UNIVERSITI PUTRA MALAYSIA

CLEAR WATER SCOUR AROUND SUBMERGED SKEWED BRIDGE WITH AND WITHOUT PIER

AMIR SAEED FARHANGI

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By

AMIR SAEED FARHANGI

Thesis Submitted to the School of Graduate Students, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

April 2016

DEDICATION

to

My beloved parents and my loving wife.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

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Chairperson : Professor Thamer Mohammad Ali, PhD
Faculty : Engineering

As recorded documents show, it is already less than a century that researchers have attempted to evaluate local scour depth around pier as a destructive phenomenon. Unfortunately, the climate changes and deforestation have changed and increased rainfall and runoff respectively in aggravated conditions to create inundated bridges. Therefore, in the last few decades, some other researchers have tried to predict scour depth under submerged bridge condition. Although their results are valuable, there are still different unstudied factors under submerged bridge condition which should be evaluated. One of the mentioned unstudied conditions is the effect of submerged skewed bridge on maximum scour depth and the present study endeavoured to determine this under clear water condition. Therefore, the main purpose of the present study is to experimentally improve existing equations about the prediction of maximum scour depth around the foundation of a submerged bridge with different angles between approaching flow and bridge deck alignments. In order to collect the required data, six different bridge models with and without pier with different angles of 0, 5, 10, 15, 22.5 and 30 degrees were used to evaluate the effect of bridge alignments on maximum scour depth. All models were tested for partially and fully submergence conditions using two different sizes of bed sediments with median sizes of 0.23 mm and 0.80 mm. A total of 48 runs were conducted. Analysis of collected data showed that deflection of approach flow along the skewed bridge thickness (girders and guard rail) is the main difference in comparison with the perpendicular approach flow direction. In actual fact, analysis of the approach flow velocity vector along the skewed bridge thickness showed that an unbalanced distribution of downward flow velocity occurred, which firstly caused unbalanced unit discharge along the upstream edge of the bridge without pier. Then, it made an unbalanced scour level along the downstream bridge edge. According to the mentioned mechanism, an equation based on mass conservation law was proposed to predict maximum scour depth with an acceptable root mean square error (RMSE) and mean absolute error (MAE) equal to 0.029 m and 0.023 m respectively. Also, a labyrinth flow between two sides of flume walls at the downstream of bridge may occur, in which its first direction is the most destructive direction toward the opposite flume wall, which is predicted by another obtained equation and changes from 34 degrees up to 65 degrees. But under submerged skewed bridge condition with pier, the existence of the pier caused maximum local scour depth around itself, and created vortices around the pier is much more than the deflection of flow along the submerged skewed thickness. Also, it was found that correction factor of pier alignment in submerged bridge is much less than the same condition in free flow. Then, relationship between dependent and independent variables firstly was determined. Finally, an equation was proposed by using dimensional analysis, collected data and multiple linear regressions with a better prediction amongst previous study with the least RMSE and MAE equal to 0.018 m and 0.014 m respectively. Also, correction factor of pier alignment in submerged bridge is almost 50% less than the same correction factor in free flow condition which was previously assumed the same. Both the proposed equations can acceptably predict maximum scour depth in comparison with the existing equations. Moreover, submergence ratios in both submerged bridge with and without pier show that maximum scour depth occurs before beginning of the bridge cresting. Although scour depth in submerged bridge without pier decreases after cresting in a short limited of submergence ratio from 0 to 0.08, it increases again as flow depth increase. Also, existence of a pier strongly affects the maximum scour depth around the flume wall which receives the deflected flow.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KEROKAN AIR JERNIH PADA JAMBATAN PENCONG TENGGELAM DENGAN DAN TANPA TIANG

Oleh

AMIR SAEED FARHANGI

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Seperti yang rekod dokumen menunjukkan, ianya sudah kurang daripada satu abad yang mana penyelidik telah mencuba untuk menilai kedalaman kerokan tempatan di keliling tiang sebagai fenomena kemusnahan. Dukacitanya, perubahan cuaca dan kemusnahan hutan masing-masing telah merubah regim hujan dan aliran air dalam keadaan yang teruk yang membuatkan jambatan tenggelam.

Oleh itu, dalam beberapa dekad yang lalu, beberapa penyelidik lain telah cuba untuk meramalkan kedalaman kerokan di bawah keadaan jambatan tenggelam. Walaupun keputusan mereka adalah berharga, masih terdapat faktor berbeza belum dikaji di bawah keadaan jambatan tenggelam yang masih perlu dinilai. Salah satu keadaan yang disebut belum pernah dikaji adalah kesan jambatan pencong tenggelam kepada kedalaman kerokan maksimum dan kajian ini berusaha menentukannya di bawah keadaan air yang jernih. Oleh itu, tujuan utama kajian ini adalah untuk menambahbaik persamaan sedia ada berkaitan ramalan kedalaman kerokan maksimum sekeliling asas jambatan tenggelam dengan sudut yang berbeza antara aliran tuju dan penjajaran dek jambatan. Dalam usaha untuk mengumpul data yang diperlukan, enam model jambatan yang berbeza dengan dan tanpa tiang dengan sudut yang berbeza 0, 5, 10, 15, 22.5 dan 30 darjah digunakan untuk menilai kesan penjajaran jambatan ke atas kedalaman kerokan maksimum. Semua model telah diuji dalam keadaan separa tenggelam dan tenggelam sepenuhnya menggunakan dua saiz sedimen dasar yang berbeza dengan saiz median 0.23 mm dan 0.80 mm. Sejumlah 48 ujian telah dijalankan. Analisis data yang diperoleh menunjukkan bahawa pesongan aliran tuju sepanjang ketebalan jambatan pencong (galang dan rel adang) adalah perbezaan utama berbanding dengan arah aliran tuju bersudut tepat. Sebenarnya, analisis vektor halaju aliran tuju sepanjang ketebalan jambatan pencong menunjukkan bahawa berlaku pengagihan tidak seimbang halaju aliran ke bawah, yang mana pertamanya ianya menyebabkan unit kadar alir tidak seimbang sepanjang pinggir hulu jambatan tanpa tiang. Kemudian, ia membuatkan tahap kerokan yang tidak seimbang sepanjang pinggir hilir jambatan. Mengikut mekanisme yang dinyatakan, satu persamaan berdasarkan hukum pemuliharaan jisim telah dicadangkan untuk meramalkan kedalaman kerokan maksimum dengan ralat punca min kuasa dua (RMSE) dan ralat min mutlak (MAE) masing-masing bersamaan dengan 0.029 m dan 0.023 m. Selain itu, aliran labirin antara kedua-dua belah dinding flum di

hilir jambatan mungkin berlaku, dengan arah pertamanya adalah arah yang paling merosakkan ke arah dinding flum yang bertentangan, yang mana ia dianggarkan oleh persamaan lain yang diperolehi, yang berubah daripada 34 darjah sehingga 65 darjah. Walau bagaimanapun, dalam keadaan jambatan pencong tenggelam dengan tiang, kewujudan tiang menyebabkan kedalaman kerokan tempatan maksimum di tiang, dan menghasilkan pusaran sekeliling tiang lebih daripada pesongan aliran di sepanjang ketebalan jambatan pencong tenggelam. Juga didapati faktor pembetulan penjajaran tiang untuk jambatan tenggelam adalah lebih kecil daripada keadaan yang sama dalam aliran bebas. Kemudian, satu hubungkait pembolehubah bersandar dan tak bersandar telah ditentukan. Akhirnya, satu persamaan dengan menggunakan analisis dimensi, data yang dikumpul dan model regresi linear berganda telah dicadangkan dengan anggaran yang lebih baik dari kajian lepas dengan RMSE dan MAE masing-masing bersamaan dengan 0.018 m dan 0.014 m. Faktor pembetulan penjajaran tiang dalam jambatan tenggelam juga adalah hampir 50% lebih kurang daripada faktor pembetulan yang sama dalam keadaan aliran bebas yang mana sebelum ini dianggap sama. Kedua-dua persamaan yang dicadangkan mampu meramalkan kedalaman kerokan maksimum yang boleh diterima berbanding dengan persamaan yang sedia ada. Selain itu, nisbah tenggelam dalam kedua-dua jambatan tenggelam dengan dan tanpa tiang menunjukkan bahawa kedalaman kerokan maksimum berlaku sebelum permulaan limpahan aliran dijambatan. Walaupun kedalaman kerokan di jambatan tenggelam tanpa tiang berkurangan selepas limpahan dijambatan dalam tempoh pendek terhad kepada nisbah tengelam daripada 0 hingga 0.08, ia meningkat semula kerana peningkatan kedalaman aliran. Tambahan lagi, kewujudan tiang sangat mempengaruhi kedalaman kerokan maksimum di sekeliling dinding flum yang menerima aliran terpesong.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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a	Effective bridge thickness [L];
B	Pier width; structure width [L];
b	Real bridge deck thickness; bottom width of scour hole [L];
b*	Width of cassion, slab footing or pile cap [L];
b_e	Equivalent width of a pier [L];
C	Empirical coefficient of time dependent in pressure flow [$M^0L^0T^0$];
C_c	Vertical contraction correction [$M^0L^0T^0$];
C_d	Discharge coefficient [$M^0L^0T^0$];
C_f	Froude number reduction [$M^0L^0T^0$];
C_o	Empirical coefficient of discharge in fully submerged orifice [$M^0L^0T^0$];
C_q	Empirical coefficient of Discharge reduction [$M^0L^0T^0$];
C_{vc}	Empirical coefficient of critical flow velocity [$M^0L^0T^0$];
CSU	Colorado State University;
C_w	Weir empirical coefficient [$M^0L^0T^0$];
D	Pier diameter [L];
d_{50}	Median size of the bed grain size [L];
EGL	Energy Gradient Line;
$y_{s(con)}$	Contraction scour depth [L];
h_b	Bridge opening height before scour [L];
h_d	Tail water depth before scour [L];
h_u	Approach flow depth [L];
h_{wc}	Weir crest elevation [L];
K_1	Flow intensity factor [$M^0L^0T^0$];
K_3	Factor for mode of sediment transport [$M^0L^0T^0$];
K_4	Factor for armouring by bed material [$M^0L^0T^0$];
K_d	Sediment size factor [$M^0L^0T^0$];
K_G	Approach channel geometry factor [$M^0L^0T^0$];
Ks	Correction factor for pier nose shape [$M^0L^0T^0$];
Kt	Time factor [$M^0L^0T^0$];
K_{yB}	Depth-size factor [$M^0L^0T^0$];
K_θ	Correction factor for angle of attack of approach flow in free flow [$M^0L^0T^0$];

$(K_\theta)_s$	Correction factor for angle of attack of approach flow in pressure flow [$M^0L^0T^0$];
k	Empirical coefficient dependent on sediment size [$M^0L^0T^0$];
k_1	Empirical coefficient dependent on the mode of bed material transport [$M^0L^0T^0$];
L	Pier length [L];
L_B	Bridge length [L];
L_C	Channel width [L];
L_w	Effective weir crest length [L];
m	Empirical exponent in Guo's method, the obstruction ratio [$M^0L^0T^0$];
MAE	Mean Absolute Error;
MLR	Multiple Linear Regression;
n	Empirical exponent in Guo's method [$M^0L^0T^0$];
P_1	Upstream flow static pressure [L];
Q	Discharge [L^3T^{-1}];
Q_{1m}	Discharge in the approach main channel transporting sediment [L^3T^{-1}];
Q_2	Total discharge through the bridge [L^3T^{-1}];
$Q_{submersed}$	Flow discharge under deck [L^3T^{-1}];
Q_{Total}	Total flow discharge [L^3T^{-1}];
Q_{weir}	Flow discharge over top of bridge deck [L^3T^{-1}];
q	Unit discharge [L^2T^{-1}];
q_{br}	Unit discharge passing through the bridge opening [L^2T^{-1}];
RMSE	Root Mean Square Error;
S_g	Specific gravity of bed grain [M^1L^{-3}];
SSE	Sum of squared distance between the actual and predicted values;
SST	Sum of squared distance between the actual and their mean;
T_0	Dimensionless initial time [$M^0L^0T^0$];
T_1	Dimensionless time for $t = t_1$, [$M^0L^0T^0$];
T_{90}	Dimensionless time corresponding to 90% of y_{se}, [$M^0L^0T^0$];
t	Time; time related to scour depth of y_s, [T];
t_e	Time of equilibrium scour depth to develop [T];
UPM	Universiti Putra Malaysia;
V	Flow velocity [LT^{-1}];
V_a	Initial (prior to scour) velocity through the bridge opening [LT^{-1}];
V_{bs}	Average velocity at equilibrium maximum scour cross section that is close to

	bridge outlet $[LT^{-1}]$;
V_c	Critical velocity due to bed grains $[LT^{-1}]$;
VPG	Vernier Point Gauge;
V_{sc}	Excavated scour hole volume $[L^3]$;
V_u	Mean approach flow velocity $[LT^{-1}]$;
V_{ue}	Effective approach velocity $[LT^{-1}]$;
W	Water surface width, The deck width [L];
W_1	Bottom width of the approach main channel [L];
W_2	Bottom width of the main channel in the contracted section [L];
WS	Water Surface;
w	Flow head of overtopping on the bridge deck [L];
x	Distance from an assumed point [L];
Y	Dimensionless time- dependent scour depth $[M^0L^0T^0]$;
Y_0	Dimensionless initial scour depth $[M^0L^0T^0]$;
y	Flow depth immediately at bridge upstream [L];
y_0	Initial scour depth [L];
y_1	Average depth in approach main channel, flow depths of wide river [L];
y_2	Flow depths of narrow river [L];
y_{mo}	Flow depth from water surface to the mean bed level of the low flow channel [L];
y_{ms}	Flow depth from the design water level to the mean scoured bed level [L];
y_o	Flow depth from water surface to the low point of the low flow channel[L];
y_s	Maximum scour depth in free flow; sampled scour depth [L];
y_{se}	Equilibrium scour depth [L];
y_{sf}	Flow depth from water surface to lowest scoured bed level [L];
$(y_s)_m$	Maximum scour depth due to submerged non-skewed bridge [L];
$(y_s)_{max}$	Total maximum equilibrium scour depth in skewed submerged bridge [L];
$(y_s)_\theta$	Maximum difference of scour depth between skewed and non-skewed bridge [L];
Z	Low chord height from the initial bed level [L];
Z_1	Height of bed stream from datum at bridge upstream [L];
Z_2	Height of bed stream from datum at bridge downstream [L];
α_1	Empirical coefficient of linear regression in Arneson's method, energy correction factor $[M^0L^0T^0]$;
α_2	Empirical coefficient of linear regression in Arneson's method $[M^0L^0T^0]$;

α_3	Empirical coefficient of linear regression in Arneson's method, energy correction factor $[M^0L^0T^0]$;
α_4	Empirical coefficient of linear regression in Arneson's method $[M^0L^0T^0]$;
β	Ratio of the bottom width of the approach main channel to the bottom width of the main channel in the contracted section $[M^0L^0T^0]$;
δg	Geometric standard deviation of particle size distribution $[M^0L^0T^0]$;
θ	Angle between pier alignment and flow direction, angle of skewed bridge axis due to un-skewed bridge $[M^0L^0T^0]$;
ɭ	Submergence index $[M^0L^0T^0]$;
λ_1	Empirical coefficient in Guo's method $[M^0L^0T^0]$;
λ_2	Empirical coefficient in Guo's method $[M^0L^0T^0]$;
ν	Kinematic viscosity $[L^2T^{-1}]$;
ρ	Fluid density $[M^1L^{-4}T^2]$;
ρ_s	Sediment density $[M^1L^{-4}T^2]$;
σ_g	Geometric standard deviation of the bed grain size distribution $[M^0L^0T^0]$;
$\emptyset$	Angle of repose of bed material $[M^0L^0T^0]$;

CHAPTER ONE

INTRODUCTION

1.1 Background

A bridge is an important and valuable structure which basically connects two separate sides of a river as a passage way above natural obstacle elements throughout the world (Melville and Coleman, 2000). However the existence of a bridge pier inside the flow stream transforms the local environment around pier (Mohamed et al., 2008). In fact, a bridge pier in contact with flow causes scour hole around pier foundations and finally may cause bridge failure (Ghorbani, 2008). Although designing knowledge about the solid structure of a bridge is well known, its stability against scouring and economical depth of buried foundation still needs to be studied more under various conditions. In any case, under prediction or over prediction of scour depth can lead to bridge failure or unnecessary expenses respectively (Debnath and Chaudhuri, 2010).

Local scour around foundation of bridge is a destructive phenomenon to the bed level around pier by dislodging and transporting bed grains. Therefore, the impinging of water flow to the pier nose as an obstacle causes some vortices such as; downward flow, horseshoe vortices, wake vortices which dislodge and entrain bed grains and finally digs a reversed conical hole around pier which may endanger the pier stability. This process that is attributed to the local scour can be created by stream flow which erodes the bed stream around piers and abutments (Lee et al., 2007). That is why many bridge collapses are related to the reduction of bridge safety factor which is results from local scour around the pier (Heydari and Ghiassi, 2011).

However, useful information has been collected in both experimental fields and theoretical study by different researchers, but the lack of knowledge about various unexpected conditions can still pose a danger to bridge stability and result in some unexpected catastrophes from time to time.

Hydraulics deficiencies are also important subjects that must be considered as a potential destructive factor which threaten bridge stability (Yanmaz and Bulut, 2001). For instance, any changes of flow condition (Temporary changes in river) may create critical situations and dig deeper local scour depth around the foundation of a bridge than predicted in the designing stage which severely endangers bridge stability.

The combination of local scour depth around bridge pier with general riverbed degradation or aggradation, changes of flow field around bridge structures, human interference and debris flow add greater complexity to the subject of bridge stability and safety (Lu et al., 2011). For example, land use with high fraction of impervious surface area can cause decrease of the ground water recharge and increase surface run-off (Falamalzi, 2014). Some inundated bridges are probably the result of some of the above-mentioned conditions. Submergence of bridge may be viewed as a basic reason for the development of deeper local scour depth around the foundation of a bridge in comparison with an ordinary local scour hole under free surface flow condition. This deeper scour depth can reduce the bridge safety factor and finally cause bridge failure by undermining. Therefore, some unstudied conditions under submerged bridge condition should be investigated.

1.2 Problem Statement

There are more than 580,000 bridges in the United States of America, with 84% of them constructed over waterways (Kwak, 2001; Deng and Cai, 2010). This huge number of bridges in just one country goes to show their importance and confirms a very significant need for their care, maintenance and safety. Every year, bridge failures are reported in various countries around the world, causing loss of human lives, enormous financial damage as well as breakdowns in communication (Lee and Sturm, 2009; and Sun and Liu, 2013). Shirhole and Holt (1991) and Briaud et al. (2014) based on the U.S. Federal Highway Administration reported that 60% of all 823 bridge failures in the U.S.A. since 1950, have been related to hydraulic flow. As cited by Macky (1990), in New Zealand alone, the expenditure on bridge repairs due to damages related to the local scour was around NZ$ 18 million per year (Melville and Coleman 2000).

In some other parts of the world like tropical areas with some high typhoon floods, bridges can be threatened by submergence as evidenced by several busy bridges in Taiwan located in East- Asia. During 1996, some typhoon floods caused collapses of bridges and serious losses (Lu et al., 2008). Another failure attributed to the pier scour occurred in China in 2006 and caused a bridge failure in Liaoning (Hong-Wu et al., 2009). Moreover, human interference in watersheds such as urban extensions, road constructions involving deforestation, mining, animal grazing and land clearing, taking sandy construction material from stream and river beds, lead to loss of permeability. Also, climate changes can basically change the runoff volume and increase the flood regime in any watershed (Huang et al., 2013). The mentioned problems bring surplus flood volume in each return period and can easily cause the inundation of bridges. In Iowa, heavy rains caused high water level in the rivers, crested the bridge and finally surrounded freight cars on 12th June 2008 (Figure 1.1).

Figure 1.1. Flood waters submerge bridge and surround freight cars in Iowa in 2008 (Associated Press, 2008).

Moreover, some limitations around the river do not allow for constructing high level bridges to avoid submergence during high floods (Verma et al., 2004). Shen et al. (2012) stated that a large number of bridges in the U.S.A. have the potential to be inundated. In addition, as a common rule in designing the foundation of a bridge, designers utilize the return period of 50 years or some recorded flood, whichever is larger (Johnson and Ayyub, 1992). Therefore, the probability of some larger flood than the designed flood that would submerge a bridge is high and should be expected. Although some researchers in the last few decades were interested to investigate the local scour depth around the foundation of a bridge under submerged bridge condition, they all used a perpendicular flow direction to the bridge deck but the probability of changes of flow direction during flood periods due to unstable river banks or bed river at its upstream is high. In other words, any changes of banks or bed river can change flow direction toward the bridge. On the other hand, no one can depict that approaching flow direction toward a bridge will always perpendicularly impinge the bridge deck. Therefore, additional scour depth in pressure flow can be aggravated by increasing angle of flow attack toward un-circular pier where the width of the projected pier increases. Although influence of different pier alignment under free flow condition has been studied well, effect of mentioned alignment in different angle under submergence condition is still unknown.

However, Abed (1991) assumed that correction factor of pier alignment under pressure flow is the same as its value under free flow. But mentioned correction factor under submerged bridge condition should be precisely evaluated wherein this coefficient strongly effects on prediction of maximum scour depth around pier. Moreover, flow behavior along submerged skewed bridge thickness is still unknown and its behavior may bring new problem or may deflect flow toward river bank. Therefore, this behavior must be also evaluated wherein it may change the maximum scour depth location from middle of river which was found by Guo et al. (2010) toward river bank or bridge abutment. Although above mentioned maximum scour depth location is important to be predicted, an equation must be able to predict maximum scour depth in different flow directions and must apply the angle which all previous researches are able to only predict it in perpendicular flow direction. In addition, the shape of scour hole and its extension toward bridge abutment because of its new position of pier alignment against flow attack can be counted as an important subject which should be also evaluated. Therefore, present study attempts to investigate various effects of different flow alignments toward submerged bridge with and without pier.

1.3 Research Objectives

The main objective of the present study is to investigate and predict the maximum local scour depth at the site of a submerged skewed bridge under clear water conditions with the following specific objectives:

1. To investigate flow behavior around a submerged skewed bridge without pier under clear water conditions.
2. To develop an equation for pressure flow to predict the maximum scour depth due to different angles between approaching flow direction and submerged skewed bridge alignment without pier under clear water conditions.
3. To determine the correction factor for the pier alignment in pressure flow $(K_\theta)_s$ under clear water conditions and to predict the maximum local scour depth around aligned pier under submerged bridge with pier.
4. To evaluate the effect of pier on pressure scour at the submerged bridge with pier in comparison to the pressure scour at submerged bridge without pier.

1.4 Scope and Limitations of the Study

As mentioned earlier, a limited number of studies have been carried out on local scour depth under pressure flow, but most of the experiments have been done under perpendicular angle between approach flow and bridge directions and the effect of different angles on local scour depth is still unknown.

The present study is also based on experimental laboratory tests including partially and fully submerged bridge under clear water conditions to evaluate the flow behavior and maximum scour depth under different angles between flow and bridge direction which leads to the ultimate aim. Overall, the process of the present study is divided into three phases: designing and constructing some models based on a proper scale of real bridge in different alignments. Then, all different models were experimentally tested in the laboratory flume with a few variable factors (to avoid difficulty in analyzing) including flow depth, sediment sizes and various bridge directions in order to collect useful and necessary data. Finally, an analytical conclusion could be derived based on the collected data.

Although the present study can be useful to evaluate and predict the local scour depth under pressure flow with some new results, it still suffers from some limitation as follows:

1. Shortage of previous available studies in this area to be compared with the present study for achievement of appropriate agreements.

2. All test have been carried out with two uniform bed grains with median size of 0.23 mm and 0.80 mm, a constant ratio of pier width to the pier length (B/L = 1/10), steady flow and under clear water condition.
3. Rectangular pier shape with a constant ratio of pier width to the pier length (B/L = 1/10) is utilized.
4. According to flume wall, results can be only used for rigid vertical abutment of bridge.
5. The range of fully flow depth was restricted by a carriage above water surface flow.

1.5 Organization of the Thesis

This thesis comprises five chapters. The first chapter introduces the problems of scour around the foundation of a submerged bridge under different flow alignments. The objectives, scope and limitations of the present study are also presented in this chapter. The next four chapters are divided as follow: Chapter Two (Literature Review) is a review of relevant literature, but the most important discussion is the scour depth around a submerged bridge pier and vertical contraction in submerged bridge. In this chapter, the evolution of scour depth around pier in both free surface flow and pressure flow conditions due to effective parameters can resolve the problem. In addition, the existing analysis of scour depth around the foundation of a bridge under pressure flow conditions is also introduced.

Chapter Three includes the experimental setup, data collection and the methodology which are explained. Proposed models and their set up are firstly described. Then, descriptions of experimental tests and the method of data collection are presented.

In Chapter Four, analyzing the collected data with graphs, figures and tables is the main purpose to provide results. Then, discussion of the results including prediction of maximum scour depth around submerged skewed foundation of bridge and some comparisons between previous studies and the present study will determine the validity and accuracy of the present study. Besides all the main aims, some other important behaviors of flow related to the different mentioned angles are discussed.

Finally, Chapter Five provides a summary and highlights the main results obtained from Chapter Four. At the end, some recommendations for future study are also made.

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