EFFECTS OF COLLARS ON LOCAL SCOUR AROUND SEMI-CIRCULAR END BRIDGE ABUTMENTS

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Approval of the thesis:

EFFECTS OF COLLARS ON LOCAL SCOUR AROUND SEMI-CIRCULAR END BRIDGE ABUTMENTS

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ABSTRACT

EFFECTS OF COLLARS ON LOCAL SCOUR AROUND SEMI-CIRCULAR END BRIDGE ABUTMENTS

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During severe floods, bed material around bridge piers and abutments are scoured by the flow and as a result, bridges are subject to damages. These damages are mostly unrepairable and can result in loss of lives and property. In this thesis study, abutment scour under clear-water condition was investigated and collars were tested as scour countermeasures around the abutments. The experimental study was carried out in a rectangular channel with an almost uniform cohesionless bed material of d_{50}=1.50 mm for a test period of 3-hours. The channel was 28.5 m long and 1.5 m wide. The erodible bed material was placed into the test section that was 5.8 m long and 0.48 m deep.

For this thesis study, 60 experiments were carried out with and without various collars placed at different elevations around the abutments. The scour formation around the abutments with collars was observed and scour reduction efficiencies of the collars were studied. Experiment results were compared with the previous studies of Doğan (2008) and Kayatürk (2005) in terms of sediment size, abutment shape and flow depth, and the effects of these factors on collar's scour reduction efficiency were studied. Based on the results of the experimental studies, it was observed that scour depths decreased as the collar width increased and the collar placed deeper into the sediment bed for a given abutment length. When the present study and the previous studies were compared, it was observed that sediment size and flow depth had no significant effect on the scour reduction performances of the collars.

Keywords: Scour, Semi-circular End Bridge Abutments, Collar, Scour Countermeasures

ÖZ

KÖPRÜ KENAR AYAKLARINA YERLEŞTİRİLEN PLAKALARIN YARI DAİRESEL KENAR AYAKLAR ETRAFINDAKİ YEREL OYULMAYA ETKİSİ

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Büyük taşkınlar sırasında köprü orta ve kenar ayakları etrafındaki yatak malzemesi aşınmakta ve köprüler zarar görmektedir. Bu hasarlar çoğu zaman onarılamaz boyutlara ulaşabilmekte, sonuç olarak can ve mal kayıplarına neden olabilmektedir. Bu tez çalışmasında, temiz su oyulması koşulu altında köprü kenar ayakları etrafında oluşan oyulmalar ve bu oyulma derinliklerinin azaltılması için yerleştirilen plakalar incelenmiştir. Deneyler, dikdörtgen bir kanalda, d_{50}=1.50 mm olan oldukça üniform ve kohezyonsuz yatak malzemesi kullanılarak 3'er saatlik periyotlarla yapılmıştır. Kanal yapısı, 28.5 m uzunluğunda ve 1.5 m genişliğindedir. Kanalda deneylerin yapıldığı kısım, 5.8 m uzunluğunda olup, 0.48 m derinliğinde oyulabilir yatak malzemesi ile doldurulmuştur.

Bu tez çalışması için 60 deney yapılmış olup, deneylerde köprü kenar ayakları, etraflarına plaka yerleştirilmeden; daha sonra ise değişik boyutlarda farklı derinliklerde plakalar yerleştirilerek test edilmiştir. Plakalar yerleştirildiğinde, kenar ayaklar etrafındaki oyulmaların formasyonları değerlendirilerek, plakaların verimleri gözlemlenmiştir. Deney sonuçları, Doğan'ın (2008) ve Kayatürk'ün (2005) deneysel çalışmaları ile sediment tane büyüklüğü, kenar ayak şekli ve su derinliği açısından kıyaslanmış, bu etmenlerin yatay plakaların oyulmaya karşı gösterdiği davranışlar üzerindeki etkisi incelenmiştir. Deneyler sonucunda, kenar ayak boyu sabit tutulup plaka genişliği arttıkça ve plaka daha derinlere yerleştirildikçe oyulma derinliğinde azalma olduğu gözlenmiştir. Mevcut tez çalışması önceki iki çalışma ile kıyaslanırken, sediment çapının ve su derinliğinin, plakaların oyulma derinliğini azaltma performansları üzerinde kayda değer bir etkisi olmadığı sonucuna varılmıştır.

Anahtar Kelimeler: Oyulma, Yarı Dairesel Köprü Kenar Ayakları, Plakalar, Oyulma Tedbirleri

TO MY FAMILY ...

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I would like to express my sincerest gratitude and appreciation to my supervisor Prof. Dr. Mustafa Göğüş and Assist. Prof. Dr. Mete Köken for their invaluable guidance, advice and encouragement throughout my whole thesis study.

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A_{total}	Total area of the abutment with collar
$A_{abutment}$	Abutment area on the horizontal plane
B	Channel width
B_a	Abutment width
B_c	Collar width around the abutment
B_t	Total width of the abutment width and collar width on horizontal
C	Cohesiveness
C_u	Uniformity coefficient
d_s	Local scour depth at the abutment at any time
$(d_s)_{max}$	Maximum scour depth at the abutment at the end of the given time duration
$(d_s)_{max,c}$	Maximum scour depth at the abutment with collar
d_{50}	Median size of sediment
d_{84}	Sediment size for which 84 % of the sediment finer
d_{60}	Sediment size for which 60 % of the sediment finer
d_{16}	Sediment size for which 16 % of the sediment finer
d_{10}	Sediment size for which 10 % of the sediment finer
F_r	Froude number of flow
g	Gravitational acceleration
K_a	Shape factor of abutment
K_G	Approach channel geometry factor
L_a	Projecting length of abutment, perpendicular to the flow
L_c	Projecting length of collar, perpendicular to the flow
R^2	Correlation coefficient
Re^*	Particle Reynolds number
Q	Discharge of the flow
S_0	Slope of the channel
S_e	Energy slope of flow

S_p	Particle shape factor
S_s	Specific gravity
T_c	Collar thickness
t	Time
U	Mean approach flow velocity
U_c	The value of the U at the threshold of grain motion
U_*	Shear velocity of the approach flow
U_{*c}	The value of the U_* at the threshold of grain motion
y	Normal flow depth
y_c	Critical flow depth at the threshold of grain motion
w	Sediment fall velocity
Z_c	Collar level on the abutment with reference to bed level
θ	Ratio of total area of the abutment and collar to the abutment area on horizontal plane
α_a	Abutment skewness
α_c	Shield's entrainment factor, dimensionless critical shear factor
σ_g	Standard deviation of particle–size distribution
φ	Angle of repose
ρ	Fluid density
ρ_s	Sediment density
μ	Dynamic viscosity of fluid
τ_0	Bed shear stress
τ_c	Critical shear stress for sediment particles to move

CHAPTER 1

INTRODUCTION

1.1 GENERAL REMARKS

Human has tried to bridge flowing waters in order to enhance the ability to manipulate resources in the adjoining shores since ancient times. Technical knowledge is required to design and construct a structure across a river. Therefore, it is often required to place vertical columns and piers in riverbed to support the load of the bridge structure in order that bending moments and shear forces acting on the bridge to be reduced. However, in the effort to reduce these forces, bridge piers and abutments unknowingly pose a different and serious challenge for engineers even in today's conditions (Chiew, 2008). The citation by Neill (1973) stating, "man who overlooks water under bridge will find bridge under water", compactly describes the danger enforced on bridges when there is an interaction between the flow-structure and the erodible bed on which the bridge is founded (Chiew, 2008).

The term "scour" becomes more significant for bridges when this interaction between the flow and erodible bed is considered since scour phenomenon is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams (Li, Kuhnle and Barkdoll, 2006).

Scour failures have a tendency to occur suddenly without prior warning and also monitoring these failures is very difficult during flood events. Bridge replacement costs, widespread economic interruption on transportation and even the loss of life assigned to bridge failures resulted from foundation scour during hydrologic events have been widely documented (Stamey, 1996, Parola et al., 1998, Morris and Pagan-Ortiz, 1999, Richardson and Davis, 2001).

Among the large number of bridge failures recorded, one of the main causes was abutment scour during flood events (Melville, 1992, Richardson and Richardson, 1993). Although, researches showed that one of the main reasons is abutment scour, it has received less attention when compared to pier scour (M. M. Abou Seida et. al., 2009). For that reason, abutment scour and especially countermeasures for this type of scour should be researched and studied to understand its mechanism and to minimize the damages that come forth.

1.2 OBJECTIVES and SCOPE

The primary objective of this thesis study is to investigate the effects of collars with different sizes that are placed at various elevations around semi-circular end abutments, on the reduction of local scour at the base of abutments. A series of experiments were conducted at the laboratory under clear-water flow conditions with semi-circular end abutments and collars of various sizes and at various depths using almost uniform sand of d_{50}=1.50 mm. In comparison with the thesis studies of Kayatürk (2005) and Doğan (2008), the abutment shape, the depth of the flow and the grain size of the uniform cohesionless bed material are altered to observe whether the results are in accordance with each other. In the discussion part, the results obtained from the above mentioned thesis studies and this one to be compared and interpreted.

1.3 SYNOPSIS OF THE THESIS

The information about bridge abutment scour is presented and the literature is reviewed in Chapter 2. The countermeasures to protect bridge abutments from scour are described and the related previous studies are also mentioned in Chapter 3. In Chapter 4, the experimental setup and the model are illustrated. Chapter 5 presents the experimental results and conclusions drawn from the experiments. In Chapter 5, the present study is compared with the previous studies of Doğan (2008) and Kayatürk (2005), and recommendations are given based on the studied conditions.

CHAPTER 2

BRIDGE ABUTMENT SCOUR

2.1 INTRODUCTION

As mentioned in Chapter 1, abutment scour appears to be the primary reason for bridge failures and potential catastrophic results; such that abutment damages can cause excessive scour resulting in bridge failures and consequently potential loss of lives (Li, Kuhnle and Barkdoll, 2006). Accordingly, it is critical to understand scour mechanism and effective parameters on local scour at bridge abutments. Therefore, before considering any countermeasures, mechanism and parameters will be investigated fundamentally in this chapter.

2.2 BRIDGE ABUTMENT SCOUR MECHANISM

In a river, bridge abutments disturb the flow by protruding into the main channel or into the floodplain and as a result causing the river flow to accelerate and separate at the upstream face of the abutment while passing the bridge abutment (M. M. Abou Seida et. al., 2009). According to Kwan (1988), the flow around abutments is a complex system of vortices, namely downflow vortex, primary vortex, secondary vortices and wake vortices (Papanicolaou et. al., 2004). When flow encounters the frontal face of the abutment, it is forced downward towards the sediment bed in a jet motion that is impinging on the bed. On the other hand, the primary vortex is formed resulting from that downflow is further deflected up parallel to the bottom surface of the abutment. In addition, the primary vortex is pushed around the tip of the abutment along the bed surface in a continuation of scour formation. According to

Papanicolaou and Hilldale (2002), these frontal vortices (downflow vortex and primary vortex) are then coupled with secondary vortices resulted from flow constriction due to the existence of the abutment and finally, wake vortices formed at the downstream end of the abutment due to the flow separation. Boundaries of the stagnant wake region are defined by the secondary and wake vortices (Papanicolaou et. al., 2004). As the strength of the primary vortex and downward flow increase, the size and depth of the scour hole increase due to erosion and removal of more sediment particles from the scour hole. Until the equilibrium condition is reached, the condition that sediments inside the scour hole can no longer be moved by the flow field and bottom shear stress, the scour hole deepens and enlarges. In equilibrium condition for clear-water scour, there is no change in the scour pattern with time; however, for live-bed scour case, the scour pattern may vary with time due to the continuous supply of sediment into the scour hole. However, in general, the scour shape around the abutments can be defined as an inverted cone with some formations of secondary groove in the river bed resulting from secondary vortices (M. M. Abou Seida et. al., 2009). Below, the abutment scour parameters and an experiment photograph of this study are shown in Figures 2.1 and 2.2 accordingly.

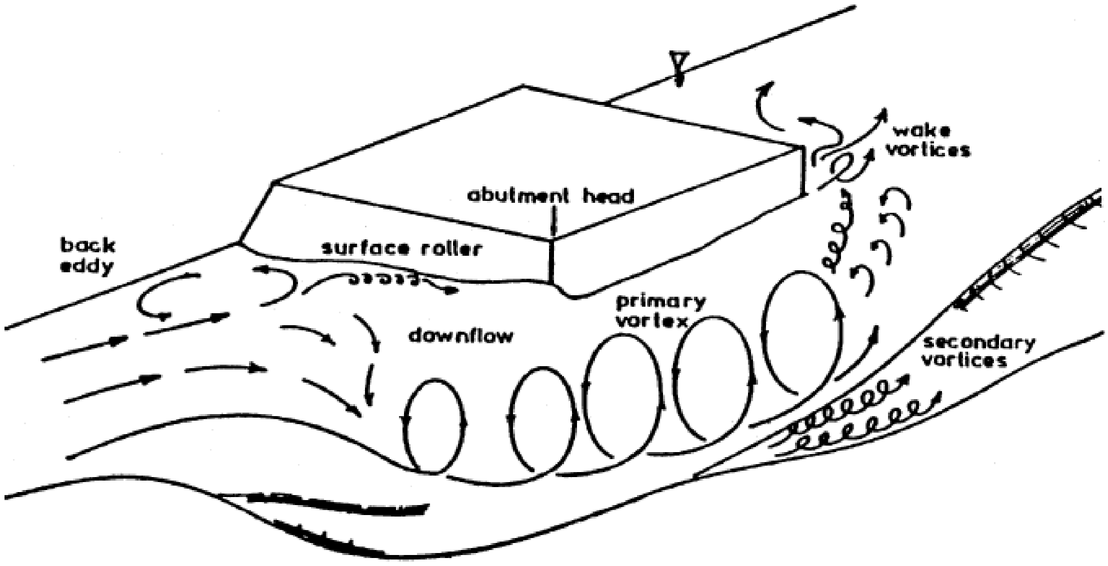


Figure 2.1 General view of the abutment scour (after Kwan, 1984)

Figure 2.2 General view of the scour hole around a semi-circular end abutment tested in this study

2.3 PARAMETERS INFLUENCING LOCAL SCOUR AT ABUTMENTS

In general, the local scour around an abutment is affected by the following parameters; fluid, flow, channel geometry, bed material, abutment geometry parameters and time (independent variable). These parameters and the related items are listed below:

1. Fluid parameters: density, viscosity and temperature.

2. Approaching flow parameters: mean flow velocity, flow depth, shear velocity, roughness and gravitational acceleration.

3. Channel geometry parameters: width, cross-sectional shape and slope.

4. Bed material (sediment) parameters: median size, grain size distribution, mass density, angle of repose and cohesiveness.

5. Abutment geometry parameters: size, shape, orientation with respect to the main flow and surface condition.

6. Time of scouring can be regarded as an independent parameter for the developing scour hole.

A list of the commonly used parameters is given in Table 2.1, usually the same parameters are identified affecting the scour depth at an abutment in different non-dimensional forms (Li, Kuhnle and Barkdoll, 2006).

Table 2.1 Parameters influencing local scour around abutments

Parameter Name	Symbols	*Attribution*
Density	ρ	FLUID
Dynamic Viscosity	μ	
Gravitational Acceleration	g	FLOW
Normal Flow Depth	y	
Mean Approach Velocity	U	
Energy Slope of Flow	S_e	
Width of Channel	B	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	w	
Particle Shape Factor	S_p	
Angle of Repose	φ	
Cohesiveness	C	
Dimensionless Critical Shear Stress	α_c	
Particle Reynolds Number	Re^*	
Length of Abutment	L_a	ABUTMENT
Skewness	α_a	
Shape of Abutment	K_a	
Time	t	TIME

The local scour depth (d_s) around a bridge abutment can be written as:

$$d_s = f\,[\rho, \mu, y, U, S_e, g, B, S_0, K_G, d_{50}, S_s, \sigma_g, w, S_p, \varphi, C, \alpha_c, Re^*, L_a, \alpha_a, K_a, t] \quad (2.1)$$

Eliminating some of these parameters for the specific conditions and making the remaining ones non-dimensional, the following parameters can be accepted as the most important those influence the abutment scour (Li, Kuhnle and Barkdoll, 2006):

$$d_s/L = f\,(t, U/U_c, L_a/d_{50}, L_a/y, \sigma_g, K_a, K_g, \alpha_a) \quad (2.2)$$

where U_c is the critical mean velocity at which initiation of particle motion starts at the channel bed.

The countermeasures against abutment scour can be selected by making use of these parameters but at the beginning of selection and design process, it is critical to understand the variables and their relative effects. Therefore, in the following sections, some of the variables are discussed in detail.

2.3.1 Time Evolution

In bridge foundation design stage, identifying the temporal change of the scour and the time needed to reach the equilibrium state of scour is very helpful in obtaining the maximum scour depth in order to avoid over-designs by knowing how much the bridge foundations required to be protected from scour and to save the funds. However, the equilibrium time reached in the laboratory conditions and real time for a design flood do not precisely match with and also estimating the time needed for the scour depth to reach its maxima is difficult (Doğan, 2008).

Scour time evolution curve might be used to predict the scour depth at a certain moment of a flood hydrograph (Li, Kuhnle and Barkdoll, 2006). A schematic diagram of the time-variation of the scour depth at a cylindrical pier is shown on Figure 2.3 (after Chabert & Engeldinger 1956).

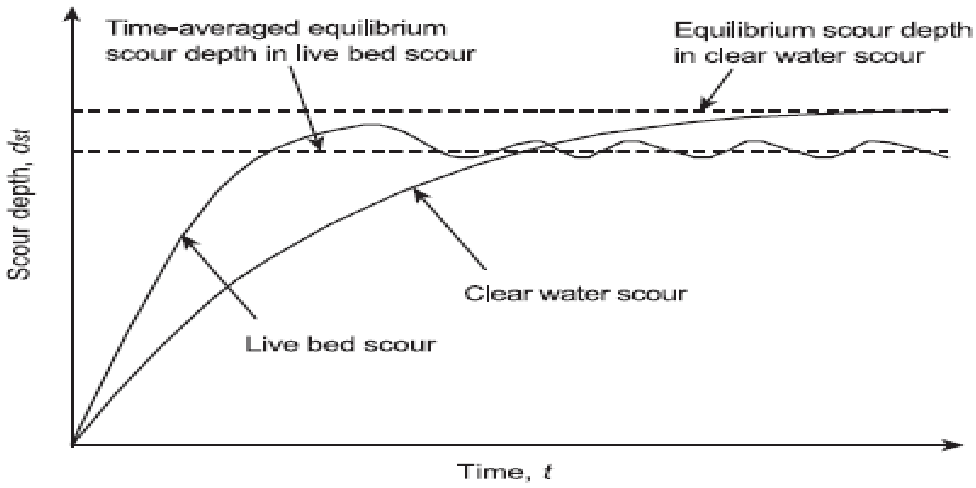


Figure 2.3 Time development of clear-water and live-bed scour (after Chabert & Engeldinger, 1956)

According to Figure 2.3, the clear-water scour depth reaches its maximum over a longer period of time than prevailing for the live-bed condition. In addition, the maximum depth of the local clear-water scour may not be reached until after several floods (Richardson and Davis, 2001). According to Melville and Chiew (1999), the time required for the equilibrium scour depth to develop increases rapidly with flow velocity in clear-water flow conditions while it decreases rapidly for the live-bed scour. It can take a very long time for the equilibrium scour hole to form due to the fact that the equilibrium clear-water scour depth is reached asymptotically with time.

"Rouse (1965), Gill (1972), Rajaratnam & Nwachukwu (1983), Dargahi (1990), Ettema (1980), Kohli & Hager (2001), Oliveto & Hager (2002) and Coleman et. al. (2003) think that the variation of the scour depth with time is logarithmic. Ahmad (1953), Franzetti et. al. (1982), Kandasamy (1989), Whitehouse (1997), Cardoso & Bettess (1999) and Ballio & Orsi (2000) propose an exponential time-variation of the scour; while Breusers (1967) and Cunha (1975) give a power law distribution" (Barbhuiya and Dey, 2004).

2.3.2 The Effect of Flow Velocity

The ratio of the shear velocity (U_*) to the critical shear velocity (U_{*c}) represents the term flow intensity. Flow intensity can also be defined as the ratio of the approach mean velocity (U) to the critical mean velocity (U_c) due to the difficulty of measuring the shear velocity under live-bed conditions (Melville and Chiew, 1999). The local scour depth in uniformly-graded sediment increases almost linearly with velocity to a maximum at the threshold velocity under clear-water flow conditions (Melville and Coleman, 2000). When the ratio $U_*/U_{*c} = 1$, the maximum scour depth is reached and the corresponding maximum scour depth is termed as the threshold peak. As the velocity exceeds the threshold velocity, the local scour depth in uniform sediment first decreases and then increases again to a second peak, but the threshold peak is not exceeded provided that the sediment is uniform (P. D. Alabi, 2006).

An increasing trend in the relationship between scour depth and flow velocity was indicated in the data of Dongol (1994). Chabert and Engeldinger (1956), Ettema (1980), Raudkivi and Ettema (1983), Laursen and Toch (1956), Breusers et al. (1977) and Chiew (1984) also observed the same trend. Generally, it was concluded that for clear-water scour conditions the maximum local scour depth in uniform sediments occurs at the threshold condition.

2.3.3 The Effect of Flow Depth

Abutment scour data obtained by Wong (1982), Tey (1984), Kwan (1988), Kandasamy (1989) and Dongol (1994) showed a trend such that the scour depth at abutment increases at a decreasing rate with flow depth. Barbhuiya & Dey (2004) also reported that for smaller flow depths the equilibrium scour depth increases significantly with increasing flow depth (y), on the other hand for higher flow depths, equilibrium scour depth is independent of flow depth.

2.3.4 The Effect of Sediment Size

When considering the effects of the sediment size on the scour, the median sediment diameter d_{50} and geometric standard deviation $\sigma_g = (d_{84} / d_{16})^{0.5}$ of particle size distribution are the two most commonly used parameters (Barbhuiya & Dey, 2004). It is important to make a distinction between clear-water and live-bed scour for studying the effect of sediment size on scour. Some early pier scour researchers argued that there is no significant effect of sediment size on local scour under live-bed conditions whereas some others proposed that the scour depth decreases with an increase in the sediment size. On the other hand, considering clear-water flow conditions, most studies have shown that sediment size has an effect on local scour (Li, Kuhnle and Barkdoll, 2006).

In addition, the coefficient of uniformity, i.e., $C_u = d_{60} / d_{10}$, is also a parameter used to identify the uniformity of a sediment sample. Sediment mixture can be defined as uniform when the value of C_u is less than 3.0 (Doğan, 2008).

Dongol (1994) used abutment length, L_a, and median sediment size, d_{50}, with the ratio of L_a / d_{50} term based on scour development to represent the sediment size effect. There were four different values of L_a / d_{50} as follows: (1) $L_a / d_{50} > 100$: fine sediment; (2) $100 > L_a / d_{50} > 40$: intermediate sediment; (3) $40 > L_a / d_{50} > 10$: coarse sediment; (4) $10 > L_a / d_{50}$: very coarse sediment (Li, Kuhnle and Barkdoll, 2006). For the case $L_a / d_{50} > 50$, the effect of L_a / d_{50} reduces on the scour development that is valid for most of the actual prototype conditions. For grain sizes with $L_a / d_{50} < 50$, the grains which obstruct the scouring process are large enough when compared to the width of the groove excavated by downflow (Melville and Coleman, 2000).

2.3.5 The Effect of Sediment Gradation

River bed materials are generally nonuniform. A measure of the nonuniformity of the sediment is geometrical standard deviation σ_g (Li, Kuhnle and Barkdoll, 2006). For the log-normally distributed sediment, σ_g is given by

$$\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \tag{2.3}$$

Clear-water or live-bed scour conditions have an influence on the effect of sediment gradation on scour depth. It is found that under the similar flow conditions for sediment with same d_{50}, the development of the scour is less in nonuniform sediments than in uniform sediments, i.e., the scour depth tends to decrease with increasing value of σ_g due to formation of armour-layers in scour holes (Barbhuiya & Dey, 2004). Ettema (1980), Wong (1982), Melville (1992) and Dongol (1994), Li, Kuhnle and Barkdoll (2006) also observed that scour depth was decreasing gradually with increasing σ_g; it is found that less scour is developed in nonuniform sediments than in uniform sediments.

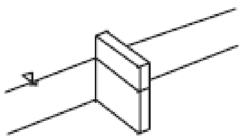
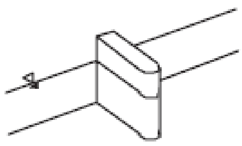
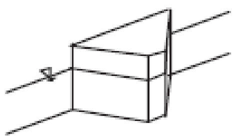
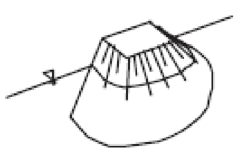
2.3.6 The Effect of Abutment Length

Abutment length and contraction ratio, termed as the inverse of the opening ratio (Barbhuiya and Dey, 2004), are two important parameters that influence the scour process and depth at an abutment. Various experimental data have shown that the scour depth increases as the abutment length increases since the opening ratio decreases when the length of the abutment is increased as Kandasamy mentioned in 1989.

2.3.7 The Effect of Abutment Shape

Depending on the shape of the abutment, the local scour magnitude at abutments differs; such that, well streamlined bodies like semi-circular ended, spill-through and wing-wall abutments produce low strength vortex that resulted from downflow and secondary flow while sharp obstructions, e.g. vertical-wall abutments are capable of producing strong vortex fields. Therefore, greater scour depths occur in the case of sharp obstructions compared with the streamlined bodies (Barbhuiya and Dey, 2004, Li, Kuhnle and Barkdoll, 2006). The effect of abutment shape on the local scour at abutments has been of interest to researchers for a long time. In order to account for the effect of shape of the abutments on the equilibrium scour depth, Melville (1992, 1995 and 1997) used shape factor K_s. Commonly used abutment shapes and corresponding values of the shape factors are shown in Table 2.2 below:

Table 2.2 Abutment shape factors (Barbhuiya and Dey, 2004)

Abutment model	Abutment shape	Shape factor, K_s
	Vertical-wall	1·00
	Semicircular ended	0·75
	45° wing-wall	0·75
	Spill-through with slope horizontal : vertical 0·5 : 1 1 : 1 1·5 : 1	 0·60 0·50 0·45

2.3.8 The Effect of Abutment Skewness

In order to give the shortest span and eliminate skewness, bridges are generally constructed at a straight reach of the river channel and normal to the flow. On the other hand, inclined abutments can be built due to the existing road layout constraints and river channel geometry. In those cases, abutment skewness is defined as the inclination of the abutment to the mean flow direction (Li, Kuhnle and Barkdoll, 2006) and in Figure 2.4 it is denoted by α as shown. The effect of abutment skewness on abutment scour has been studied by various researchers, among which are Ahmad (1953), Laursen (1958), Garde et. al. (1961), Sastry (1962), Field (1971), Zaghloul (1983), Kwan (1984) and Kandasamy (1985). It has been generally found after studies applied to both live-bed and clear-water flow conditions that the scour depth increases with an increase in α for α ≤ 90° (Li, Kuhnle and Barkdoll, 2006).

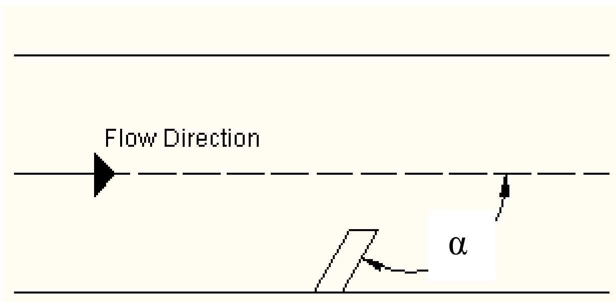


Figure 2.4 Abutment skewness angle

2.4 CLOSURE

The local scour at bridge abutments is a complex phenomenon that involves numbers of parameters. However, the basic mechanism of the abutment scour can be summarized such that the downflow at the upstream face of an abutment and associated primary vortex with the secondary and wake vortices erode the material from the base region of the abutment and create local scour hole (Doğan, 2008). The parameters affecting the scour phenomenon are listed and explained shortly within this chapter.

CHAPTER 3

BRIDGE ABUTMENT SCOUR COUNTERMEASURES

3.1 GENERAL REMARKS

As mentioned in the previous chapters, bridge abutment scour is a common cause of bridge failures that often result in excessive repairs, substantial traffic interruption, loss of accessibility and sometimes loss of lives (Kayatürk, 2005). As a result, bridge failures resulting from scour at bridge abutments have increased the researches and studies in scour prediction and scour countermeasures. The main aim of the studies related with the countermeasures against bridge abutment scour is to determine design guidelines for countermeasures that are effective in preventing or reducing local scour at the abutments so as for the bridges to be built in future and to save and rehabilitate the existing bridges from scour failures (Li, Kuhnle and Barkdoll, 2006).

Several studies have investigated scour countermeasures for bridge abutments or provided suggestions for the countermeasures. Notably, NCHRP, Report 587 “Countermeasures to Protect Bridge Abutments from Scour” and the FHWA Hydraulic Engineering Circular No. 23 (HEC 23) “Bridge Scour And Stream Instability Countermeasures Experience, Selection, and Design Guidance” (2001) addresses various countermeasures. In addition, FHWA NJ’s “Handbook of Scour Countermeasures Designs” Final Report in September 2005, defined a countermeasure by HEC-23 as “a measure incorporated at a stream/bridge crossing system to monitor, control, inhibit, change, delay, or minimize stream and bridge stability problems and scour”. As can be understood from this definition, selection of a countermeasure is directly dependent on the state of the problem.

In addition to determining the state of the problem, it is important to consider limitations enforced by environmental regulation, relative cost, availability, serviceability, constructability and design constraints while selecting the countermeasures. The criteria for countermeasure selection usually include the set of considerations below (NCHRP, Report 587, 2007):

- Technical effectiveness,
- Constructability,
- Durability and maintainability,
- Aesthetics and environmental issues,
- Cost.

In order to cope with the scour at bridge elements, firstly it is important to identify the problem and set the conditions of the problematic area of the bridge site. Then, selection of the countermeasure type can be made accordingly.

3.2 COUNTERMEASURE CONCEPTS

The primary concepts for abutment scour mitigation are bank hardening, embankment stabilizing, and flow altering (NCHRP, Report 587, 2007). Bank hardening countermeasures such as riprap, cable-tied blocks, geo-bags, partially grouted riprap, and interlocking devices aim to armor or strengthen the surface of a bank in order to resist the hydrodynamic forces resulted from flow around an abutment. Embankment-stabilizing countermeasures increase the slope stability of the earthfill embankment at an abutment so that the embankment does not fail geotechnically when scour hole forms at the toe of the embankment. The aim of flow-altering countermeasures is to reduce the stresses caused by flow on the bed and banks such that the bed or bank material will not be eroded, e.g. spur dikes, stone walls, collars, submerged vanes, and guidebanks. The detailed explanation and presentation of these groups are given in NCHRP, Report 587 (2007).

3.3 ABUTMENT SCOUR COUNTERMEASURES

The abutment scour countermeasures, their advantages and disadvantages against abutment scour are presented in Table 3.1.

Table 3.1 Advantages and disadvantages of various countermeasures (Handbook of Scour Countermeasures Designs, FHWA NJ, 2005)

Countermeasure	Advantages	Disadvantages
Local Scour at Abutment		
Peak Flood Closure	Low initial cost	Limits access, constant monitoring
Monitoring	Low initial cost	Does not prevent scour
Riprap	Familiarity, relatively low cost and maintenance, easy to construct, ability to adjust to minor scour	Can wash out, disturbs channel ecosystem until vegetation reestablished
Gabions	Relatively low cost, ability to adjust to minor scour	Can be undermined, stones can wash out of wire mesh, disturbs channel ecosystem
Cable-tied Blocks	Will not wash out as easily	More difficult to construct, higher maintenance
Tile Mats	Will not wash out as easily	More difficult to construct, higher maintenance, easier for water to lift
Alarm Systems	Low initial cost	Provides no scour protection, must be checked periodically

Table 3.1 (continued)

Articulated Mattress	Coherent structure, individual block will not wash out	More difficult to construct, easier for water to lift
Concrete-filled Mattress	Rocks will not wash out, relative ease of construction	Can be undermined, easy for water to lift
Locking Blocks	Coherent structure, individual block will not wash out	More difficult to construct, easier for water to lift
Pavement	Conceptually appealing	High cost and maintenance, can be undermined, easy for water to lift
Rock Bolting	Strong, low maintenance	Costly, only for abutments on bedrock
Grouted Riprap	Rocks will not wash out, relative ease of construction	Can be undermined, easy for water to lift
Sacrificial Piles	Conceptually appealing	Not effective, high cost
Grout Bags	Ease of construction, low cost	Bags can wash out
Sheet Piling	Stops flow, helpful in dewatering	Scour can occur near sheet piling, construction difficult, rust
Hinged-Slab/Tethered Block System	Will not erode under extreme velocities	Could be subject to edge undermining
River Control		
Spur Dikes / Guide Banks	Proven effective	Can wash out, need to protect guide bank walls, obstructs navigation

Table 3.1 (continued)

Submerged Vanes	Elegant approach, not too expensive, effective	Obstructs navigation, possible debris snags, construction difficult
Collars	Low cost and maintenance, effective	Does not eliminate scour, not much experience
Attached Vanes	Low cost and maintenance, effective	Does not eliminate scour, not much experience

3.4 CONCLUSION

Scour, especially abutment scour, appear to be the major concern when consideration is safety of hydraulic structures. However, despite that many studies and researches have been carried, the problem of scour is not effectively figured out and fully understood. When these studies and researches are reviewed, it can be concluded that scour depths could be reduced by using different countermeasures. Yet, further studies are still required to predict the scour depth correctly and to save the structures from scour failure by finding techniques to prevent or reduce the scour in a cost effective manner (Khwairakpam and Mazumdar, 2009). Therefore, there is a need for more extensive studies and explorations of innovative concepts for scour countermeasures. In this context, various types of countermeasures are applied for different cases; however, some types are not researched in detail, such as collars (Li, Kuhnle and Barkdoll, 2006). This thesis study aims to improve the results of the previous studies related with collars and to carry forward the researches with regard to effects of collars on local scour around abutments by performing experiments on semi-circular end abutments equipped with collars. The experimental setup of this study and the methodology are given in detail within the upcoming chapters.

CHAPTER 4

EXPERIMENTAL SETUP

4.1 THE FLUME

Experiments of this study were conducted in a channel in the Hydromechanics Laboratory at Middle East Technical University, METU, in Ankara.

A rectangular channel with transparent walls, 28.5 m length and 1.5 m width with a slope of S_0=0.001 was filled with erodible almost uniform sediment of d_{50}=1.5 mm. The depth of the sand layer was 0.48 m having a length of 5.8 m in the flow direction. The discharge of the experimental setup was supplied by a pump from a constant-head water tank. A control gate was equipped at the end of the channel to adjust the flow depths.

Figure 4.1 shows the side view of the experimental setup.

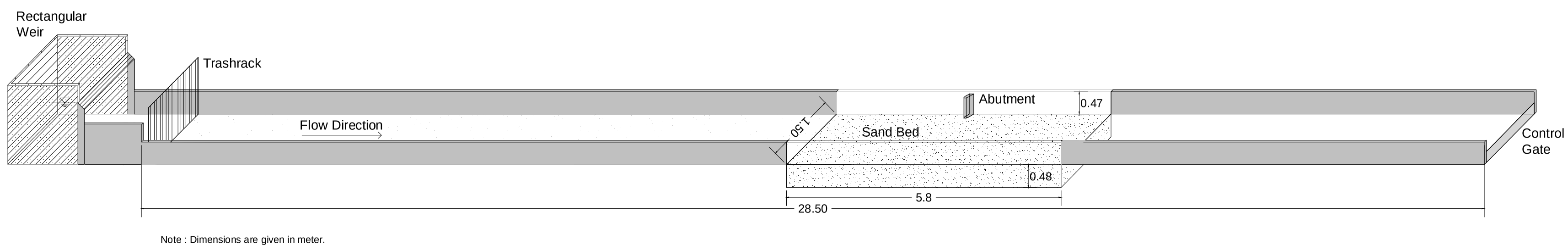


Figure 4.1 Side view of the experimental setup

4.2 THE ABUTMENT MODEL

All the abutment models used during the experiments were constructed from plexiglass and had a constant width of 10 cm and variable lengths of 40 cm, 35 cm, 30 cm, 25 cm, 20 cm and 15 cm. Below, Figures 4.2 to 4.6 show some of the abutment models and abutment-collar arrangements used in the experiments.

Figure 4.2 Abutment L_a=20 cm with collar B_c=10 cm at Z_c/y=-0.25

Figure 4.3 Abutment L_a=25 cm without collar

Figure 4.4 Abutment L_a=25 cm with collar B_c=5 cm at Z_c/y=0

Figure 4.5 Abutment L_a=25 cm with collar B_c=7.5 cm at Z_c/y=-0.25

Figure 4.6 Abutment L_a=30 cm with collar B_c=5.0 cm at Z_c/y=-0.50

4.3 SAND MATERIAL

The bed material in the flume was almost uniform and had a median size diameter of d_{50}=1.50 mm with σ_g=1.29 geometric standard deviation of particle size distribution and uniformity coefficient of C_u=1.7.

4.4 U / U_c RATIO

The shear velocity ratio U_*/U_{*c} and the mean velocity ratio U/U_c can be used as a measure of the flow intensity in scouring problems (Li, Kuhnle and Barkdoll, 2006). In these experiments, the ratio of U/U_c was used to determine the water depth satisfying the clear-water flow condition for the U/U_c=0.9 ratio, where U is the average velocity of the approach flow and U_c is the value of U at the threshold of grain motion. Before starting the experiments, first, the critical water depth for the initiation of grain motion y_c=12.1 cm was observed when the discharge was Q=0.0678 m^3/s. Then, the required flow depth for U/U_c=0.9 ratio is calculated as y=13.5 cm for the given discharge by adjusting the gate at the end of the channel. During this procedure, the threshold condition of bed material motion was defined as a condition for which the finer materials may move, but the elevation of the bed would not be lower more than 1 mm to 2 mm during the test duration (Doğan, 2008).

4.5 MEASUREMENT AND DEVICE

The flow discharge was measured with a sharp-crested rectangular weir having a width of 1.5 m and a height of 0.30 m mounted at the upstream section of the flume. In order to have uniform flow conditions, turbulence of the flow was reduced using bricks and sheet-iron strainer at the entrance of the channel. Uniform flow condition was necessary to measure the water depth in the channel and the scour depth around the abutment, correctly. When the necessary conditions obtained, the maximum scour depths were measured using a point-gauge with an accuracy of ±1 mm without disturbing the shape of the scour hole. Moreover, in order to get a 3-dimensional view of the sediment bed around the abutment for scoured and deposited zones, the channel bed is scanned by an acoustic device (Sea Tek 5 MHz Ultrasonic Ranging System) to determine the relative scour and deposition depths with respect to the sediment bed level (see Figure 4.7 below).

Figure 4.7 Acoustic device used in the experiments

CHAPTER 5

APPLICATION OF COLLAR TO CONTROL SCOURING AROUND ABUTMENTS

5.1 GENERAL

The primary objective of this thesis study is to investigate the effects of collars around semi-circular end abutments, on the reduction of local scour at the base of abutments by comparing the experimental results with the ones of Doğan's (2008) and Kayatürk's (2005), and make contributions to use of collars for scour reduction.

5.2 LITERATURE REVIEW

Secondary and wake vortices added to the primary vortex at the upstream corner of the abutment erode material from the base region of the abutment causing local scour hole. The depth of this scour hole can be reduced by placing an obstacle around the abutment that prevents the hole to deepen any further (Doğan, 2008). Herein, when the previous studies are reviewed, collars are used to reduce scour hole depth in such a way to "block the downflow at the leading edge of piers and abutments and eliminate scour-inducing secondary vortices" (Li, Kuhnle and Barkdoll, 2006). However, it should be noted that these researches are mainly focused on preventing local scour at bridge piers. Kapoor and Keana (1994), Kumar et. al. (1999) and Borghei et. al. (2004) are some of the researchers studied with collars on pier scour.

Collars are being studied as a countermeasure for their efficiency on preventing bridge abutment scour mainly in the last few years. Kayatürk, in her doctoral thesis (2005), studied the time development of the local scour around the bridge abutment with and without collars of various sizes installed at different elevations. Scour preventing efficiency of a collar is determined as a function of its size and vertical location on the abutment. According to the results of that study, it was concluded that as the collars placed below the bed material, the local scour depth decreases; besides, collars placed above the bed level reduced the scour depth yet not effective as collars below the bed level. On the other hand, the scour depth decreases as the collar size increases. The effects of the collar size on the scour reduction can be grouped as; when the abutment length, L_a, is greater than the flow depth, y, i.e., $L_a/y>1$, the reduction efficiency increases with increasing collar width B_c and increases as the collar elevation penetrating deeper in the sand bed providing the clear-water flow conditions, $U_*/U_{*c} = 0.90$. On the other hand, when the abutment length is smaller than the flow depth, the collars placed at the bed level shows higher scour reducing efficiency than placed at other elevations. The experimental results showed that collars also reduced the rate of temporal development of the scour hole in addition to reducing the scour depths (Masjedi A. et. al., 2010). Moreover, in the doctoral study of Kayatürk (2005) partial collars were proposed as an economical solution for scour depth reduction.

In 2006, Li, Kuhnle and Barkdoll conducted experiments on “countermeasures against scour at abutments”. A series of flat, horizontal and steel collars having different lengths and widths were also tested in a laboratory flume under clear-water flow conditions at a vertical-face wingwall abutment at the edge of a main channel (typical configuration of older bridges on smaller streams). Collars were found to protect the bridge abutment efficiently by eliminating secondary vortices that ordinarily would cause local scour. According to the results of that study, “the minimum collar dimensions that eliminated local scour were a flow perpendicular width of 0.23 L_a (L_a is the abutment length perpendicular to the flow direction) and a flow parallel length of 0.7 times the flow parallel abutment width. It was determined that a vertical location of 0.08 y (where y is the main channel flow depth) below the mean bed sediment elevation gave the best results of scour reduction. In addition, the collar not only reduced the scour magnitude near the abutment, but also retarded the development of the scour hole" (Li, Kuhnle and Barkdoll, 2006).

Doğan (2008), carried out a series of experiments under clear-water flow conditions in a rectangular channel with uniform non-cohesive sediment of d_{50}=0.90 mm grain size diameter. Rectangular collars placed around the rectangular abutments (in plan view) used at different elevations. In Doğan's study since one of the main objectives is to compare the results of the conducted experiments with Kayatürk's results, similar parameters were used. Doğan's study also aimed to draw a conclusion about the effect of sediment particle size of the bed material on the performance of the collar against abutment scour. The experiments carried out under clear-water flow condition of U_*/U_{*c} = 0.90 with a different flow depth from Kayatürk's and satisfying the condition that $L_a/y>1$ for all abutment lengths. According to results of Doğan's study (2008), regardless of the flow depth, when the clear-water flow condition was satisfied, decreasing L_a/B_c resulted in increasing scour reduction efficiency. On the other hand, as L_a/B_c increased, the collar depths shifted deeper into the bed level. In general, Doğan's results (2008) with a grain size diameter of 0.90 mm gave almost the same results of Kayatürk's results (2005) with a grain size of 1.48 mm.

In the literature review presented above, the need for further studies related with collar use for abutment scour reduction is obvious. It is also important to relate the previous studies with the new studies in order to compare the results and to make contributions to the existing results. For that reason, this study aims to make comparisons with the studies of Doğan (2008) and Kayatürk (2005), and to obtain new data for collar use and to get a better understanding of collar effect for decreasing local scour around abutments.

5.3 DIMENSIONAL ANALYSIS

The dimensional analysis obtained by Kayatürk (2005) was used in this thesis study, also. The maximum scour depth around an abutment in existence of collar, $(d_s)_{max,c}$ was defined as a function of the following parameters for clear-water scour condition:

$$(d_s)_{\max,c} = f\begin{Bmatrix} L_a, B_a, B_c, Z_c, T_c, U, y, S_0, g, \\ \rho_s, \rho, \mu, d_{50}, \sigma_g, t, B \end{Bmatrix} \quad (5.1)$$

where, B_c=collar width, Z_c=elevation of the collar with respect to the sand level, and T_c=collar thickness. Figure 5.1 shows a sketch of the collar-abutment arrangement with the related parameters.

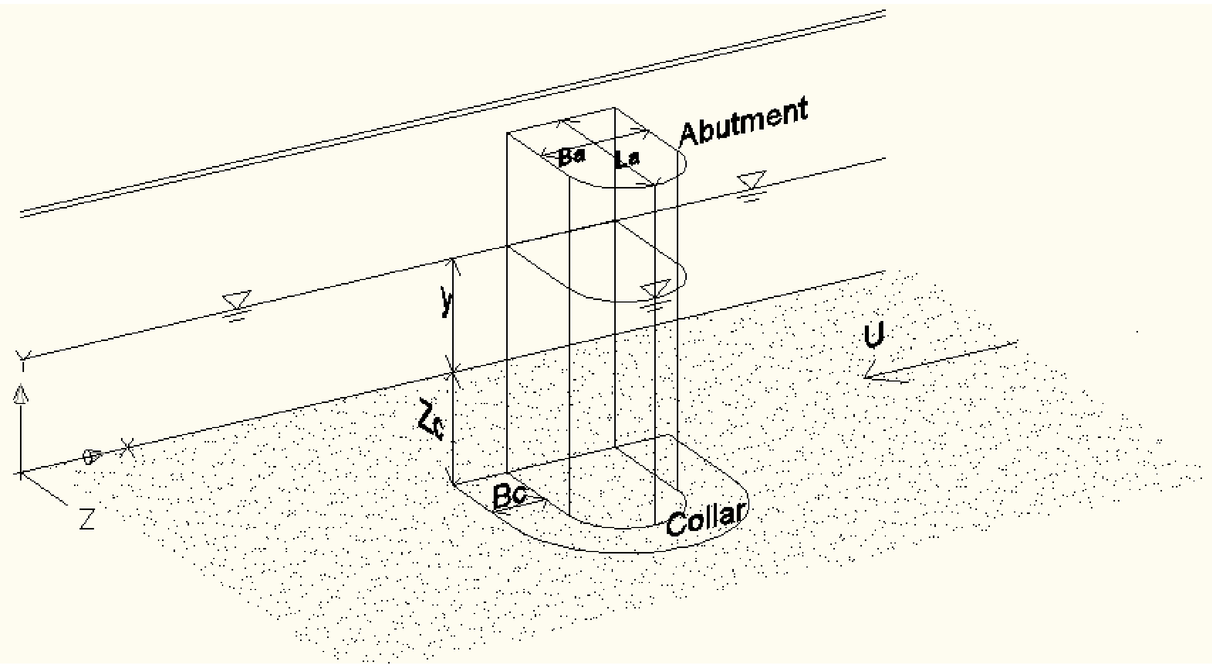


Figure 5.1 Definition sketch of the collar-abutment arrangement

The Buckingham's π theorem gives the following dimensionless terms:

$$\frac{(d_s)_{max,c}}{y} = f\left\{\frac{L_a}{y}, \frac{B_a}{y}, \frac{B_c}{y}, \frac{Z_c}{y}, \frac{T_c}{y}, \frac{\rho_s}{\rho}, \frac{U}{\sqrt{gy}}, \frac{B}{y}, \frac{\mu}{Uy\rho}, \frac{Ut}{y}, S_0, \sigma_g, \frac{d_{50}}{y}\right\} \tag{5.2}$$

Same as Kayatürk's (2005) and Doğan's (2008) studies, the experiments of this study were conducted with one sediment size and with constant parameters of bed slope, channel width, collar thickness, abutment width, duration of the experiment, flow depth and discharge. Therefore, Equation (5.2) can be simplified as:

$$\frac{(d_s)_{max,c}}{y} = f\left(\frac{L_a}{B_c}, \frac{Z_c}{y}, \frac{L_a}{B_a}\right) \tag{5.3}$$

The reduction in the scour depth around the bridge abutments as compared to the case without collar, $(d_s)_{max,c}$ can be given as:

$$\frac{(d_s)_{max} - (d_s)_{max,c}}{(d_s)_{max}} = f\left(\frac{L_a}{B_c}, \frac{Z_c}{y}, \frac{L_a}{B_a}\right) \tag{5.4}$$

The above equations are valid for Fr = $U/\sqrt{g.y}$ = 0.29, Re = (U.ρ.y)/μ = 45200 and U/U_c = 0.90 where μ ≈1x10^{-3} N.sec/m^2, ρ = 1000 kg/m^3.

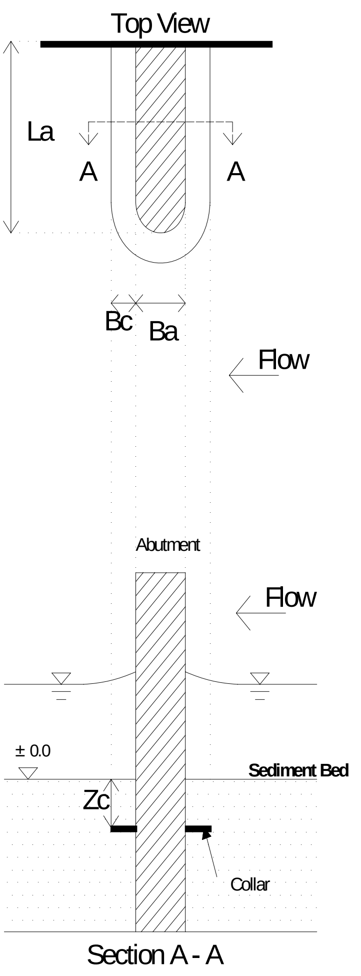
5.4 EXPERIMENTAL PROCEDURE

The experimental model was setup in the Hydromechanics Laboratory at METU. The collars were cut from 3 mm thick plexiglass plates. The elevations and widths of the collars were changed for each experiment. All the abutments used in this study were semi-circular end abutments with lengths of L_a= 15, 20, 25, 30, 35 and 40 cm and with a constant width of Ba=10 cm. Since the effect of streamwise abutment length on the development of the scour hole is small, the widths of the abutments were kept constant (Oliveto and Hager, 2002 and Kayatürk, 2005).

From preliminary experiments it was observed that the threshold condition of the bed material movement, that is $U/U_c \approx 1.00$, was attained at the flow depth of y=12.1 cm for the discharge of Q=0.0678 m^3/s. In order to get the flow depth corresponding to the condition of $U/U_c \approx 0.90$ for the same discharge, the flow control gate at the downstream end of the channel was raised gradually and finally the depth of y=13.5 cm was obtained. After these conditions were accomplished, the abutment to be tested was placed in the channel, the sand bed was leveled and the experiment was started. The scour formation and the maximum depth of the scour hole around the abutment were investigated after the 3-hour continued run under clear-water flow conditions. The maximum scour depths were measured with a point-gauge at the end of each 3-hour run (the data related with the abutments and collars tested in each experiment are given in Table 5.1). When the experiment was completed, the channel was drained and the collar was demounted carefully without disturbing the scour formation to record the data properly. At the end of each experiment, before starting the new run, the sand bed was levelled with a steel plate that could move over the rails mounted along the sidewalls of the channel.

On the other hand, the experiments with the acoustic device, used to get the 3-dimensional views of the sediment bed after scour formation, were conducted for the abutments of L_a=20 cm and L_a=35 cm without collar and with collars of B_c=5 cm and B_c=10 cm. Using varying number of transducers slightly submerged in water, the flow depths at downstream, upstream zones and around the abutment were measured. The scour depths and sediment depths in the sediment deposition zones were determined. These depths were non-dimensionalized dividing them by the flow depth of y=13.5 cm. The depth measurement accuracy of the acoustic device was found to be ± 0.1 mm by comparing the measured depths by those obtained using point-gauge.

Table 5.1 Abutment and collar sizes used in the tests

Abutment	Z_c (cm) = ±0.0, -3.4, -6.8 (with respect to the sediment bed)			
	Type	L_a (cm)	Case	B_c (cm)
	1	15	a	10.0
			b	7.5
			c	5.0
	2	20	a	10.0
			b	7.5
			c	5.0
	3	25	a	10.0
			b	7.5
			c	5.0
	4	30	a	10.0
			b	7.5
			c	5.0
	5	35	a	10.0
			b	7.5
			c	5.0
	6	40	a	10.0
			b	7.5
			c	5.0

5.5 SCOUR MECHANISM

Downflow vortex, primary vortex, wake vortices and secondary vortices cause local scour around bridge abutments eroding material from base region of the abutment. According to Papanicolaou and Hilldale (2002), frontal vortices, i.e., downflow vortex and primary vortex are coupled with secondary vortices resulted from flow constriction due to the existence of the abutment and finally, wake vortices formed at the downstream end of the abutment due to the flow separation (Papanicolaou et. al., 2004).

Function of collars for preventing abutment scour can be understood better when the scour mechanism is considered, such that at any level above the bed collars separate the flow into two regions as above and below the collar. For the region above the collar, downflow is blocked by the collar and as a result, its strength of impingement at the bed decreases. On the other hand, below the collar, strength of the downflow and primary vortex decreases. Briefly, the size of the collar and its location on the abutment with respect to the bed affect the efficiency of the collar in scour reduction (Kayatürk, 2005).

5.6 DISCUSSION OF RESULTS

5.6.1 Scour Profiles around the Abutment with and without Collar

Within the scope of this study totally 60 experiments were conducted. 54 of these experiments were conducted with abutments of L_a=15 cm, 20 cm, 25 cm, 30 cm, 35 cm and 40 cm for a period of 3-hours, placing the collars of B_c=5 cm, 7.5 cm and 10 cm widths at three different locations on the abutments. The remaining 6 experiments were carried out with the same abutments but without collars for the same time period to get the maximum scour depths around the abutments. Table 5.2 shows the results of all the experiments conducted for the conditions with and without collars in terms of maximum scour depths and collar efficiencies as well as the abutment and flow properties. In Table 5.2; $(d_s)_{max}$ stands for the maximum scour depth around the abutment having no collar around it, and $(d_s)_{max,c}$ represents the maximum scour depth around the abutment where collars are placed at various elevations for scour reduction. The last column of the table shows the percent reduction of the maximum scour depth obtained with the collars.

Table 5.2 Experimental data for Q=0.0678 m^3/s, y=13.5 cm and B_a=10 cm

Run no	La (cm)	Bc (cm)	La/Bc	La/Ba	Zc (cm)	y (cm)	Zc/y	Θ	(ds)max (cm)	(ds)max,c (cm)	% Reduction in max. scour depth
R1	15.0	5.0	3.0	1.5	0.0	13.5	0.00		11.2	5.3	52.7%
R2	15.0	5.0	3.0	1.5	-3.4	13.5	-0.25	3.15	11.2	5.0	**55.4%**
R3	15.0	5.0	3.0	1.5	-6.8	13.5	-0.50		11.2	6.7	40.2%
R4	15.0	7.5	2.0	1.5	0.0	13.5	0.00		11.2	4.7	**58.0%**
R5	15.0	7.5	2.0	1.5	-3.4	13.5	-0.25	4.31	11.2	5.2	53.6%
R6	15.0	7.5	2.0	1.5	-6.8	13.5	-0.50		11.2	6.8	39.3%
R7	15.0	10.0	1.5	1.5	0.0	13.5	0.00		11.2	4.0	**64.3%**
R8	15.0	10.0	1.5	1.5	-3.4	13.5	-0.25	5.63	11.2	5.1	54.5%
R9	15.0	10.0	1.5	1.5	-6.8	13.5	-0.50		11.2	6.8	39.3%
R10	20.0	5.0	4.0	2.0	0.0	13.5	0.00		12.0	8.5	29.2%
R11	20.0	5.0	4.0	2.0	-3.4	13.5	-0.25	2.81	12.0	7.6	**36.7%**
R12	20.0	5.0	4.0	2.0	-6.8	13.5	-0.50		12.0	8.6	28.3%
R13	20.0	7.5	2.7	2.0	0.0	13.5	0.00		12.0	9.7	19.2%
R14	20.0	7.5	2.7	2.0	-3.4	13.5	-0.25	3.77	12.0	7.4	**38.3%**
R15	20.0	7.5	2.7	2.0	-6.8	13.5	-0.50		12.0	7.4	**38.3%**
R16	20.0	10.0	2.0	2.0	0.0	13.5	0.00		12.0	6.0	**50.0%**
R17	20.0	10.0	2.0	2.0	-3.4	13.5	-0.25	4.85	12.0	6.2	48.3%
R18	20.0	10.0	2.0	2.0	-6.8	13.5	-0.50		12.0	7.8	35.0%
R19	25.0	5.0	5.0	2.5	0.0	13.5	0.00		15.5	12.9	16.8%
R20	25.0	5.0	5.0	2.5	-3.4	13.5	-0.25	2.63	15.5	10.1	34.8%
R21	25.0	5.0	5.0	2.5	-6.8	13.5	-0.50		15.5	9.5	**38.7%**
R22	25.0	7.5	3.3	2.5	0.0	13.5	0.00		15.5	9.8	36.8%
R23	25.0	7.5	3.3	2.5	-3.4	13.5	-0.25	3.48	15.5	11.1	28.4%
R24	25.0	7.5	3.3	2.5	-6.8	13.5	-0.50		15.5	9.2	**40.6%**
R25	25.0	10.0	2.5	2.5	0.0	13.5	0.00		15.5	9.5	38.7%
R26	25.0	10.0	2.5	2.5	-3.4	13.5	-0.25	4.43	15.5	7.5	**51.6%**
R27	25.0	10.0	2.5	2.5	-6.8	13.5	-0.50		15.5	8.0	48.4%
R28	30.0	5.0	6.0	3.0	0.0	13.5	0.00		17.8	16.2	9.0%
R29	30.0	5.0	6.0	3.0	-3.4	13.5	-0.25	2.51	17.8	13.1	26.4%
R30	30.0	5.0	6.0	3.0	-6.8	13.5	-0.50		17.8	10.7	**39.9%**
R31	30.0	7.5	4.0	3.0	0.0	13.5	0.00		17.8	11.2	37.1%
R32	30.0	7.5	4.0	3.0	-3.4	13.5	-0.25	3.30	17.8	10.2	42.7%
R33	30.0	7.5	4.0	3.0	-6.8	13.5	-0.50		17.8	9.8	**44.9%**
R34	30.0	10.0	3.0	3.0	0.0	13.5	0.00		17.8	13.2	25.8%
R35	30.0	10.0	3.0	3.0	-3.4	13.5	-0.25	4.17	17.8	8.5	**52.2%**
R36	30.0	10.0	3.0	3.0	-6.8	13.5	-0.50		17.8	9.0	49.4%
R37	35.0	5.0	7.0	3.5	0.0	13.5	0.00		19.1	16.1	15.7%
R38	35.0	5.0	7.0	3.5	-3.4	13.5	-0.25	2.43	19.1	14.0	26.7%
R39	35.0	5.0	7.0	3.5	-6.8	13.5	-0.50		19.1	12.9	**32.5%**
R40	35.0	7.5	4.7	3.5	0.0	13.5	0.00		19.1	17.9	6.3%
R41	35.0	7.5	4.7	3.5	-3.4	13.5	-0.25	3.18	19.1	16.2	15.2%
R42	35.0	7.5	4.7	3.5	-6.8	13.5	-0.50		19.1	12.8	**33.0%**
R43	35.0	10.0	3.5	3.5	0.0	13.5	0.00		19.1	11.7	38.7%
R44	35.0	10.0	3.5	3.5	-3.4	13.5	-0.25	3.98	19.1	10.0	**47.6%**
R45	35.0	10.0	3.5	3.5	-6.8	13.5	-0.50		19.1	11.9	37.7%
R46	40.0	5.0	8.0	4.0	0.0	13.5	0.00		21.2	18.9	10.8%
R47	40.0	5.0	8.0	4.0	-3.4	13.5	-0.25	2.37	21.2	17.8	16.0%
R48	40.0	5.0	8.0	4.0	-6.8	13.5	-0.50		21.2	16.1	**24.1%**
R49	40.0	7.5	5.3	4.0	0.0	13.5	0.00		21.2	18.3	13.7%
R50	40.0	7.5	5.3	4.0	-3.4	13.5	-0.25	3.08	21.2	18.0	15.1%
R51	40.0	7.5	5.3	4.0	-6.8	13.5	-0.50		21.2	15.2	**28.3%**
R52	40.0	10.0	4.0	4.0	0.0	13.5	0.00		21.2	18.7	11.8%
R53	40.0	10.0	4.0	4.0	-3.4	13.5	-0.25	3.85	21.2	15.2	28.3%
R54	40.0	10.0	4.0	4.0	-6.8	13.5	-0.50		21.2	11.0	**48.1%**

The summary of the results of the experiments for each abutment tested are presented in the following sections:

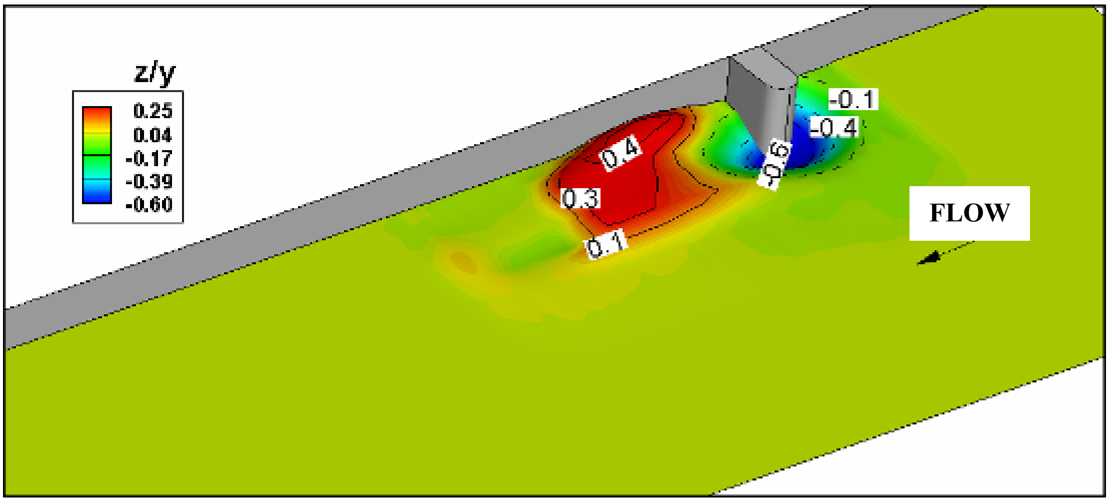
1. The abutment of L_a=15 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

When the collars are placed at an elevation of $Z_c/y=0$, the maximum scour reductions are observed for the collars of B_c=7.5 cm and 10 cm. During scour formation, the maximum scour depths are observed at the upstream side of the abutment and the bed material is swept away towards the downstream of the abutment. For the experiments with L_a=15 cm, it could be clearly seen that the scour does not penetrate below the collars when they are placed at the depths of $Z_c/y=-0.5$. Among the experiments, the maximum scour reduction efficiency is observed at $Z_c/y=0$ for B_c=10 cm.

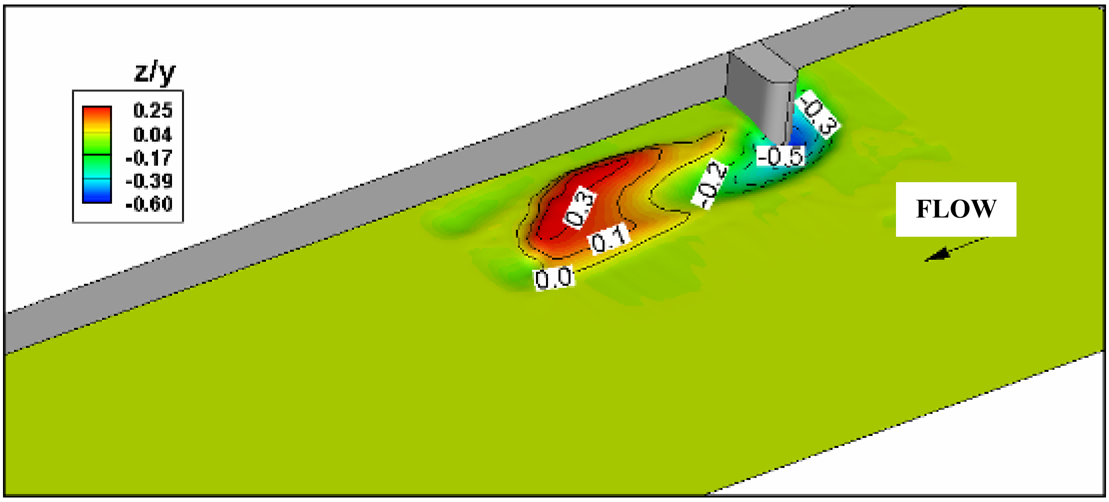
2. The abutment of L_a=20 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

The best collar performance for L_a=20 cm is obtained at the elevation of $Z_c/y=0$ for the collar of B_c=10 cm. On the other hand, for B_c=5 cm, the maximum collar efficiency is observed at $Z_c/y=-0.25$ while for B_c=7.5 cm, the minimum scour depth is observed both at $Z_c/y=-0.25$ and $Z_c/y=-0.5$.

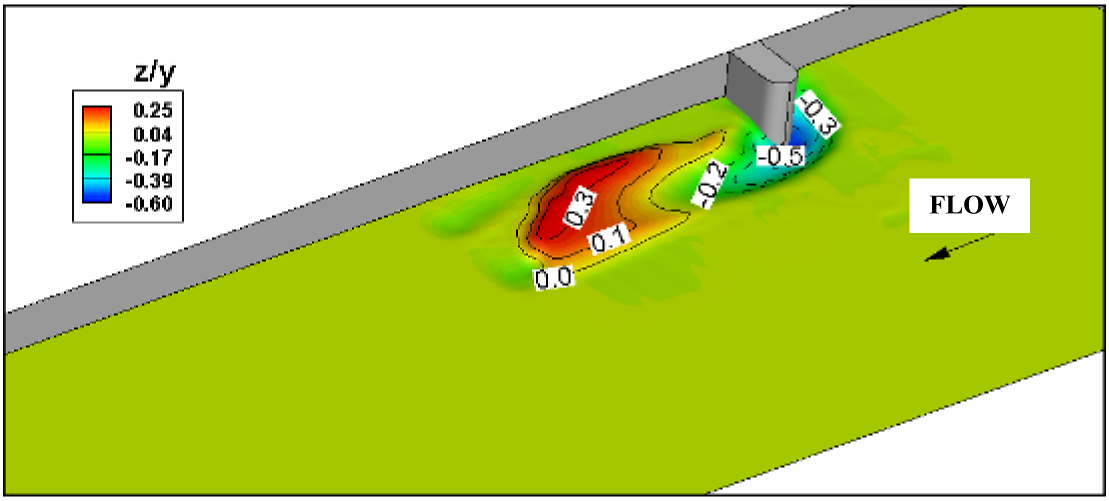
The 3-D views of the scour hole and deposition around the abutment of L_a=20 cm for the cases of without and with collars of B_c=5 cm and 10 cm placed at various Z_c/y values are plotted and given in Figure 5.2.



a) L_a=20 cm, without collar

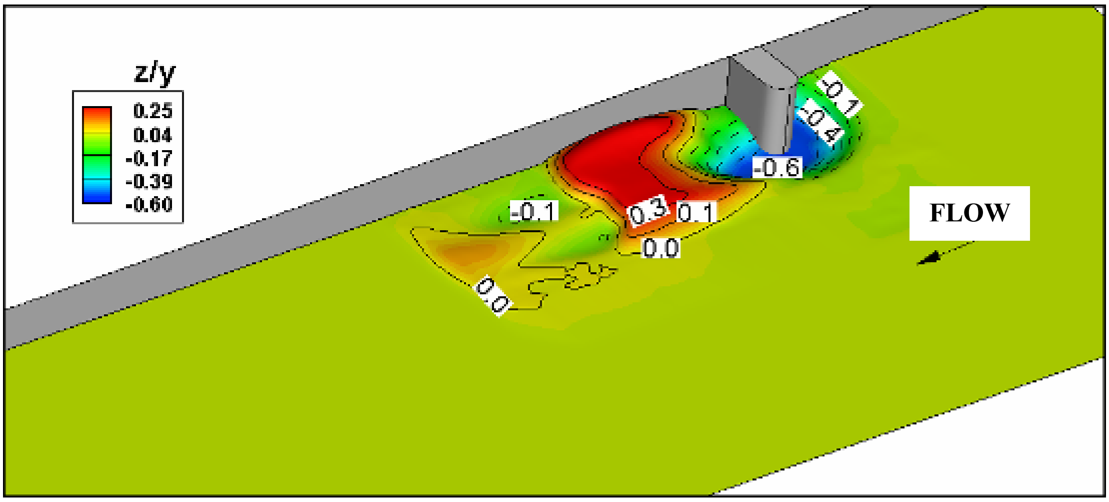


b) L_a=20 cm, B_c=5 cm, Z_c/y=0

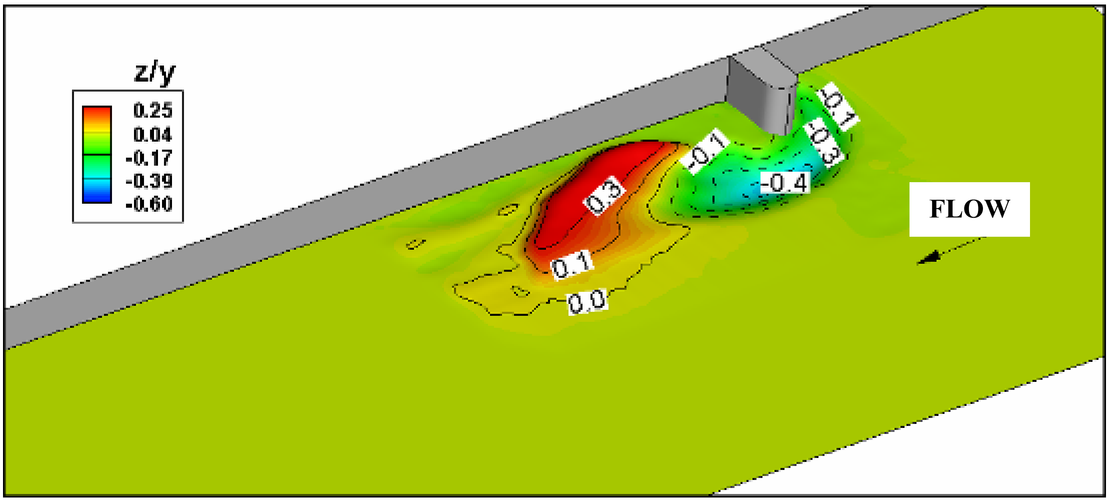


c) L_a=20 cm, B_c=5 cm, Z_c/y=-0.25

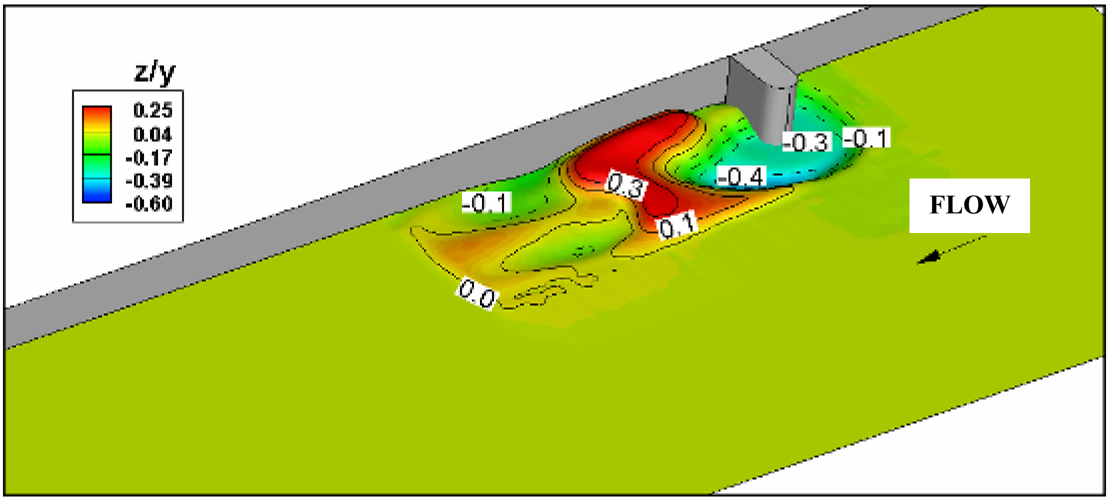
Figure 5.2 3-D views of the scour and deposition pattern around L_a=20 cm



d) L_a=20 cm, B_c=5 cm, Z_c/y=-0.50

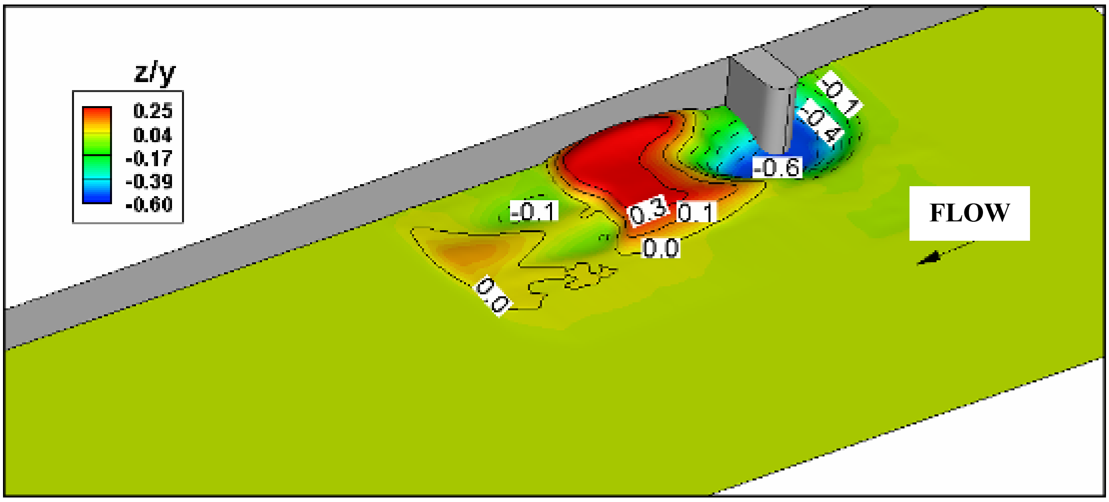


e) L_a=20 cm, B_c=10 cm, Z_c/y=0



f) L_a=20 cm, B_c=10 cm, Z_c/y=-0.25

Figure 5.2 (continued)



g) L_a=20 cm, B_c=10 cm, Z_c/y=-0.50

Figure 5.2 (continued)

3. The abutment of L_a=25 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

The maximum scour reductions are obtained at Z_c/y=-0.5 for the collars of B_c= 5 cm and 7.5 cm at L_a=25 cm. However, it should be noted that for B_c=10 cm at Z_c/y= -0.25 and -0.5, the scour depth values are very close to each other. As a result, according to the observations of this experiment, it may be concluded that for L_a=25 cm, Z_c/y=-0.5 gives the best scour reduction.

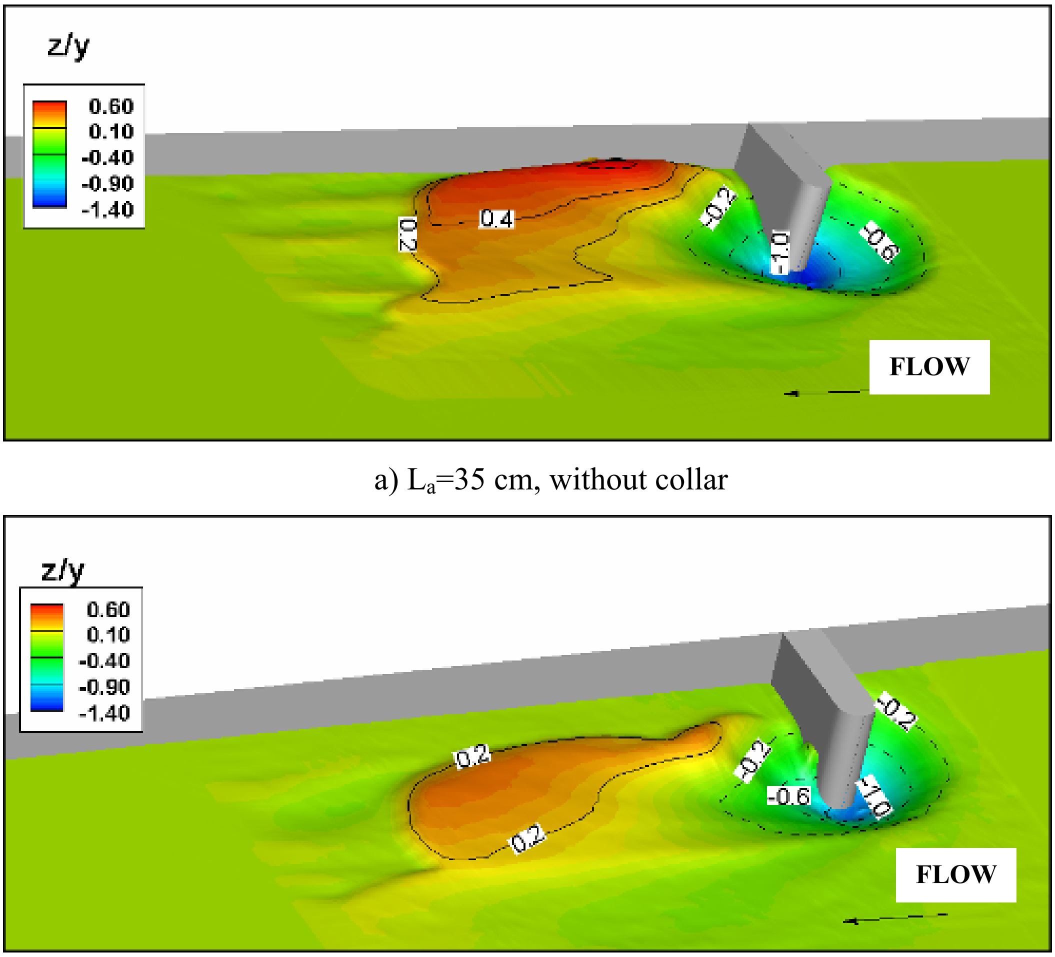
4. The abutment of L_a=30 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

The bed profiles of L_a=30 cm show that the maximum scour reduction performance is observed at Z_c/y=-0.25 for B_c=10 cm while it is at Z_c/y=-0.50 for the collars of B_c=5.0 cm and 7.5 cm. However, it should be kept in mind that the maximum scour reduction performance of the collars of B_c=10 cm at Z_c/y=-0.25 and -0.50 are very close to each other. The maximum collar efficiencies improve as the width of the collars increase.

5. The abutment of L_a=35 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

For the collar of B_c=10 cm at Z_c/y=-0.25, the maximum collar efficiency is obtained. The maximum collar efficiencies for other collars tested; B_c=5.0 cm and 7.5 cm are obtained at dimensionless collar location of Z_c/y=-0.50.

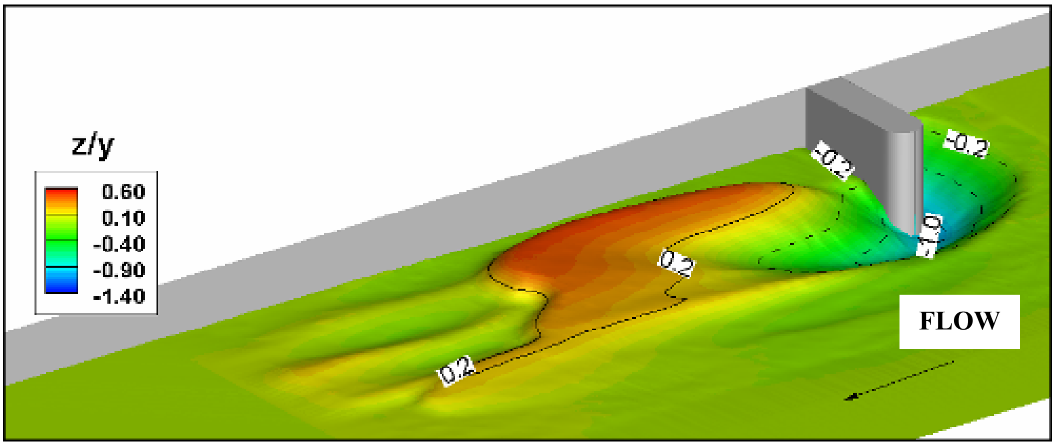
The 3-D views of the scour and deposition patterns around the abutment of L_a=35 cm for the cases without collar and with collars of B_c=5 cm and 10 cm placed at various Z_c/y values were plotted and given in Figure 5.3.



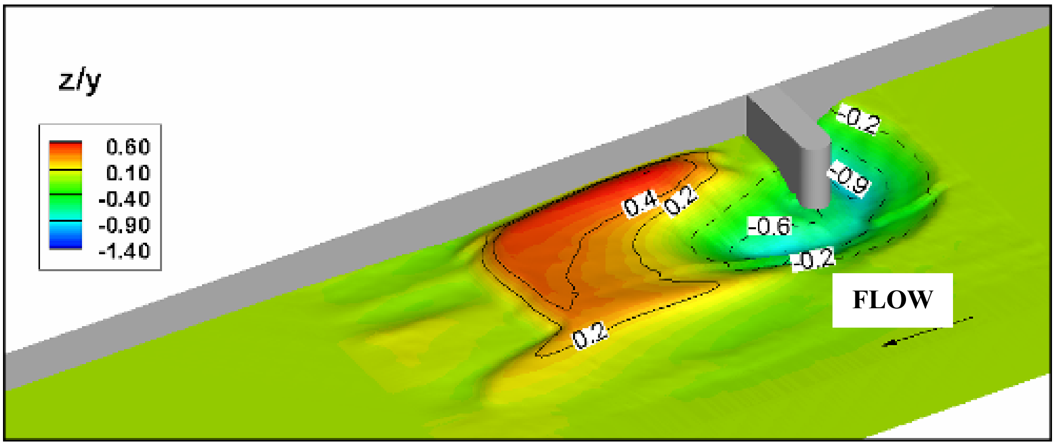
a) L_a=35 cm, without collar

b) L_a=35 cm, B_c=5 cm, Z_c/y=0

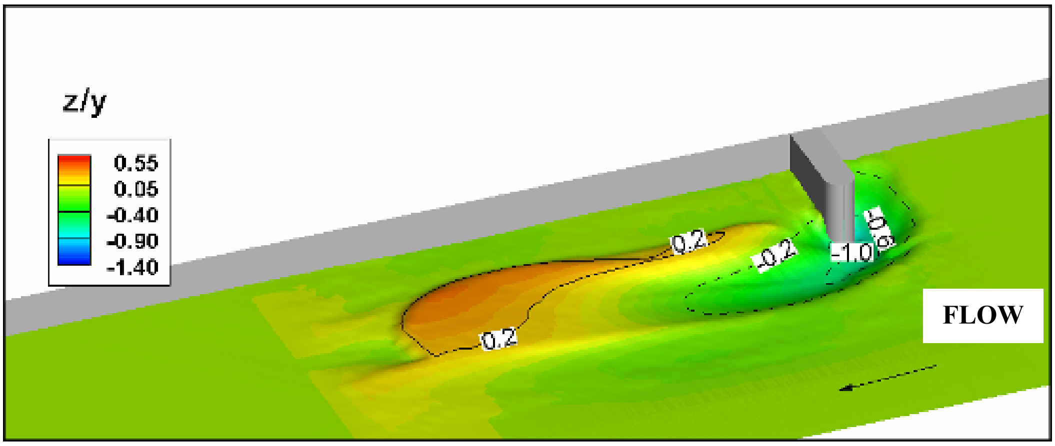
Figure 5.3 3-D views of the scour and deposition pattern around L_a=35 cm



c) L_a=35 cm, B_c=5 cm, Z_c/y=-0.25

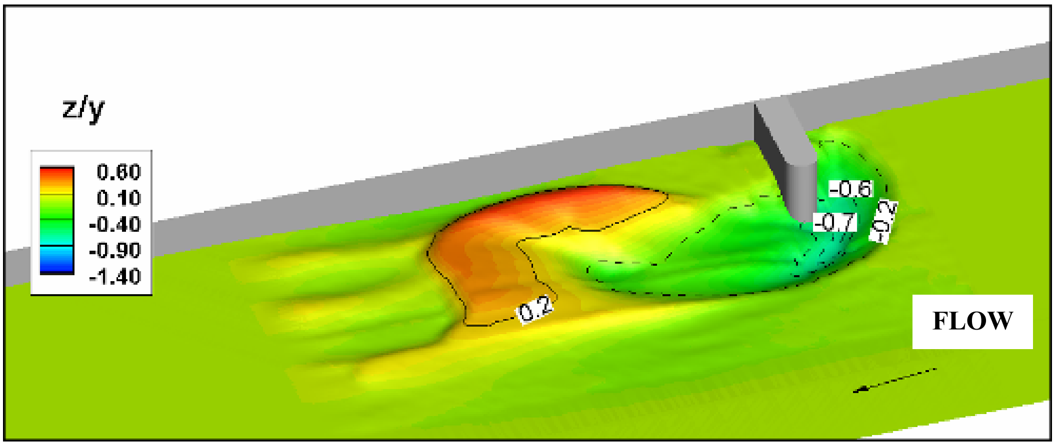


d) L_a=35 cm, B_c=5 cm, Z_c/y=-0.50

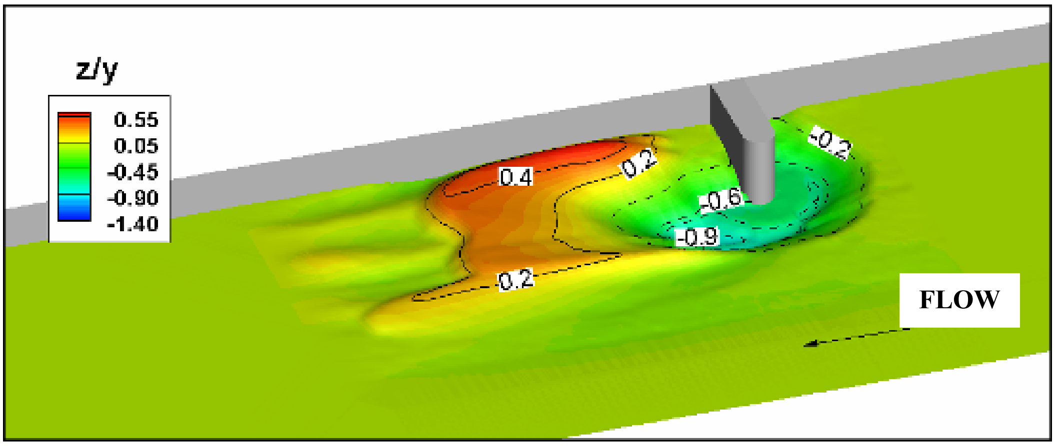


e) L_a=35 cm, B_c=10 cm, Z_c/y=0

Figure 5.3 (continued)



f) L_a=35 cm, B_c=10 cm, Z_c/y=-0.25



g) L_a=35 cm, B_c=10 cm, Z_c/y=-0.50

Figure 5.3 (continued)

6. The abutment of L_a=40 cm; B_c=5, 7.5, 10 cm, Z_c/y=0, -0.25, -0.50

The experimental results of the longest abutment of L_a=40 cm showed the maximum scour reduction efficiency at Z_c/y=-0.5 for B_c=10 cm. All the collars tested around the abutment of La=40 cm yield the minimum scour depths at the dimensionless elevation of Z_c/y=-0.50. In addition, it should also be noted that the scour reductions of this abutment are the lowest ones compared with other abutment lengths tested.

5.6.2 Maximum Scour Reduction around the Abutments with Collars

Abutment length, collar width and collar location effects on the reduction of the maximum scour depth are shown in Figure 5.4 along with Figures 5.5 and 5.6 which present the results of Doğan’s (2008) and Kayatürk’s (2005) studies. From the graph, it can be seen that for small values of L_a/B_c, i.e., less than about 2.0, the maximum reductions in the scour depths are obtained when the collars are located at the bed level, $Z_c/y=0$. On the other hand, for the range of $2< L_a/B_c <5$, the maximum scour reduction depths fluctuate between $Z_c/y=-0.25$ and $Z_c/y=-0.50$. Moreover, the relative depth of $Z_c/y=-0.50$ gives the maximum scour reduction performance for all abutments having L_a/B_c values greater than and equal to 5, similar to Kayatürk’s and Doğan’s results. According to the results of this study and the previous studies, it can be seen that an increase in the collar width, also increases scour reduction performances of the collars, but on the other hand, when the abutment length increases, the scour reduction efficiency of the collar decreases.

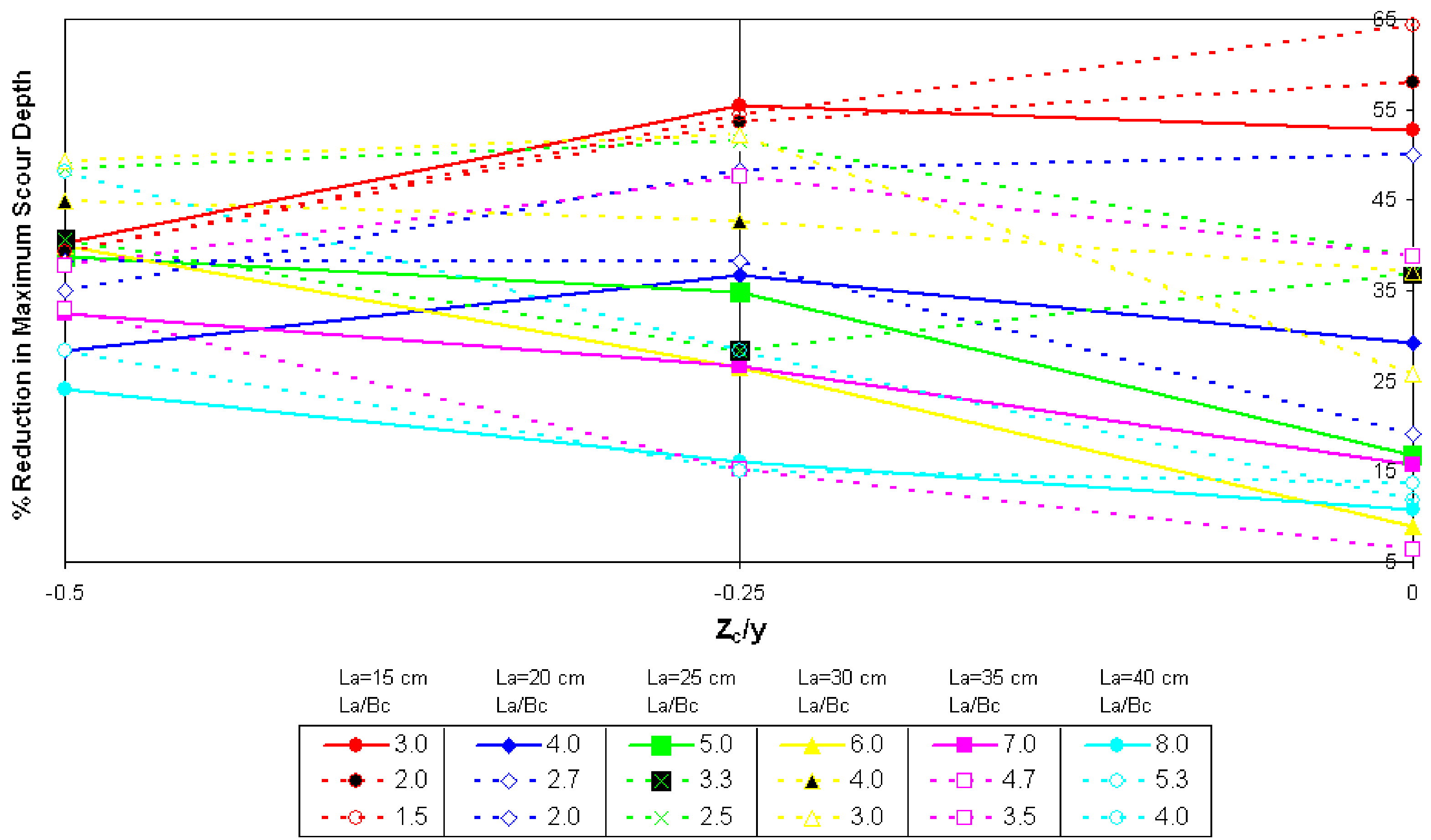


Figure 5.4 Effect of collar size and elevation on the maximum scour depth around the abutments of various lengths (Q=0.0678 m^3/s, y= 13.5 cm, d_{50} = 1.5 mm)

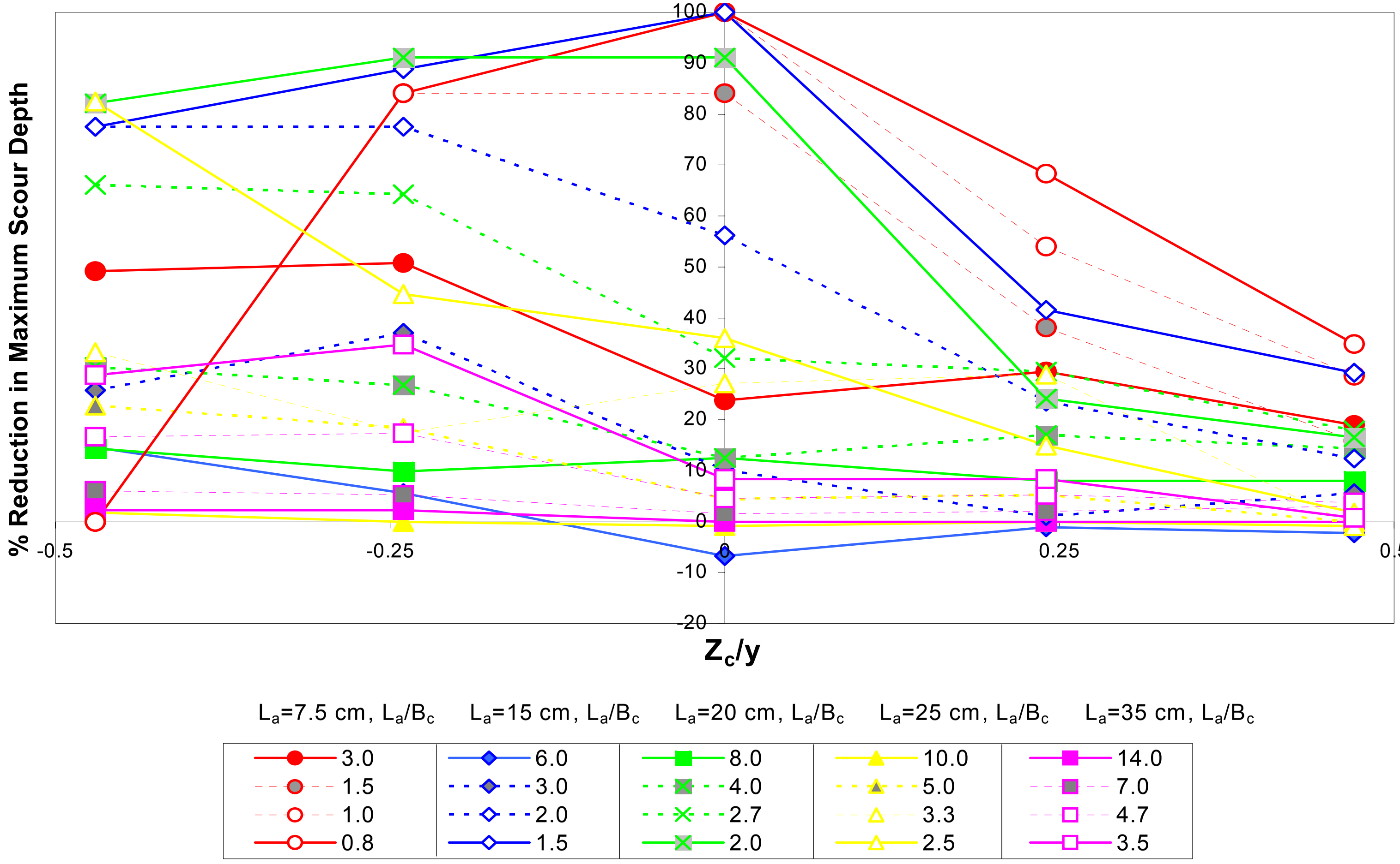


Figure 5.5 Effect of collar size and elevation on the maximum scour depth around the abutments of various lengths (Q=0.017 m^3/s, y= 4.25 cm, d_{50} = 0.90 mm) (Doğan, 2008)

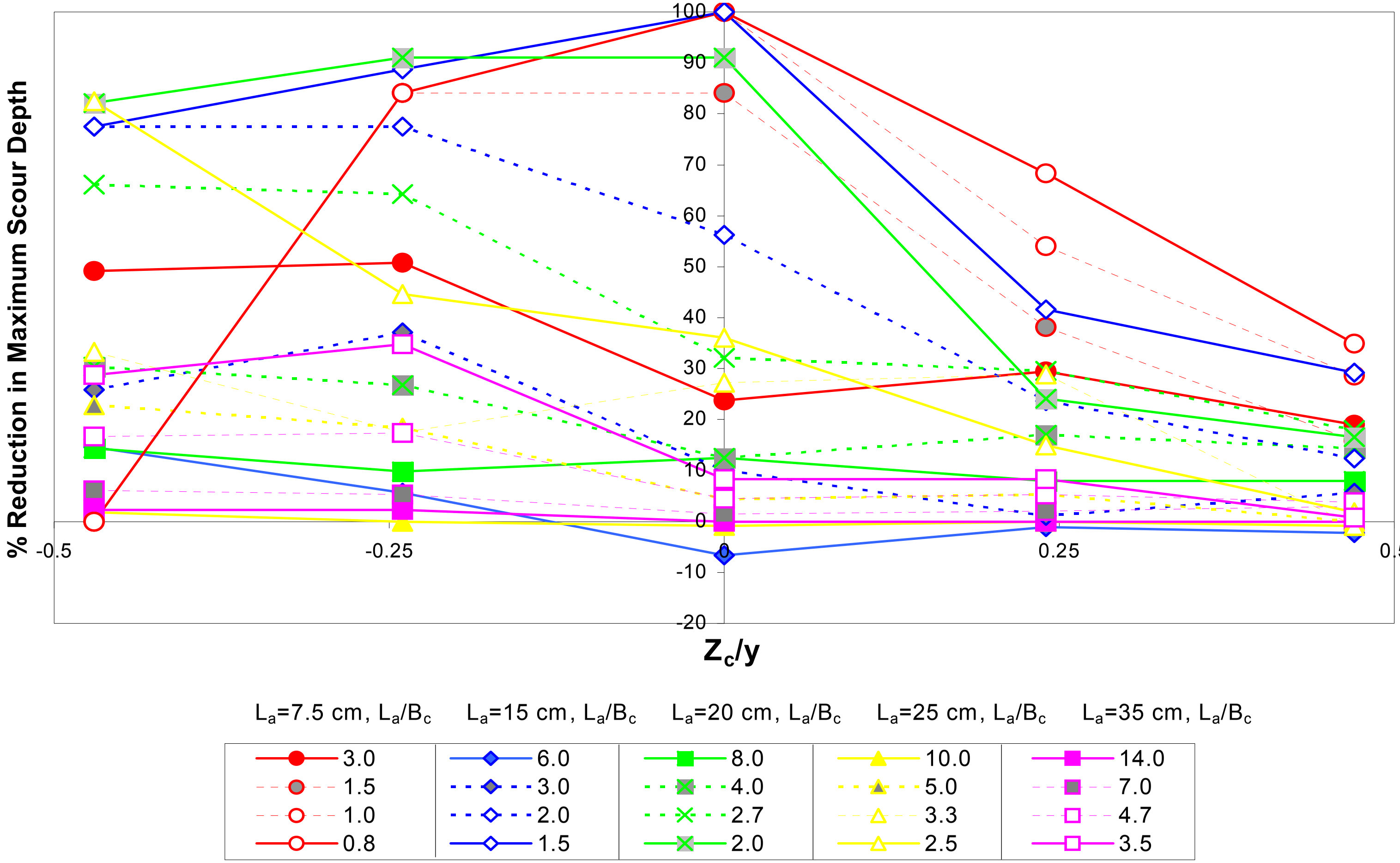


Figure 5.6 Effect of collar size and elevation on the maximum scour depth around the abutments of various lengths (Q=0.050 m^3/s, y = 10 cm, d_{50} = 1.48 mm) (Kayatürk, 2005)

In Table 5.3 in addition to $[(d_s)_{max,c} / y]_{opt}$ and $[Z_c / y]_{opt}$, which are the values corresponding to the "maximum % reductions in maximum scour depths" obtained from Table 5.2 for an abutment of known length and collar size, θ value which is the ratio of the "total area of the abutment and collar" to "the abutment area" on the horizontal plane are also shown, i.e.,

$$\theta = \frac{A_{total}}{A_{abutment}} \qquad (5.5)$$

Here the parameter θ is defined to show the effect of the areal sizes of the abutment and the collar on the scour.

Table 5.3 Optimum design parameters of an abutment-collar arrangement

			RESULTS OF PRESENT STUDY		
L_a/B_a	L_a/B_c	θ ($A_{total}/A_{abutment}$)	$[Z_c/y]_{opt}$	$[(d_s)_{max,c}/y]_{opt}$	$[\%Reduction]_{opt}$
	3.00	3.15	-0.25	0.37	55.36
	2.00	4.31	0.00	0.35	58.04
	1.50	5.63	0.00	0.30	64.29
1.50					
	4.00	2.81	-0.25	0.56	36.67
	2.67	3.77	-0.50	0.55	38.33
	2.00	4.85	0.00	0.44	50.00
2.00					
	5.00	2.63	-0.50	0.70	38.71
	3.33	3.48	-0.50	0.68	40.65
	2.50	4.43	-0.25	0.56	51.61
2.50					
	6.00	2.51	-0.50	0.79	39.89
	4.00	3.30	-0.50	0.73	44.94
	3.00	4.17	-0.25	0.63	52.25
3.00					
	7.00	2.43	-0.50	0.96	32.46
	4.67	3.18	-0.50	0.95	32.98
	3.50	3.98	-0.25	0.74	47.64
3.50					
	8.00	2.37	-0.50	1.19	24.06
	5.33	3.08	-0.50	1.13	28.30
	4.00	3.85	-0.50	0.81	48.11
4.00					

			DOĞAN'S RESULTS (2008)			*KAYATÜRK'S RESULTS (2005)*		
L_a/B_a	L_a/B_c	θ ($A_{total}/A_{abutment}$)	$[Z_c/y]_{opt}$	$[(d_s)_{max,c}/y]_{opt}$	$[\%Reduction]_{opt}$	$[Z_c/y]_{opt}$	$[(d_s)_{max,c}/y]_{opt}$	$[\%Reduction]_{opt}$
	6	1.75	-0.47	1.79	14.6	*-0.5*	*0.97*	*23*
	3	2.67	-0.24	1.32	37.1	*-0.5*	*0.5*	*60*
	2	3.75	-0.24	0.47	77.5	*-0.25*	*0.25*	*80*
1.5	1.5	5	0	0	100	*0*	*0.18*	*86*
	8	1.69	-0.47	2.26	14.3	*-0.5*	*1.29*	*16*
	4	2.5	-0.47	1.84	30.4	*-0.5*	*0.96*	*37*
	2.67	3.44	-0.47	0.89	66.1	*-0.5*	*0.6*	*61*
2	2	4.5	0	0.24	91.1	*-0.5*	*0.5*	*67*
	10	1.65	-0.47	2.64	1.8	*-0.5*	*1.47*	*20*
	5	2.4	-0.47	2.07	22.8	*-0.5*	*1.19*	*35*
	3.33	3.25	-0.47	1.79	33.3	*-0.5*	*0.98*	*46*
2.5	2.5	4.2	-0.47	0.47	82.5	*-0.5*	*0.61*	*67*
	14	1.61	-0.47	3.04	2.3	*-0.5*	*1.99*	*1*
	7	2.29	-0.47	2.92	6.1	*-0.5*	*1.95*	*2.9*
	4.67	3.04	-0.24	2.56	17.4	*-0.5*	*1.76*	*12.4*
3.5	3.5	3.86	-0.24	2.02	34.8	*-0.5*	*1.45*	*28*

In Figure 5.7, $[(d_s)_{max,c} / y]_{opt}$ versus θ values of this study are shown as a function of L_a/B_a and the relevant plots of two studies; Doğan's (2008) and Kayatürk's (2008) are also given for comparison. In Figure 5.7, it is seen that $[(d_s)_{max,c} / y]_{opt}$ values decrease with increasing θ values for a given value of L_a/B_a. The rate of decrease of $[(d_s)_{max,c} / y]_{opt}$ with increasing θ decreases as L_a/B_a values get smaller. For a given L_a/B_a value, as the total area increases, i.e. the collar area increases, the maximum scour depth decreases accordingly. The data points given in Figures 5.8 and 5.9 show the similar trends described above. Referring to these figures one can also determine the optimum location of the collar to be placed on the abutment, $(Z_c/y)_{opt}$, by finding the value of $[(d_s)_{max,c} / y]_{opt}$ from a given θ and L_a/B_c.

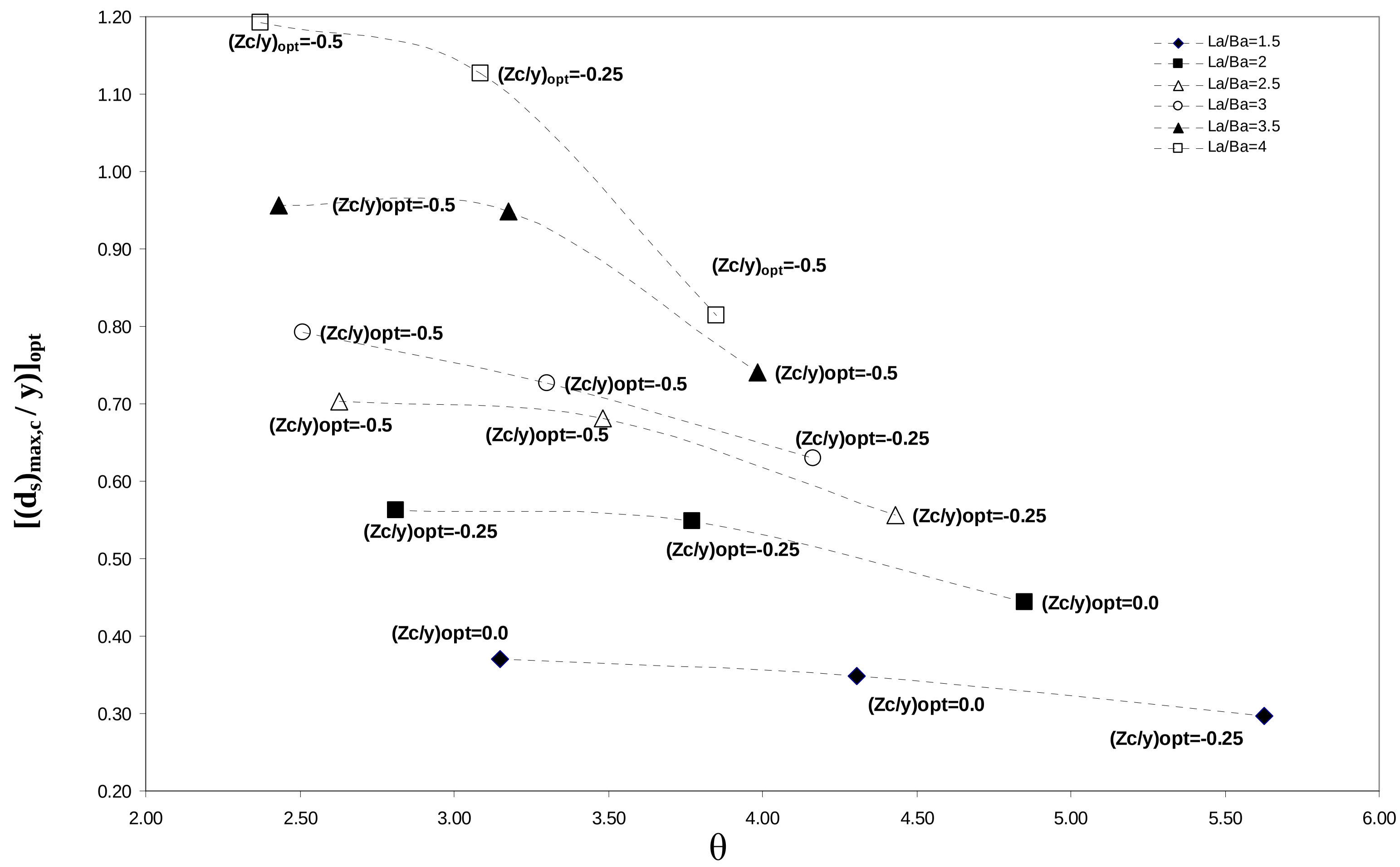


Figure 5.7 Variation of $[(d_s)_{max,c} / y]_{opt}$ with θ (Q=0.0678 m^3/s, y=13.5 cm, F_r=0.29, U/U_c=0.90, d_{50} = 1.50 mm, t=3 hrs)

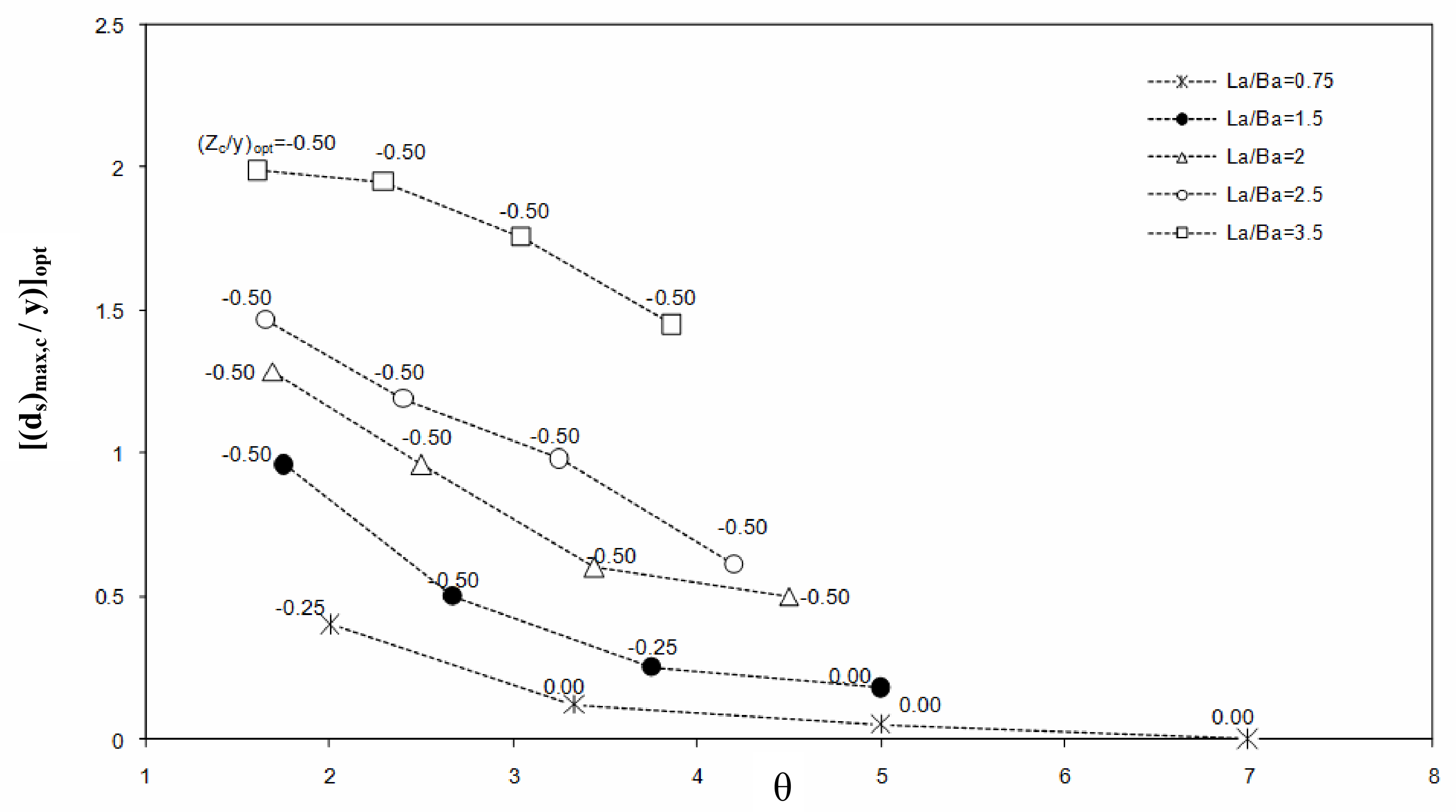


Figure 5.8 Variation of $[(d_s)_{max,c} / y]_{opt}$ with θ (Q=0.017 m^3/s, y=4.25 cm, F_r=0.41, U_*/U_{*c}=0.90, d_{50} = 0.90 mm, t=6 hrs) (Doğan, 2008)

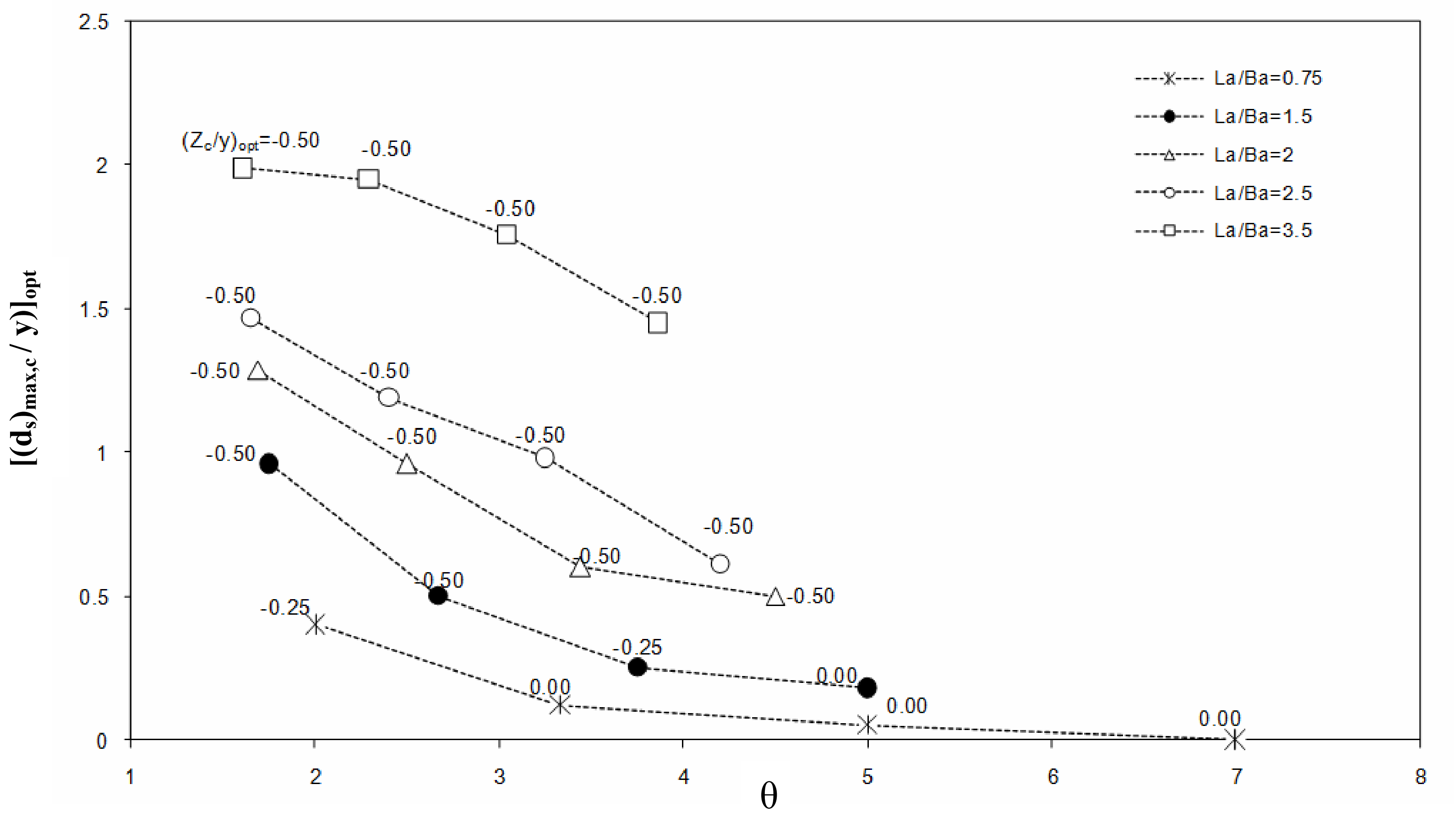


Figure 5.9 Variation of $[(d_s)_{max,c} / y]_{opt}$ with θ (Q=0.050 m^3/s, y=10 cm, F_r=0.34, U_*/U_{*c}=0.90, d_{50} =1.48 mm, t= 6hrs) (Kayatürk, 2005)

An alternative form of the data given in Figure 5.7 is presented in Figure 5.10, $[(d_s)_{max,c} / y]_{opt}$ versus $\sqrt{\theta(L_a / B_c)}$ as well as the data around a single curve. The best fit lines of the data given in Figure 5.10 for three different studies, which are applicable only for the flow conditions under which they were obtained, can be used to determine the $[(d_s)_{max,c} / y]_{opt}$ for known θ and L_a/B_c values of an abutment. Here, it should be kept in mind that the best fit line of the present data falls far below the other best fit lines due to the short experiment period of t=3 hours. It can be claimed that for longer experiment period; such as t=6 hours as the other studies, the data points of the present study fall far above and may be they would coincide with those of Kayatürk's data since the mean diameters of the bed materials of both studies are almost the same.

The variation of $[Z_c/y]_{opt}$ with L_a/B_c is shown in Figure 5.11 for the present study as well as those of Kayatürk's (2005) and Doğan's (2008) data. $[Z_c/y]_{opt}$ values of Figure 5.11 can be classified in three zones as a function of L_a/B_c as summarized below:

For the data of present study:

$$[Z_c/y]_{opt} = 0 \qquad \text{for } L_a/B_c \leq 2.0$$
$$-0.50 \leq [Z_c/y]_{opt} \leq -0.25 \qquad \text{for } 2.0 \leq L_a/B_c \leq 5.0 \qquad (5.6)$$
$$[Z_c/y]_{opt} = -0.50 \qquad \text{for } 5.0 < L_a/B_c$$

The above relations are valid within the range of L_a/B_c between 1.5 and 8.

<u>Doğan's study (2008):</u>

$$[Z_c/y]_{opt} = 0 \qquad \text{for } L_a/B_c \leq 2.0$$
$$-0.47 \leq [Z_c/y]_{opt} \leq -0.24 \qquad \text{for } 2.0 < L_a/B_c < 5.0 \qquad (5.7)$$
$$[Z_c/y]_{opt} = -0.47 \qquad \text{for } 5.0 \leq L_a/B_c \leq 14.0$$

<u>Kayatürk's study (2005):</u>

$$[Z_c/y]_{opt} = 0 \qquad \text{for } L_a/B_c = 2.0$$
$$-0.50 \leq [Z_c/y]_{opt} \leq -0.25 \qquad \text{for } 2.0 \leq L_a/B_c \leq 3.0 \qquad (5.8)$$

$$[Z_c/y]_{opt} = -0.50 \qquad \text{for } 3.0 < L_a/B_c \leq 14$$

The above relations of Kayatürk’s and Doğan’s studies are valid within the range of L_a/B_c between 0.75 and 14.

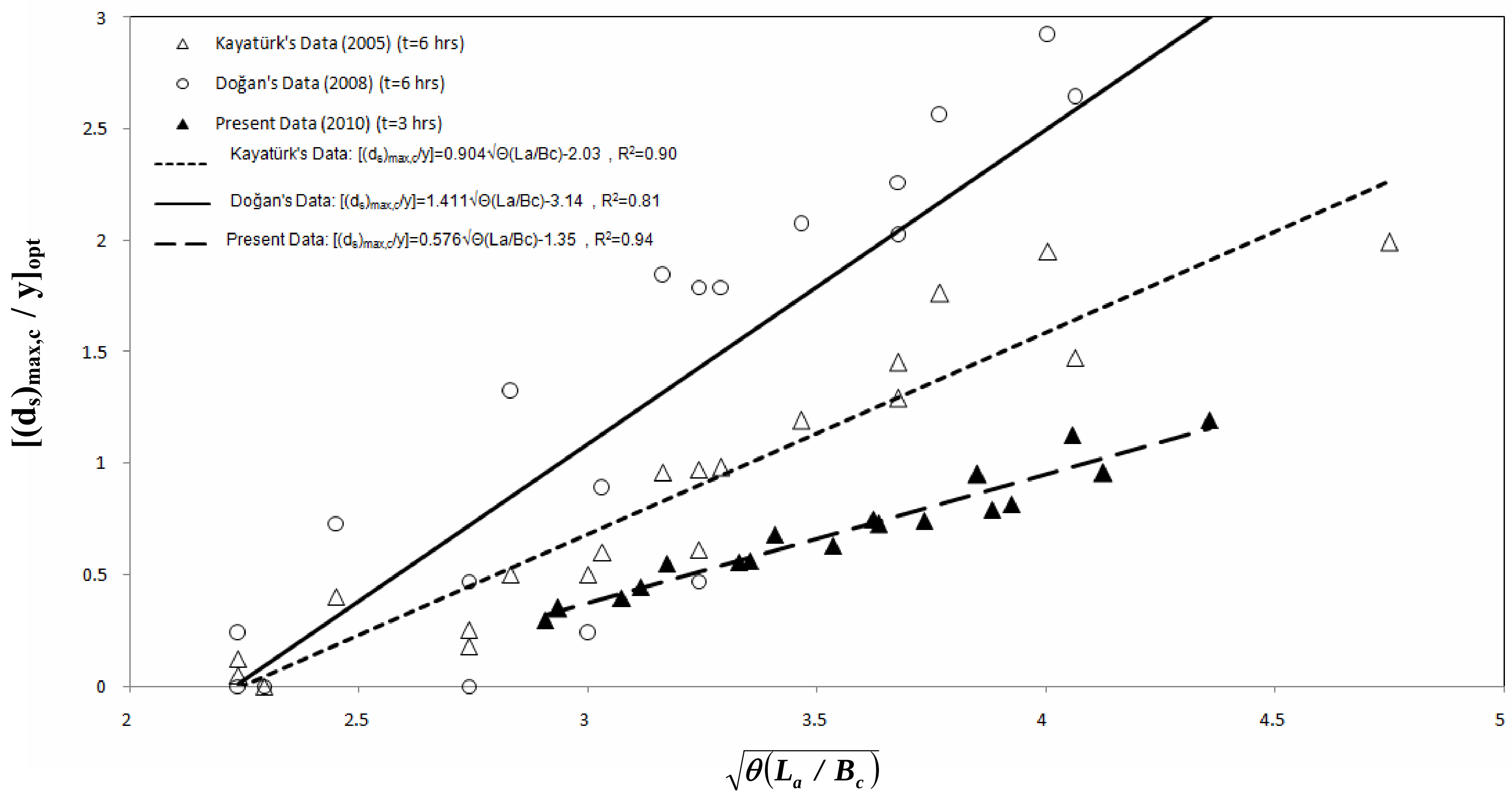


Figure 5.10 Variation of $[(d_s)_{max,c} / y]_{opt}$ with $\sqrt{\theta(L_a / B_c)}$

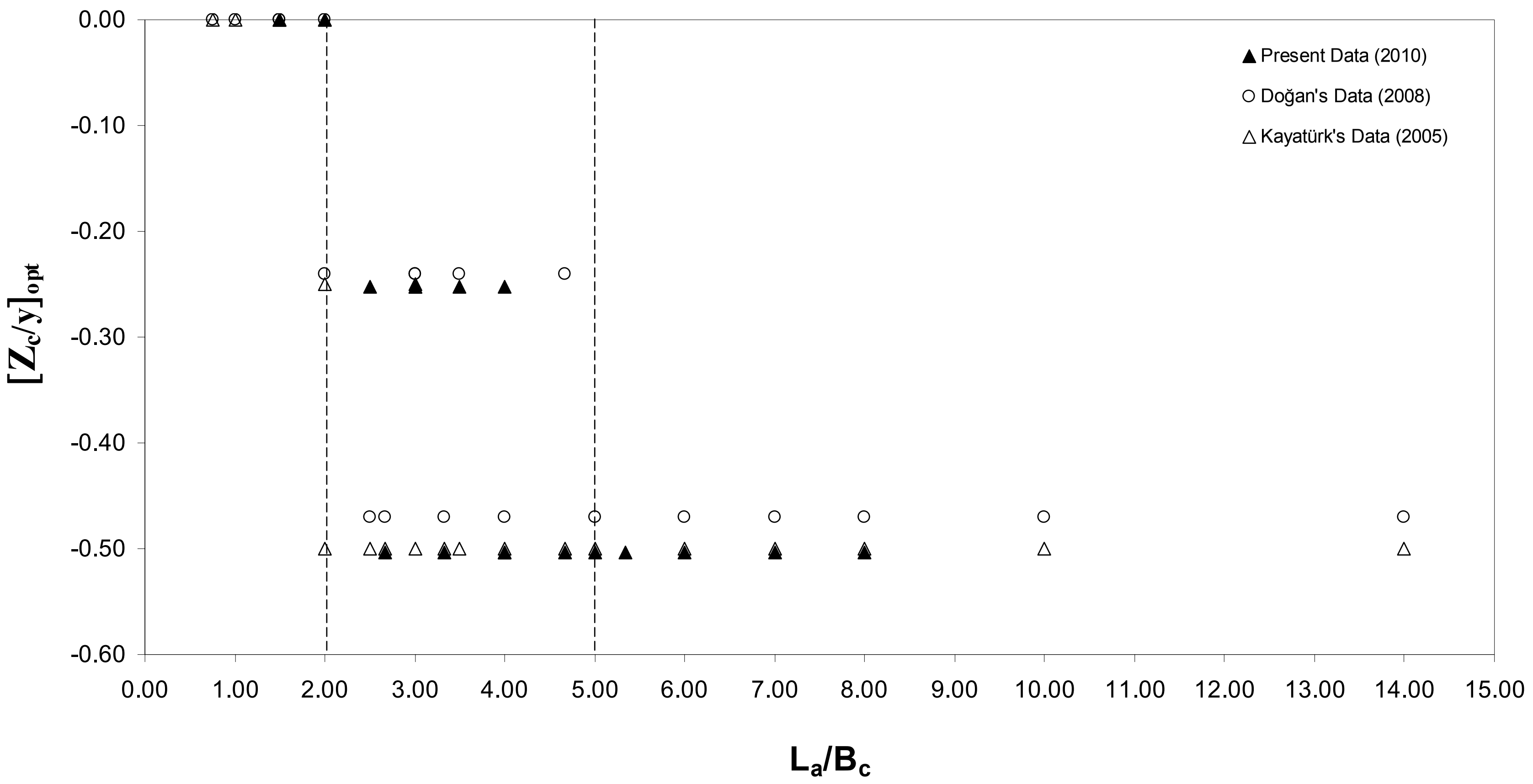


Figure 5.11 Variation of $[Z_c/y]_{opt}$ with L_a/B_c

The variation of [%Reduction]$_{opt}$ with respect to L_a/B_c is shown in Figure 5.12. When this figure is compared with the previous studies, it is seen that the experiments of this study give higher collar scour reduction efficiencies for $L_a/B_c \geq 3$; however, for $L_a/B_c < 3$ the efficiencies are less than the results of the previous studies. Here, when comparing the results it should be noticed that this study is different from other studies of Kayatürk and Doğan, in terms of sediment size, abutment and collar shapes.

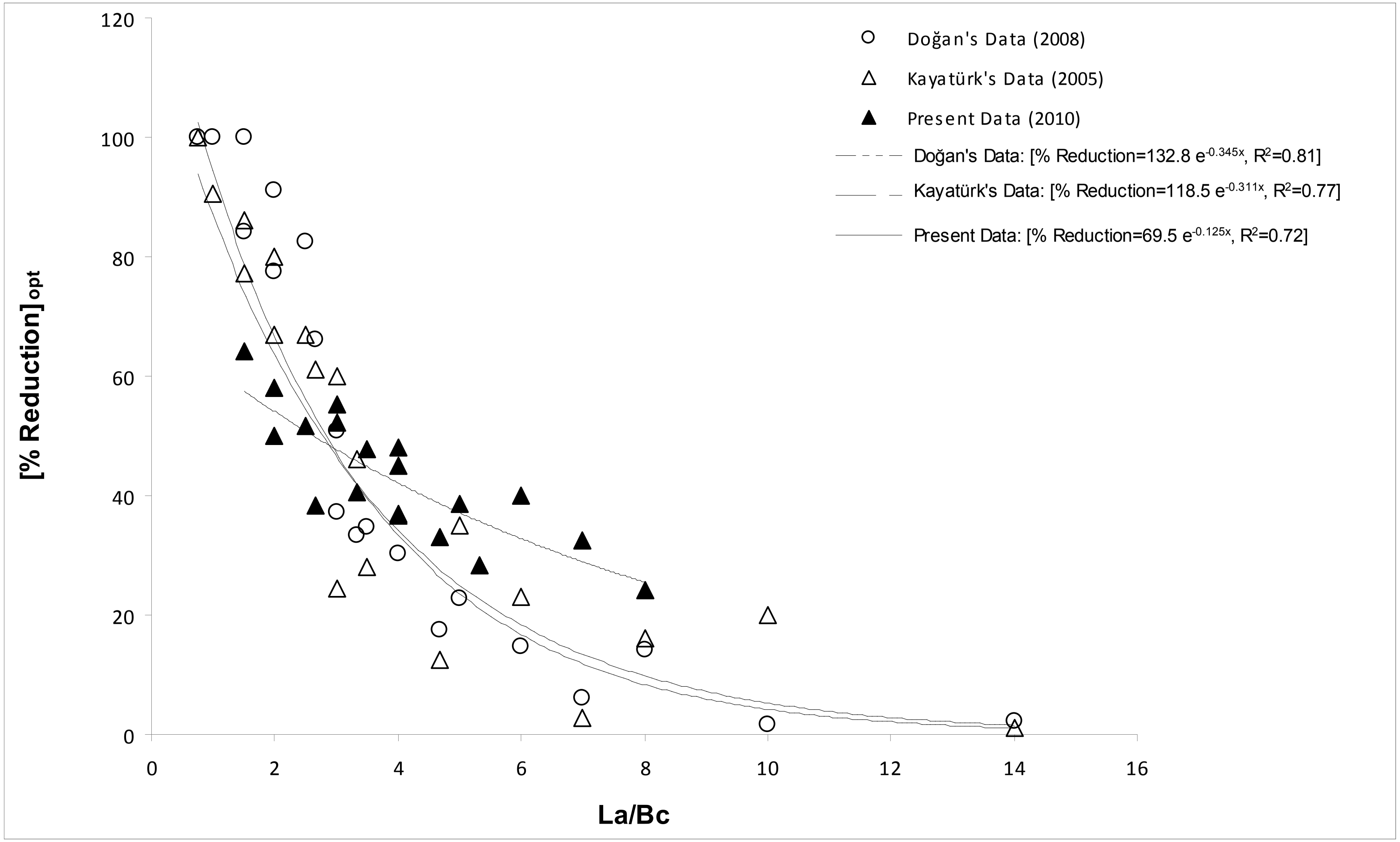


Figure 5.12 Variation of $[\%\text{Reduction}]_{opt}$ with L_a/B_c

5.7 SUMMARY, CONCLUSIONS and RECOMMENDATIONS

5.7.1 Summary

The function of a collar placed around a bridge abutment is to protect the sediment bed from direct impact of the downflow by deflecting the flow (Zarrati A. R. et. al., 2004). In other words, collars work as a "downflow-halting" device during scour hole formation and eliminate the secondary vortices forming around the abutment (Li, Kuhnle and Barkdoll, 2006). The size of the collar and its vertical location on the abutment with respect to the bed affect collar's scour reduction efficiency around the abutment. As the size of the collar, B_c, increases, the depth of the scour hole decreases; but increasing the abutment length decreases the scour reduction efficiency. On the other hand, lowering the collar elevation results in less flow to penetrate under the collar and as a result weaker downflow is formed under the collar. However, it should be pointed out that placing the collar deeper into the sediment bed may not lead to a significant increase in the collar's scour reduction efficiency (Zarrati A. R. et. al., 2004).

5.7.2 Conclusions

The results of this study are compared with the other two studies of Kayatürk (2005) and Doğan (2008). As mentioned in the previous sections; discharges, flow depths, sediment diameters and abutment shapes used in the experiments of those studies which are briefly presented in Table 5.4, were different from those of this study.

Table 5.4 Some of the important parameters of abutment, flow and sediment used in the Present, Doğan's and Kayatürk's studies

	Present Study	**Doğan (2008)**	**Kayatürk (2005)**
Abutment Shape	Semi-circular end	Rectangular	Rectangular
Abutment Length, L_a, (cm)	15, 20, 25, 30, 35 and 40	7.5, 15, 20, 25 and 35	7.5, 15, 20, 25 and 35
Collar width, B_c, (cm)	5, 7.5 and 10 cm	2.5, 5, 7.5 and 10 cm	2.5, 5, 7.5 and 10 cm
Collar Shape	Semi-circular end	Rectangular	Rectangular
Discharge (m^3/s)	0.0678	0.017	0.050
Flow Depth (cm)	13.5	4.25	10
Sediment diameter , d_{50}, (mm)	1.50	0.90	1.48
Flow Conditions	Clear-water	Clear-water	Clear-water
U/U_c , U_*/U_{*c}	U/U_c =0.90	U_*/U_{*c} =0.90	U_*/U_{*c} =0.90
Experiment duration	3 hours	6 hours	6 hours

The results of these studies are very similar and the following conclusions can be drawn:

- Collars can be used as effective scour countermeasures for semi-circular end abutments as well as rectangular abutments.

- As the size of the collar, B_c, or θ increases, the depth of the scour hole around the abutment of given length decreases (Figure 5.7).

- The dimensionless maximum scour depth corresponding to the optimum collar size, $(d_s)_{max,c} / y$, increases as the dimensionless collar length, L_a/B_a, increases for a given collar size, θ, (Figure 5.8).

- Almost the same classification can be made for the optimum locations of the collars which will produce the maximum scour reduction around the abutment, $(Z_c/y)_{opt}$, as a function of L_a/B_c regardless of the abutment shape (Figure 5.11).

- The scour reduction efficiency of a collar, $[\% \text{ Reduction}]_{opt,}$, decreases as L_a/B_c value increases. $[\% \text{ Reduction}]_{opt,}$ values corresponding to a collar of known L_a/B_c can be estimated using Figure 5.12 not only for semi-circular end abutments but also for rectangular abutments of earlier studies.

5.7.3 Recommendations

It should be emphasized as a general comment that abutment scour is not adequately documented despite its importance on bridge vulnerability (Balio & Orsi, 2001). To this respect, a number of recommendations concerning future works about abutment scour and collars are given as follows:

- The similar studies can be done with other abutments of different shapes such as wing-wall and spill-through to determine the effect of collars on the scour reduction.

- Collars were tested under laboratory conditions; however, it would be useful to test the effectiveness of collars on the field since relatively large errors should be expected when predicting abutment scour on the base of literature models (Balio & Orsi, 2001). In addition, to make collar application as a practical scour countermeasure for abutments, collar-placing methods should also be studied.

- In this study and other previous studies, collars were tested under clear-water flow conditions since there is no sediment supply to the system and thus, clear-water flow condition results in deeper scour holes. On the other hand, abutment scour under live-bed conditions should be tested in further researches for a better understanding of abutment scour and collar efficiency, although it is difficult to observe and measure the scour depth under the collar around the abutment (Li, Kuhnle and Barkdoll, 2006).

- Future studies should also take into consideration of abutment/pier interactions affecting collars' scour reduction efficiencies regarding both abutment and pier scour.

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APPENDIX

Table A.1 Sample data obtained to draw 3-D views of scour formation around the abutment of L_a=20 cm with collar of B_c=5 cm at Z_c/y=0

X (cm)	Y (cm)	Scouring&Deposition (cm)
-30	1	-0.17
-30	3	-0.21
-30	5	-0.24
-30	7	-0.25
-30	9	-0.32
-30	11	-0.26
-30	13	-0.24
-30	15	-0.36
-30	17	-0.31
-30	19	-0.19
-30	21	-0.19
-30	23	-0.23
-30	25	-0.23
-30	27	-0.17
-30	29	-0.21
-30	31	-0.13
-30	33	-0.19
-30	35	-0.09
-30	37	-0.03
-30	39	0.02
-30	41	0.00
-30	43	0.07
-30	45	-0.08
-30	47	0.10
-30	49	-0.14
-30	51	-0.10

X/y	Y/y	Z/y
-2.222	0.074	-0.013
-2.222	0.222	-0.016
-2.222	0.370	-0.018
-2.222	0.519	-0.019
-2.222	0.667	-0.024
-2.222	0.815	-0.019
-2.222	0.963	-0.018
-2.222	1.111	-0.026
-2.222	1.259	-0.023
-2.222	1.407	-0.014
-2.222	1.556	-0.014
-2.222	1.704	-0.017
-2.222	1.852	-0.017
-2.222	2.000	-0.012
-2.222	2.148	-0.016
-2.222	2.296	-0.010
-2.222	2.444	-0.014
-2.222	2.593	-0.007
-2.222	2.741	-0.002
-2.222	2.889	0.001
-2.222	3.037	0.000
-2.222	3.185	0.005
-2.222	3.333	-0.006
-2.222	3.481	0.007
-2.222	3.630	-0.010
-2.222	3.778	-0.007

Note: y = 13.5 cm (normal flow depth)