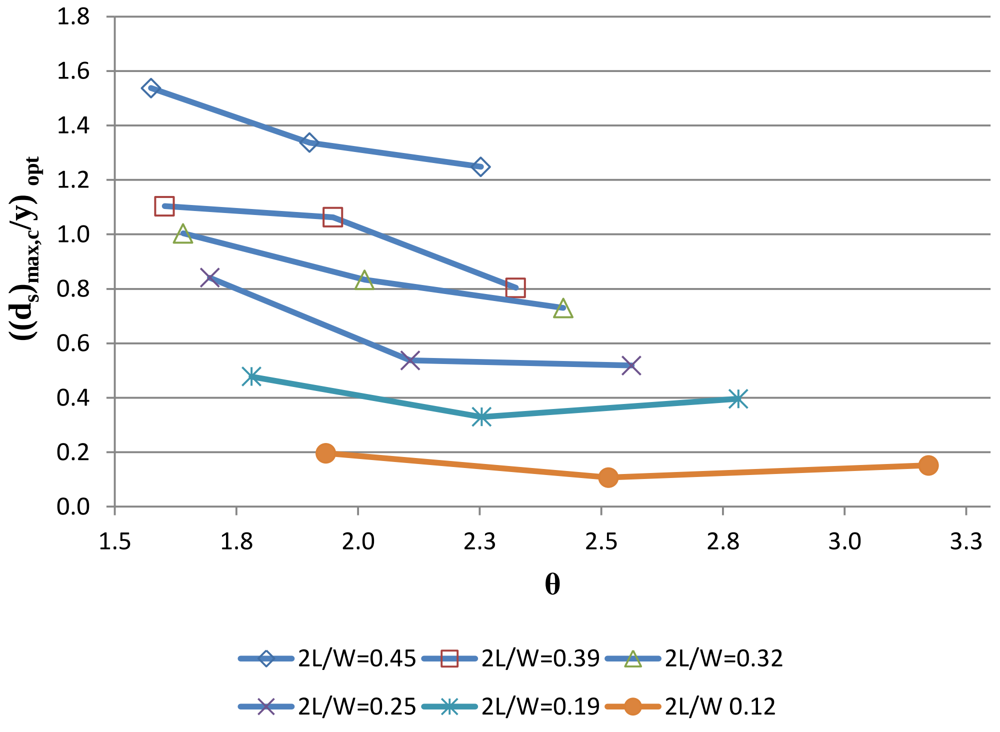


Figure 5-4: Variation of $((d_s)_{max,c}/y)_{opt}$ with respect to θ.

Instead of $((d_s)_{max,c}/y)_{opt}$ vs θ, graph that involves $((d_s)_{max,c}/y)_{opt}$ vs $[\theta(L_a /B_c]^{0.5}$ can also be used. It can be seen from the Figure 5-5 that for contraction ratios 2L/W≥0.25, increasing $[\theta(L_a /B_c)]^{0.5}$ causes higher maximum scour depths. From Figure 5-5 by knowing abutment length L_a, collar with B_c and θ for a specific contraction ratio, optimum value of the maximum scour depth, $((d_s)_{max,c}/y)_{opt}$ can be determined.

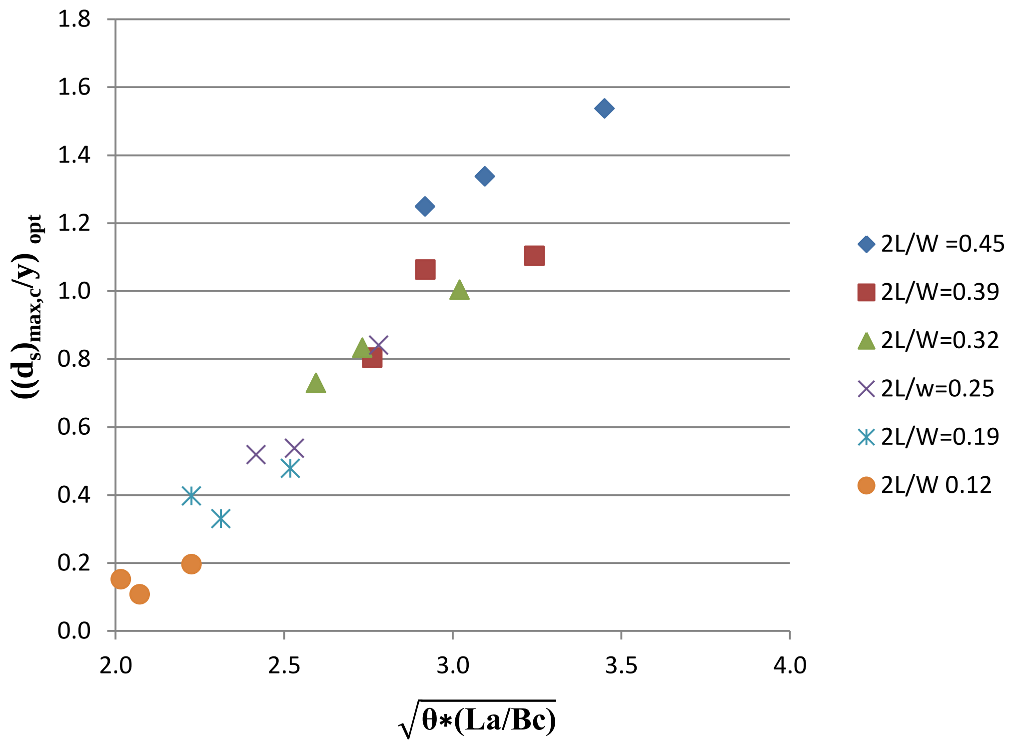


Figure 5-5: Variation of $((d_s)_{max,c}/y)_{opt}$ with respect to $[\theta(L_a/B_c]^{0.5}$.

Figure 5-6 show the optimum location of collars with respect to L_a/B_c for a given contraction ratio. As it can be seen from the Figure 5-6 optimum location of collars depends on L_a/B_c ratio and it can be summarized as follow;

$(Z_c/y)_{opt}$ =-0.5 $2< L_a/B_c$ where $2L/W \geq 0.25$

$(Z_c/y)_{opt}$ =-0. 5 $L_a/B_c<2$ where 2L/W=0.19

$(Z_c/y)_{opt}$ =0 $2< L_a/B_c<3$ where 2L/W=0.19

$(Z_c/y)_{opt}$ =-0. 5 $3<L_a/B_c$ where 2L/W=0.19

$(Z_c/y)_{opt}$ =-0.25 $L_a/B_c<1.5$ & $2< L_a/B_c$ where 2L/W=0.12

$(Z_c/y)_{opt}$ =0 $1.5<L_a/B_c<2$ where 2L/W=0.12

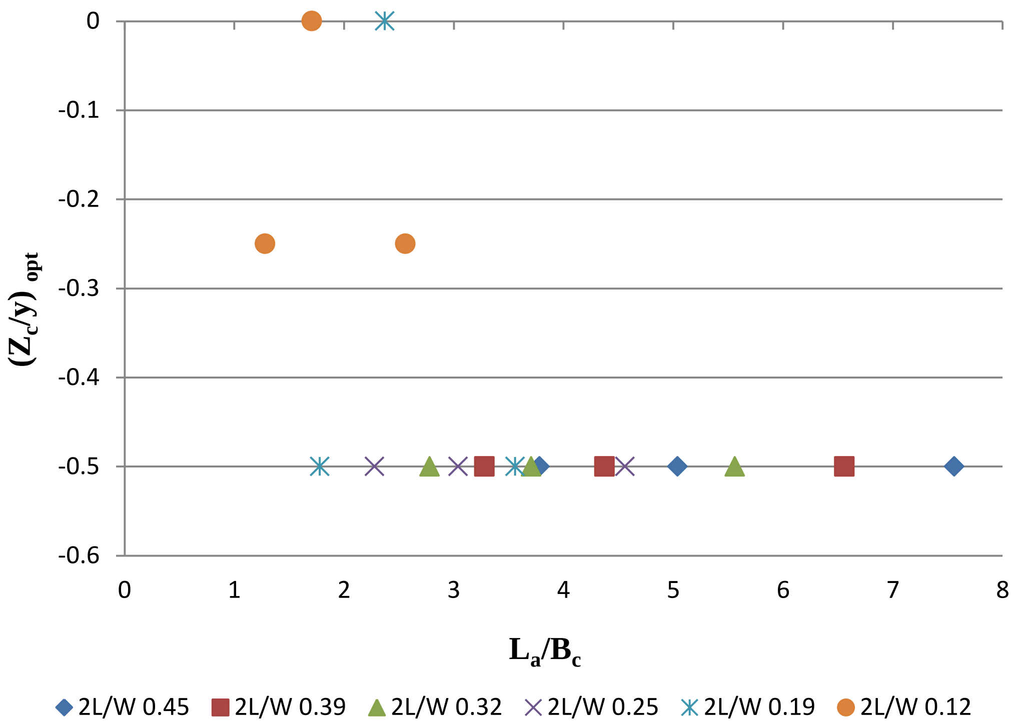


Figure 5-6: Variation of $(Z_c/y)_{opt}$ with respect to L_a/B_c .

5.5 Experiments with Single Abutment

There are different types of scour as mentioned before. Scour types are defined in Chapter-2. In the earlier experiments two spill-through abutments placed into the channel so that flow is contracted in the waterway due to the existence of the abutments. By removing one of the abutments, effect of contraction becomes negligible because abutment length is very small compared to channel width. Experiments and result are presented in Table 5-2 and Table 5-3.

Table 5-2: Experimental Conditions for Single Abutment Configuration.

Single Abutment Configuration							
L_a (cm)	d_s (cm)	$d_{s,c}$ (cm)	L/W	L_a/y	d_s/y	$d_{s,c}/y$	% Reduction due to Collar
37.80	21.85	11.90	0.23	2.80	1.62	0.88	45.54
32.80	19.30	9.20	0.19	2.43	1.43	0.68	52.33
27.80	16.10	8.40	0.16	2.06	1.19	0.62	47.83
22.80	12.85	6.10	0.13	1.69	0.95	0.45	52.53

Table 5-3: Experimental Conditions for Multiple Abutment Configuration.

Multiple Abutment Configuration							
L_a (cm)	d_s (cm)	$d_{s,c}$ (cm)	2L/W	L_a/y	d_s/y	$d_{s,c}/y$	% Reduction due to Collar
37.80	22.73	16.85	0.45	2.80	1.68	1.25	25.87
32.80	19.80	10.85	0.39	2.43	1.47	0.80	45.20
27.80	17.17	9.85	0.32	2.06	1.27	0.73	42.63
22.80	13.61	6.45	0.25	1.69	1.01	0.48	52.61

Figure 5-7 shows the reduction in maximum scour depth with changing abutment length for single abutment configuration. Collar application for single abutment case provides average of 50% reduction in maximum scour depth and independent of dimensionless abutment length L_a/y.

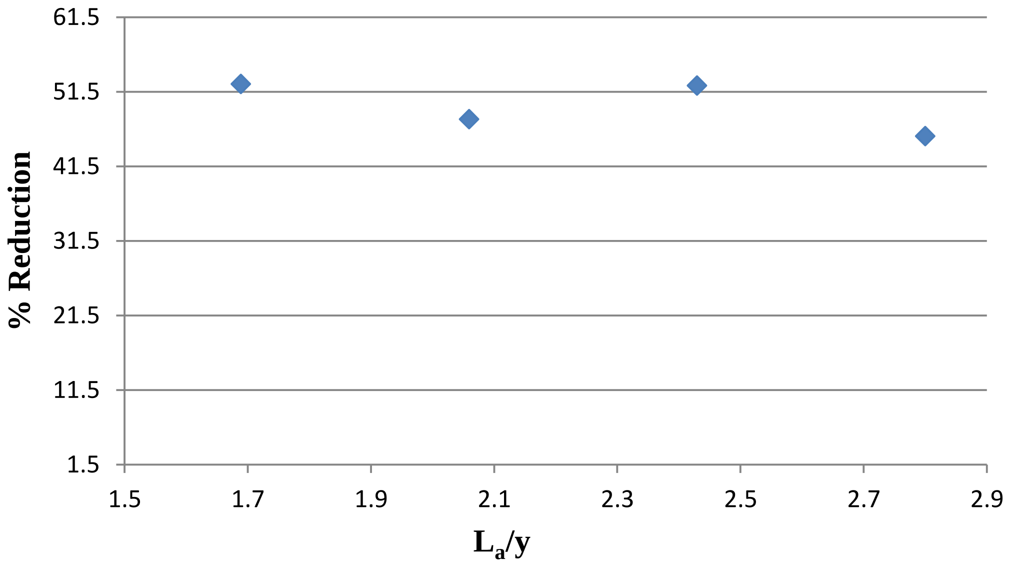


Figure 5-7: Distribution of percent reduction with abutment length for single abutment.

Figure 5-8 shows the reduction in maximum scour depth with changing abutment length for multiple abutment configurations. Reduction in maximum scour depth decreases with increasing dimensionless abutment length.

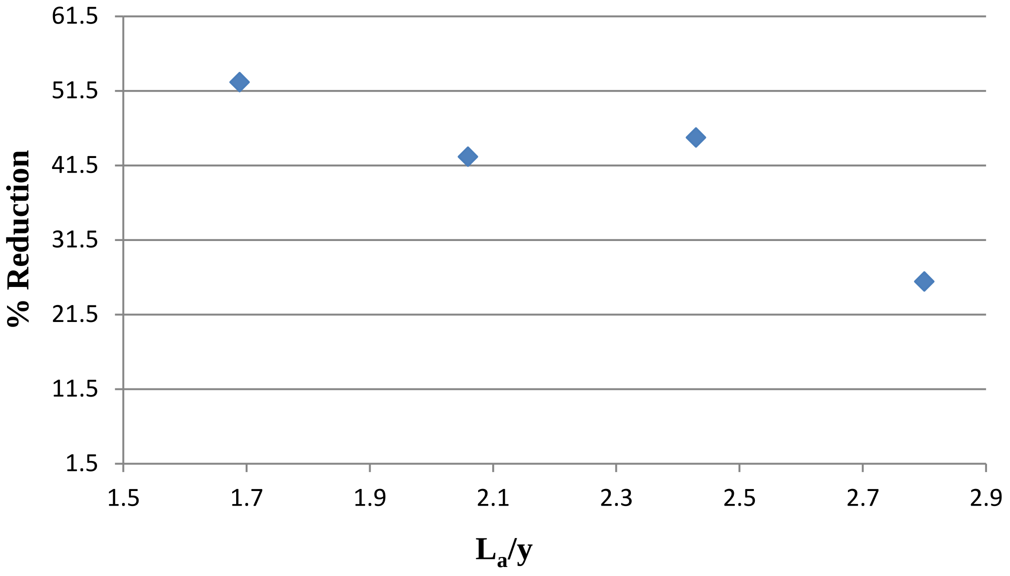


Figure 5-8: Distribution of percent reduction with abutment length for multiple abutment.

Figure 5-9 shows the comparison between maximum scour depths for the single and multiple abutment configurations without collar application. Maximum scour depth increases with increasing dimensionless abutment length L_a/y for both single and multiple abutment case. Maximum scour depth for the multiple abutment case is slightly higher than the case with single abutment so effect of contraction on maximum scour depth is almost negligible.

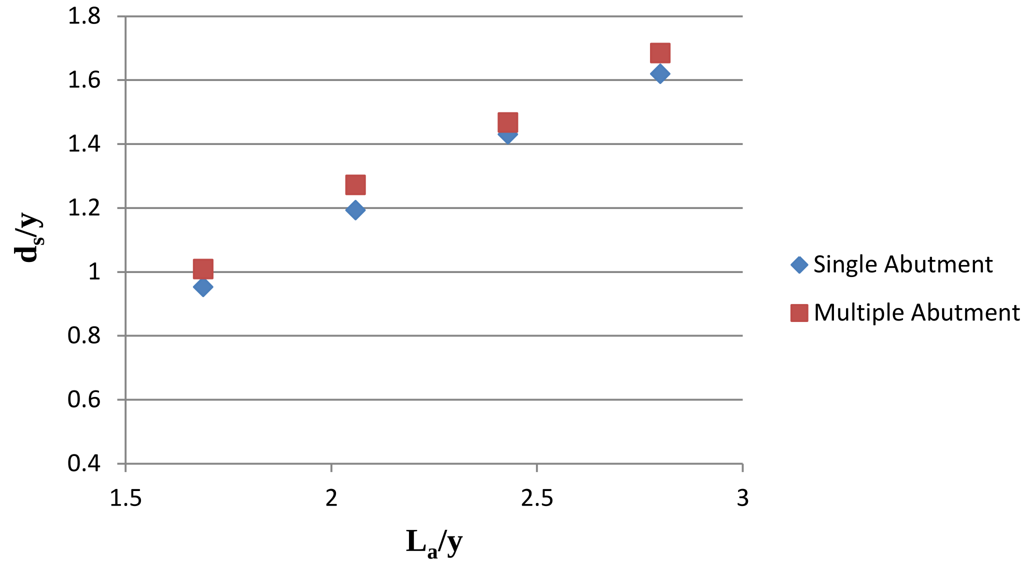


Figure 5-9: Comparison of maximum scour depths for single and multiple abutment case without collar application.

In Figure 5-10 shows the comparison between maximum scour depths for single and multiple abutment configurations with collar application. As it can be seen from the figure, maximum scour depth increases with increasing dimensionless abutment length for both single and multiple abutment configurations. Moreover, difference between maximum scour depths increases with increasing dimensionless abutment length. Therefore, collars are more effective for single abutment configuration compared to the multiple abutment configuration for the dimensionless abutment length, L_a/y greater than 2.1.

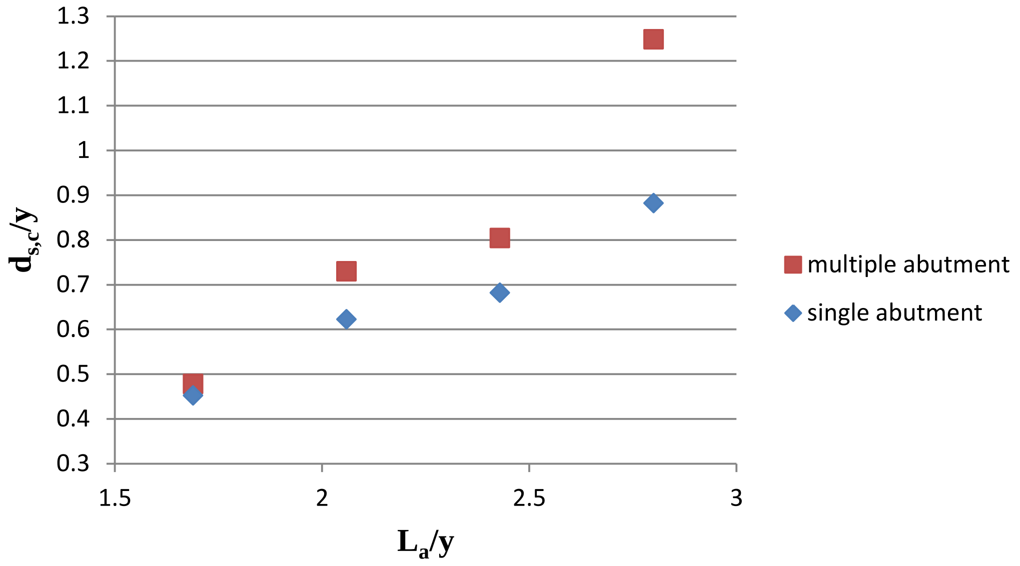


Figure 5-10: Comparison of maximum scour depths for single and multiple abutment case with collar application.

5.6 Temporal Evolution of Scour

Total numbers of 6 experiments were conducted to evaluate temporal evolution of scour hole around abutments with lengths of 37.8 and 12.8 cm at two different sections. For the abutment length of 37.8 cm collar with a width of 10 cm was applied to Z_c/y=-0.5 which gave the best performance in scour depth reduction while collar with a width of 10 cm at Z_c/y =0 is applied to the abutment with a length of 12.8 which is the worst scenario for the optimum reduction. Figure 5-11 shows the two sections that experimental data was obtained.

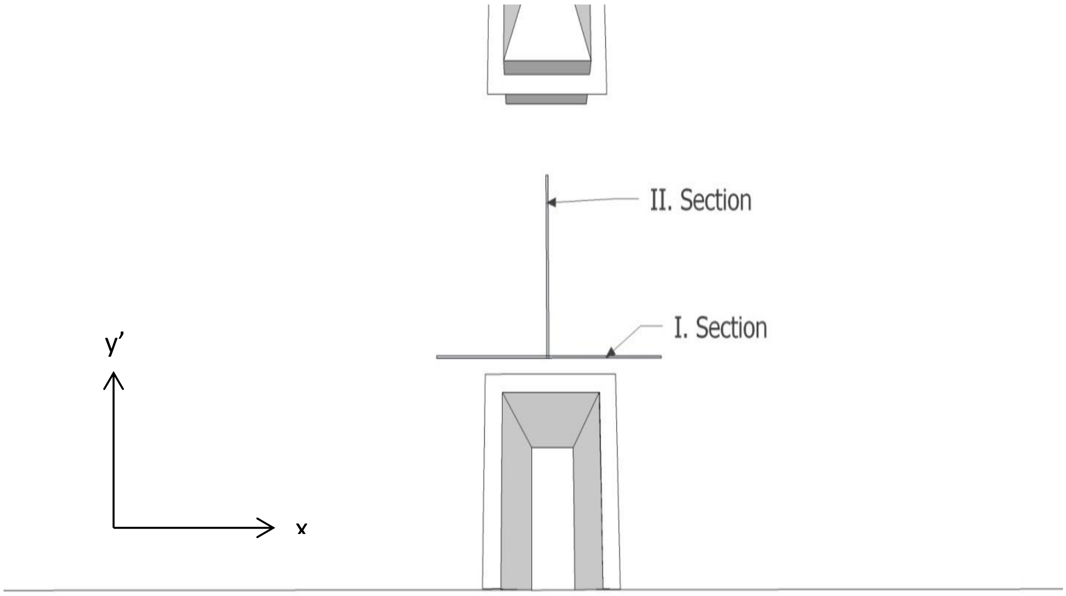


Figure 5-11: Sections used in experiments.

5.6.1 Results of Temporal Evolution of Scour

Figure 5-12 shows the temporal evolution of scour during 4 hours of experiment with an increment of half hour at section I for the abutment with a length of 37.8 cm that corresponds to contraction ratio of 0.45. Experiment was conducted without a collar plate. Position of maximum scour depth remained unchanged during the each time interval of the experiment. After the first hour of the experiment rate of development of scour is reduced. Maximum scour depth observed as 1.2y at the end of first hour while at the end it was observed as 1.5y at a position of -0.9 x/y.

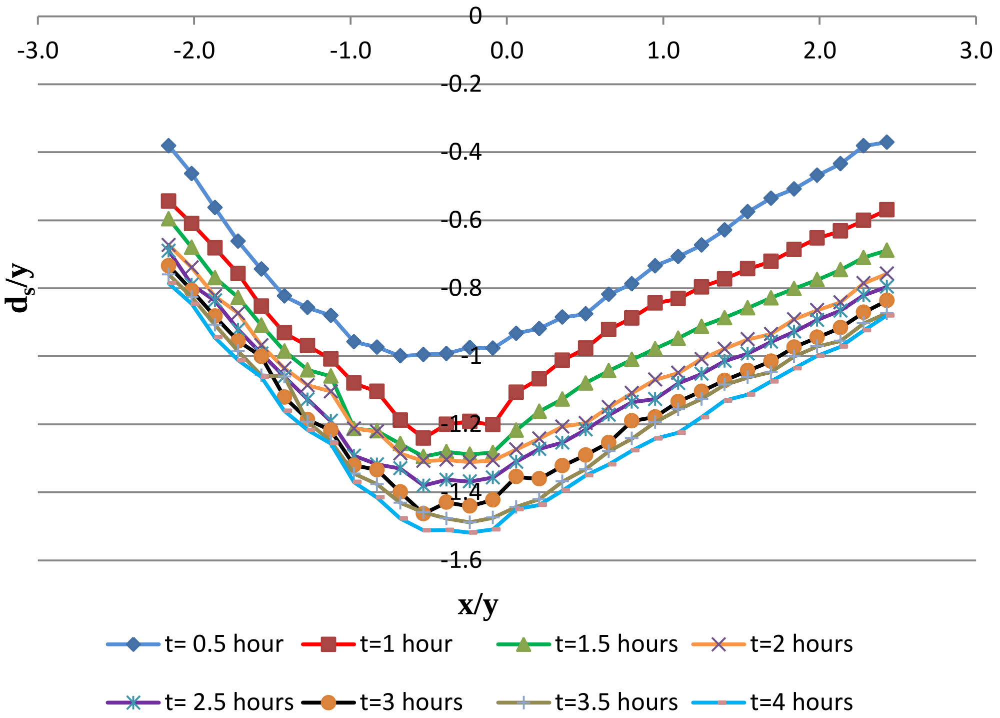


Figure 5-12: Temporal variation of scour hole without collar for the contraction ratio of 2L/W=0.45 at section I.

Figure 5-13 shows the temporal evolution of scour during 4 hours of experiment with an increment of half hour at section I for the abutment with a length of 37.8 cm that corresponds to contraction ratio of 0.45 with the collar plate. At the first half hour of the experiment scour hole was formed at downstream of the abutment. After the first hour scour hole at the downstream started to be filled with sand and at the end of the experiment scour hole was formed at the upstream of the abutment with a maximum scour depth of 1y that is observed at -1.3x/y. Therefore, maximum scour depth was reduced by 33% and position of maximum scour hole was shifted away from abutment due to the collar.

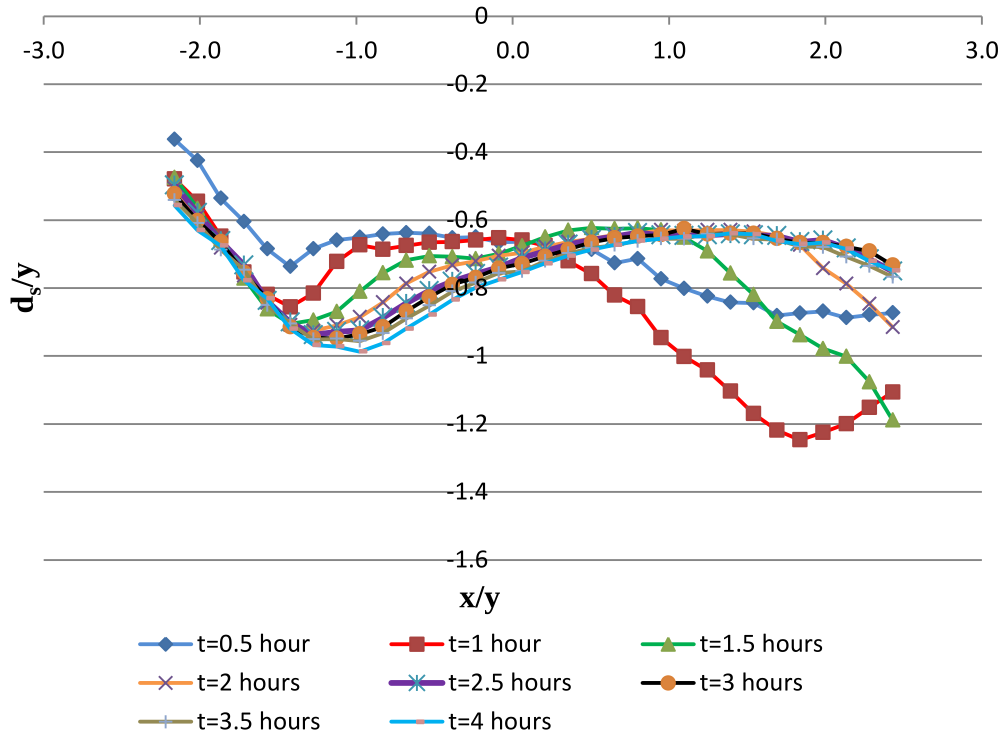


Figure 5-13: Temporal variation of scour hole with collar protection for the contraction ratio of 2L/W=0.45 at section I.

Time evolution of maximum scour depth at section I for the contraction ratio of 0.45 is compared for the cases with and without collar in Figure 5-14. Maximum scour depth for the case with collar is slightly higher than the maximum scour depth for the case without collar. After the first hour, the effect of collar in reducing the maximum scour depth started to be observed. There is a dramatic difference in the maximum scour depths after the second hour.

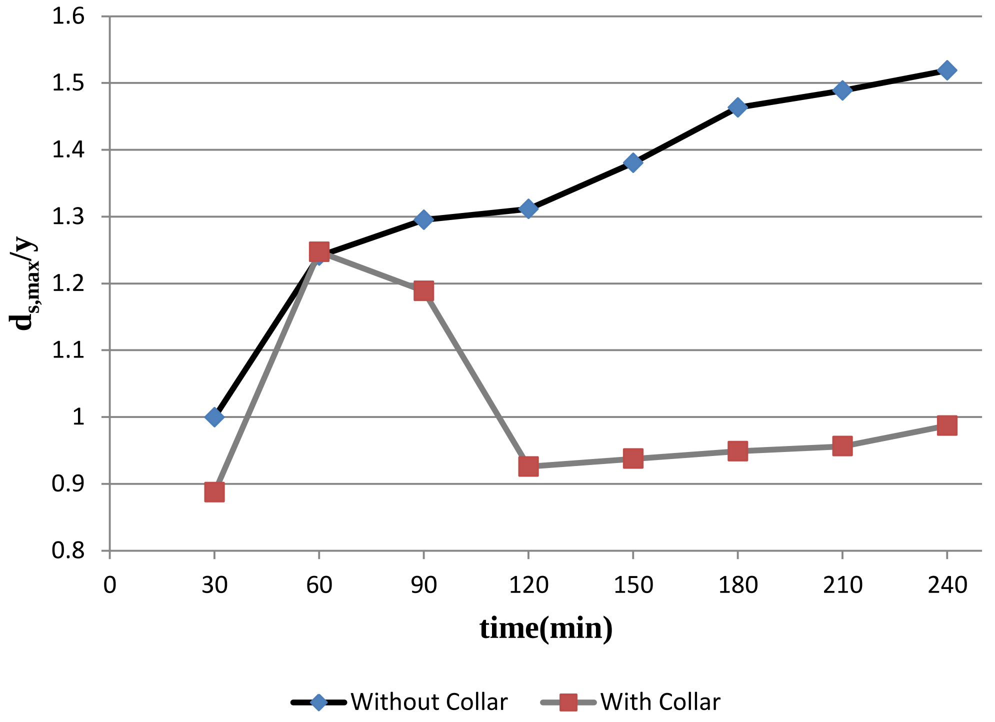


Figure 5-14: Variation of maximum scour depths with time for cases with and without collar at section I.

Figure 5-15 shows the temporal evolution of scour during 4 hours of experiment with an increment of half hour at section two for the abutment with a length of 37.8 cm that corresponds to contraction ratio of 0.45 without a collar plate. As it can be seen from the Figure position of maximum scour depth remained unchanged throughout the experiment. Maximum scour depth after 4 hours was observed as 1.5y at 3.3 y'/y.

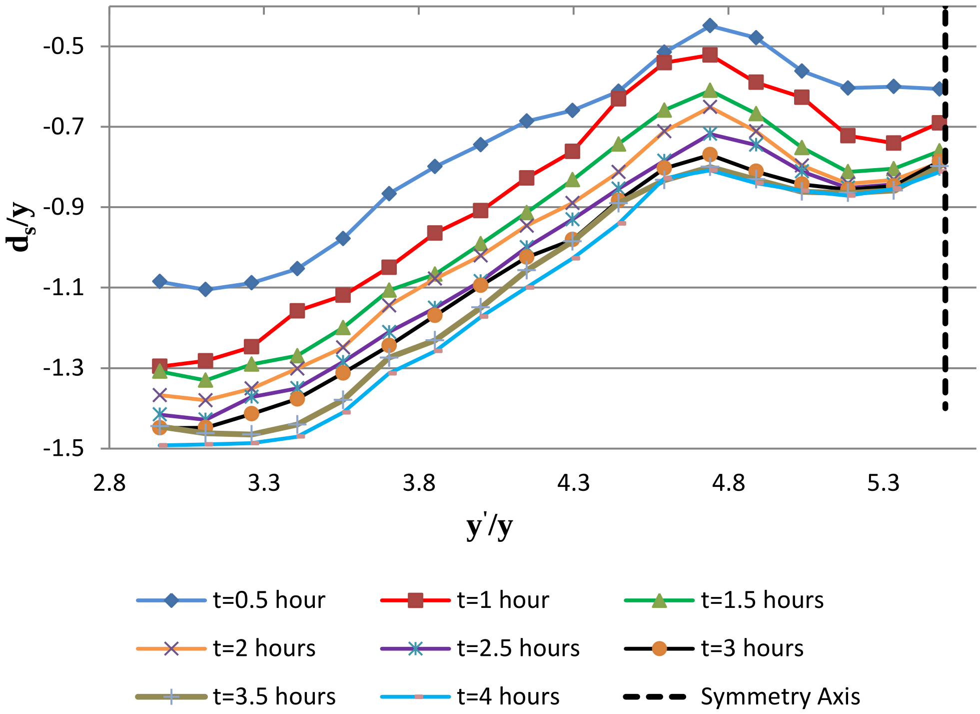


Figure 5-15: Temporal variation of scour hole without collar for the contraction ratio of 2L/W=0.45 at section II.

Figure 5-16 shows the temporal evolution of scour during 4 hours of experiment with an increment of half hour at section two for the abutment with a length of 37.8 cm that corresponds to contraction ratio of 0.45 with the collar plate. At the first half hour of the experiment maximum scour depth formed close to collar as 0.9y at 4.5 y'/y. At the end of the experiment maximum scour depth is measured as 1.1y and shifted away from abutment and formed at the 3.5y'/y. Collar application reduced the maximum scour depth by 27% and shifted the hole slightly away from the abutment.

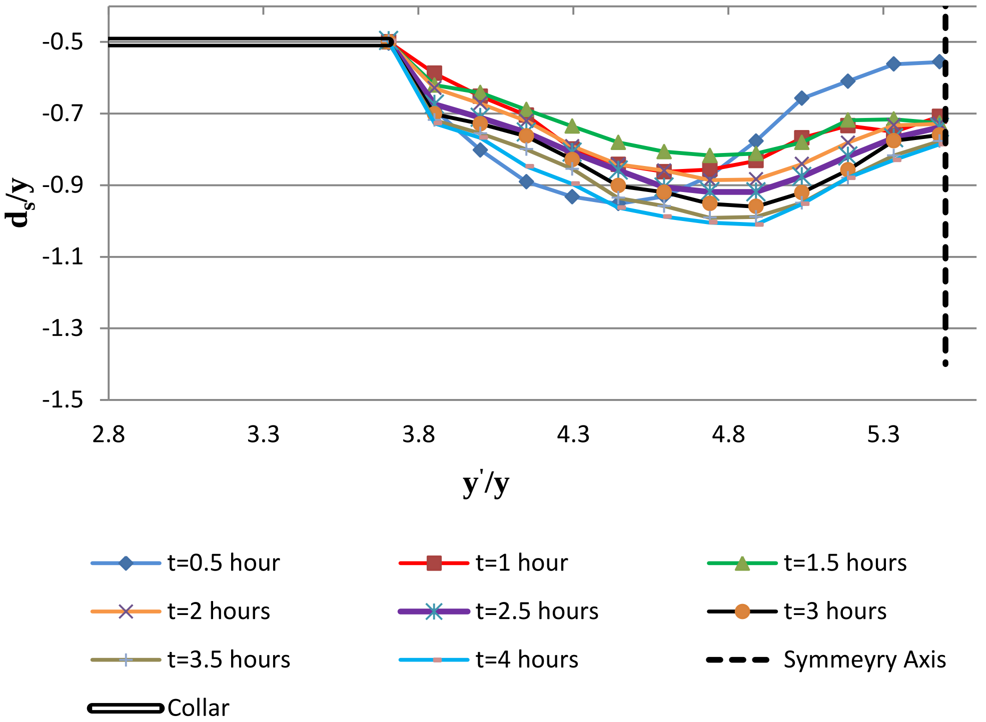


Figure 5-16: Temporal variation of scour hole with collar protection for the contraction ratio of 2L/W=0.45 at section II.

In the experiments it is observed that collar with a width of 10 cm at sand surface did not effective in reducing maximum scour depth. Optimum position of the collars for a contraction ratio of 0.12 is observed at Z_c=-0.25. Figure 5-17 and Figure 5-18 shows the temporal variation of maximum scour depth for section II without and with collar respectively. Collar application did not affect the maximum scour depth but it shifted the position of maximum scour depth away from the abutment.

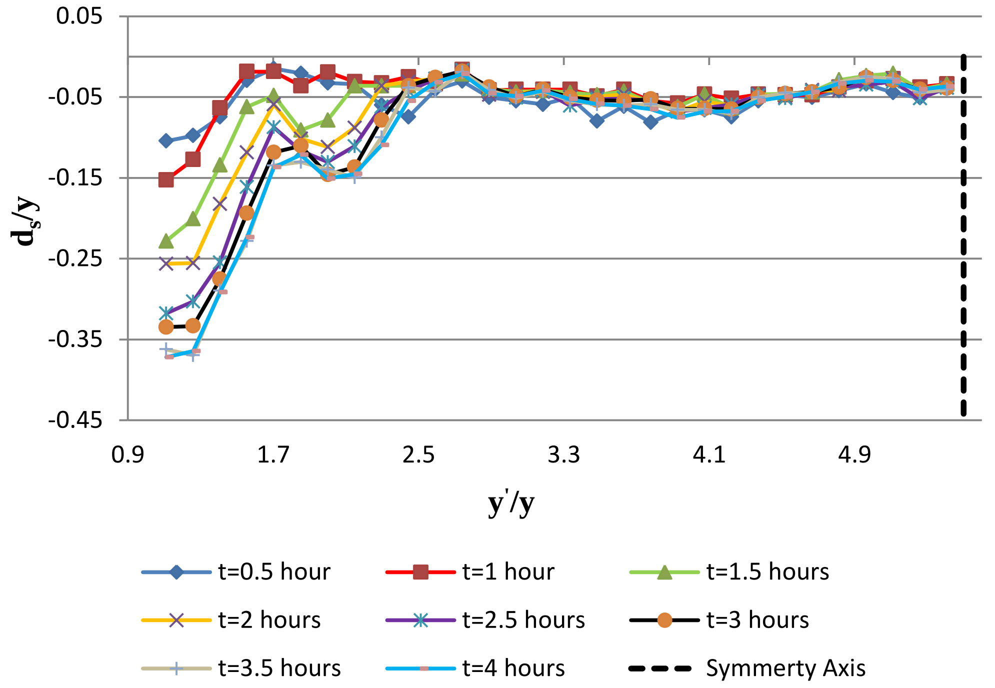


Figure 5-17: Temporal variation of scour hole without collar protection for the contraction ratio of 2L/W=0.12 at section II.

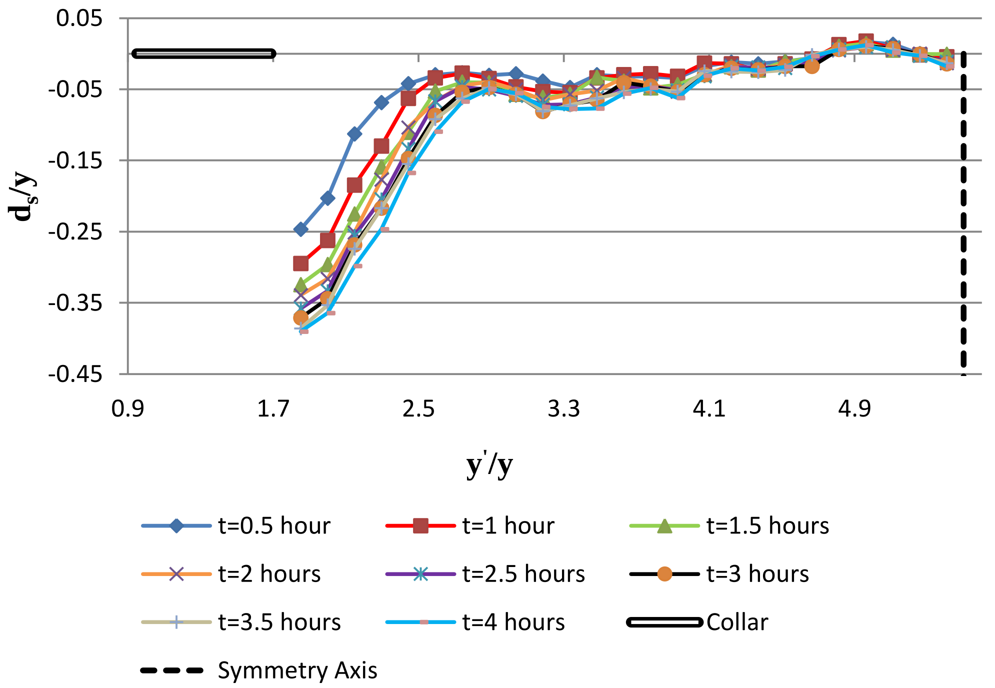


Figure 5-18: Temporal variation of scour hole with collar protection for the contraction ratio of 2L/W=0.12 at section II.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

Laboratory experiments were conducted to assess effect of contraction ratio as well as collars, which were attached spill-through abutments at different vertical elevations, on scour development around spill-through abutments. Moreover, optimum locations for collars were determined which causes maximum reduction in the maximum scour depth compared to the experiments without collar application. In addition, temporal variation of scour around abutments was investigated for the highest and lowest contraction ratio with applying collars at optimum locations. Results of the study can be summarized as follows for different cases;

- Collars are effective in reducing scour depth as well as shifting its position away from abutments for both single and multiple abutment configurations.
- For multiple abutment configuration, the best efficiency for the reduction in maximum scour depth was obtained by applying the widest collars at deeper elevations if the contraction ratio, $2L/W \geq 0.25$.
- For multiple abutment configurations, the best efficiency for the reduction in maximum scour depth was obtained by applying collars at different elevations. The widest collar application did not necessarily provide the best efficiency if contraction ratio, $2L/W < 0.25$. Optimum position and size of the abutment can be selected from the Figures.

- For multiple abutment configuration, even if the reduction is small for some of the cases where $2L/W<0.25$, it should be noted that the position of the maximum scour depth is occurring at a larger distance to the abutment compared with the case without collars
- For single abutment configuration, collars at deeper levels provide average of 50% reduction.
- Collars are more effective for single abutment configuration compared to the multiple abutment configurations for the dimensionless abutment length, $L_a/y> 2.1$.

6.2 Recommendations

Scour is a complex phenomenon which is affected by lots of parameters. In this study collars at different elevations were tested for scour reduction by keeping some parameters constant. Some recommendations for further studies are given below;

- In this study experiments were conducted under clear-water conditions and flow intensity, U/U_c ratio is selected as 0.9. In order to make further evaluation for the scour development with and without collars different flow intensities can be used especially for closer values to 1.
- Although maximum scour can be observed near the threshold of live-bed conditions, further studies can be made under live-bed conditions for better understanding of the phenomenon.
- Different shaped abutments can be tested instead of spill-through abutments with different contraction ratios.
- Experiments are limited to the laboratory conditions. Collars can be applied in the field to observe real impact on scour prevention.

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