



**UNIVERSITI PUTRA MALAYSIA**

**PHYSICAL MODELING ON LOCAL SCOUR AT COMPLEX PIERS**

**SEYED ATA AMINI**

**FK 2009 95**



**PHYSICAL MODELING ON LOCAL SCOUR AT  
COMPLEX PIERS**

**SEYED ATA AMINI**

**DOCTOR OF PHILOSOPHY  
UNIVERSITI PUTRA MALAYSIA**

**2009**



**PHYSICAL MODELING ON LOCAL SCOUR AT COMPLEX PIERS**

**By**

**SEYED ATA AMINI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia  
In Fulfilment of Requirements for Degree of Doctor of Philosophy**

**December 2009**



**Dedicated**

**To**

**My parents and my lovely family, wife and son.**



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

## **PHYSICAL MODELING ON LOCAL SCOUR AT COMPLEX PIERS**

By

**SEYED ATA AMINI**

**December 2009**

**Chairperson: Associate Professor Thamer Mohammad Ali**

**Faculty: Engineering**

Over the past decades, great strides have been made in the ability to accurately predict design scour depths at simple bridge pier structures. While, many bridge piers are complex in shape, consisting of several components (e.g., column, pile cap and pile group). There is a general lack of confidence in available methods for predicting local scour at complex piers. The main objective of the research is to provide accurate estimating of geometrical characteristics of complex pier and its location relative to undisturbed streambed on scour depth, for improving existing scour prediction methods. Furthermore, the collected data can fill voids in existing data for pier with complex geometries in various locations. In this research, an experimental study on multiple piles and complex piers and its components were conducted. The variables investigated were the dimensions of complex piers and the models location relative to initial streambed. In addition, in the experiments on pile group, the pile spacing, arrangement and



submergence ratio were examined. A wide range of experiments on individual components including pile group, pile cap and column and combination of these components such as the column mounted on the pile cap and complex piers were studied. Flow conditions and sediment characteristics were kept constant for all of the experiments. The flow discharge, water depth and flow velocity readings were taken using an Area Velocity Module (AVM). Cohesionless uniform sediment was used with the mean particle sizes,  $d_{50}=0.8$  mm and geometric standard deviation of particles,  $\sigma_g=1.34$ . The experiments were performed under clear-water conditions at threshold flow intensity. The results of experiments on individual components were used to present new methods to predict local scour at pile group, pile cap and column, which is useful to be used for predicting scour at multiple piles and complex piers. Outcomes of verifying these methods show that proposed methods give reasonable scour depth prediction. In addition, it was found that, besides the parameters that affect scour at a uniform pier, the scour depth at complex piers and its components are highly depend on their locations relative to initial streambed. The experimental data obtained on complex pier models was used to evaluate predictions of existing methods. Federal Highway Administration, Hydraulic Engineering Circular No. 18, HEC-18, Florida Department of Transportation, FDOT and Coleman methods for complex piers, were examined. It was found that the results of HEC-18 method have a much larger scatter than FDOT and Coleman methods. In addition, the measured scour depths produced by isolated components were used to evaluate superposition methodology. The upshots indicate that this methodology do not accurately predict the observed scour depth at composite structures.



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

**PERMODELAN FIZIKAL Pengerukan TEMPATAN PADA TIANG  
SAMBUT KOMPLEKS**

Oleh

**SEYED ATA AMINI**

**Disember 2009**

**Pengerusi: Prof. Madya Thamer Mohammad Ali**

**Fakulti: Kejuruteraan**

Pada beberapa dekad yang lepas, kemajuan telah dibuat dalam keupayaan kaedah meramal ketepatan kedalaman rekabentuk kerukan pada struktur-struktur ringkas tiang sambut. Namun, banyak tiang sambut adalah dalam bentuk kompleks, yang terdiri daripada beberapa bahagian (cth: tiang, cerucuk tetopi, dan cerucuk kumpulan). Secara umumnya terdapat kekurangan dalam kaedah sediaada untuk meramalkan kerukan setempat yang kompleks. Objektif utama penyelidikan adalah untuk menghasilkan kaedah yang tepat dalam menganggarkan sifat geometri tiang sambut yang kompleks dan lokasi berkenaan berdasarkan kepada dasar saluran tidak terganggu terhadap kedalaman kerukan. Ini adalah untuk tujuan memperbaiki kewujudan kaedah ramalan kerukan. Tambahan pula, data terkumpul menjadi tidak sah berdasarkan data yang wujud untuk geometri tiang sambut yang kompleks di lokasi yang pelbagai. Pemboleh ubah pada siasatan ini adalah rekabentuk struktural tiang sambut yang kompleks dan lokasinya berhubung dengan permulaan dasar saluran. Tambahan lagi, eksperimen-eksperimen terhadap cerucuk kumpulan, ruang cerucuk, nisbah susunan dan nisbah



peneggelaman telah diselidiki. Kajian terhadap air jernih kerukan di tiang sambut yang kompleks dan bahagian-bahagian bawah aliran stabil pada had halaju telah dilakukan. Kajian juga telah dilakukan pada jarak lebar eksperimen pada bahagian-bahagian tunggal termasuk cerucuk kumpulan, cerucuk tetopi dan tiang serta gabungan bahagian-bahagian tersebut seperti tiang menaik pada cerucuk tetopi dan tiang sambut yang kompleks (cerucuk kumpulan, cerucuk tetopi dan tiang). Kedalaman aliran pada 0.24 m telah ditetapkan untuk kesemua eksperimen. Aliran pembebasan, kedalaman air dan bacaan halaju aliran telah diambil menggunakan Modul Luas Halaju (AVM). Ketidakeleketan enapan seragam digunakan dengan purata saiz zarah,  $d_{50}=0.8$  mm dan piawai geometrik lencongan zarah,  $\sigma_g=1.34$ . Eksperimen-eksperimen telah dilaksanakan di bawah keadaan air jernih pada rintangan arus kuat. Keputusan eksperimen pada bahagian-bahagian tunggal digunakan untuk menunjukkan kaedah baru untuk meramal kerukan setempat pada cerucuk kumpulan, cerucuk tetopi dan tiang di mana sangat berguna digunakan dalam kaedah meramal superposisi kerukan pada tiang sambut yang kompleks. Hasil daripada kaedah-kaedah ini menunjukkan kaedah ramalan kedalaman kerukan adalah munasabah. Tambahan pula, telah dijumpai, parameter yang mempengaruhi pengilap pada tiang sambut yang seragam, kedalaman kerukan pada tiang sambut yang kompleks dan bahagian-bahagiannya adalah bergantung kepada lokasi awalan dasar saluran. Bagaimanapun, data eksperimen yang diperoleh pada model-model tiang sambut yang kompleks digunakan untuk menilai kaedah ramalan yang wujud. Pentadbiran Persekutuan Lebuhraya, Pekeliling Kejuruteraan Hidraulik No. 18, HEC-18, Jabaan Pengangkutan Florida, FDOT dan kaedah-kaedah Coleman (untuk tiang sambut yang kompleks telah diselidiki. Ditemui bahawa keputusan kaedah HEC-18 mempunyai taburan yang besar daripada kaedah-kaedah FODT dan Coleman. Tambahan lagi, ukuran kedalaman kerukan yang dihasilkan oleh bahagian-bahagian





tercerai digunakan untuk menilai kaedah superposisi. Keputusan menunjukkan bahawa kaedah ini tidak tepat meramal kedalaman kerukan pada struktur-struktur gabungan.

## **ACKNOWLEDGEMENTS**

First and foremost, I would like to give grace to the Almighty God for sparing my life and for seeing me through the completion of this research work. I wish to also express my sincere appreciation and deep sense of gratitude to my supervisor Assoc. Prof. Thamer M. Ali for his guidance, encouragement and personal concern throughout the course of this research work. I would like to extend my gratitude to my supervisory committee for their guidance and support on this research.

My heartfelt gratitude is extended to Prof. Bruce Melville for the critical insight, invaluable guidance and comments on my experiments and results provided to me during the period of research for this thesis as well as during the writing-up papers process. His wealth of knowledge and enthusiasm to share them with me is most appreciated.

This research is performed under a financial support of Fundamental Research Grant Scheme (FRGS) given by University Putra Malaysia (grant No. 07-10-07- 429FR) and the experiments were conducted in the hydraulic laboratory in National Hydraulic Research Institute of Malaysia (NAHRIM) which these supports are strongly appreciated. The experiments were carried out with the prodigious help of hydraulic laboratory staff at NAHRIM to whom I express my gratitude.



It is also my great pleasure to give a due recognition to my family members for their all the time love, understanding and support in the course of this program and also for their prayers and words of encouragement whenever my enthusiasm waned. Specifically, I want to use this opportunity to express my sincere thankfulness to my father and mother for their constant support for my education over the years. I only hope that I can be as helpful to them in life as they have been to me.

This study would not have been possible without the encouragement, patience and overwhelming support of the author's wife Atefeh and author's son, Aran, during the period of this research who are especially acknowledged.



I certify that a Thesis Examination Committee has met on 30 December 2009 to conduct the final examination of Seyed Ata Amini on his thesis entitled “Physical Modeling on Local Scour at Complex Piers” in accordance with the Universities and University Colleges Act 1971 and Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Examination Committee were as follows:

**Ir. Mohd Amin Mohd Soom, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Ir. Lee Teang Shui, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Jamaloddin Noorzaei, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Behzad Ataie-Ashtiani, PhD**

Professor  
Civil Engineering Department  
Sharif University of Technology  
Iran  
(Eternal Examiner)

---

**BUJANG BIN KIM HUAT, PhD**

Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 12 February 2010



This thesis was submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of supervisory committee were as follow:

**Thamer A. Mohammad Ali**

Associate Professor  
Department of Civil Engineering  
Faculty of Engineering, University Putra Malaysia  
(Chairperson)

**Abdul H. Ghazali**

Associate Professor  
Department of Civil Engineering  
Faculty of Engineering, University Putra Malaysia  
(Member)

**Bujang B. K. H.**

Professor  
Department of Civil Engineering  
Faculty of Engineering, University Putra Malaysia  
(Member)

**Azlan A. Aziz**

Senior Lecturer  
Department of Civil Engineering  
Faculty of Engineering,  
University Putra Malaysia  
(Member)

---

**HASANAH MOHD GHAZALI, PhD**  
Professor and Dean  
School of Graduate Studies  
University Putra Malaysia

Date: 17 March 2010



## DECLARATION

I declare that the thesis is my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at University Putra Malaysia or at any other institution.

---

Ata Amini

Date: 26 January 2010



# TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	iii
<b>ABSTRACT</b>	iv
<b>ABSTRAK</b>	vi
<b>ACKNOWLEDGEMENTS</b>	ix
<b>APPROVAL</b>	xi
<b>DECLARATION</b>	xiii
<b>LIST OF TABLES</b>	xvii
<b>LIST OF FIGURES</b>	xviii
<b>ABBREVIATIONS</b>	xxiii
<b>CHAPTERS</b>	
<b>1</b>	<b>INTRODUCTION</b>
	1.1 Background 1
	1.2 Type of Scour 2
	1.3 Problem Statements 11
	1.4 Objectives of the Study 14
	1.5 Scope and Limitations 14
	1.6 Thesis Layout 16
<b>2</b>	<b>LITERATURE REVIEW</b>
	2.1 Introduction 17
	2.2 Mechanism of Scour 18
	2.3 Local Scour Conditions 20
	2.3.1 Clear-Water Scour 21
	2.3.2 Live-Bed Scour 21
	2.4 Classification of Local Scour Parameters 22
	2.5 Parameters Influencing Local Scour 24
	2.5.1 Flow Velocity 24
	2.5.2 Flow depth 25
	2.5.3 Sediment Characteristics 26
	2.5.4 Pier Size 31
	2.5.5 Pier Shape 32
	2.5.6 Angle of Attack 34



	2.5.7 Time	35
	2.5.8 Contraction Ratio	39
	2.6 Dimensional Analysis for Local Scour	39
	2.7 Equations for Local Scour Prediction	41
	2.8 Local Scour Countermeasures	43
	2.9 Numerical Methods	44
	2.10 Effect of Foundation Geometry	46
	2.11 Local Scour at Pile Groups	51
	2.12 Local Scour at Complex Piers	57
	2.13 Dimensional analysis for complex piers	69
	2.14 Experimental Data at Complex Piers	70
	2.14.1 Jones' Experiments	70
	2.14.2 Coleman's Experiments	71
	2.14.3 Sheppard's Experiments	72
	2.15 Superposition of the Scour Components	73
	2.16 Critical Literature Review	75
<b>3</b>	<b>MATERIALS AND METHODS</b>	
	3.1 Introduction	77
	3.2 Experimental Facilities	78
	3.2.1 The Flume	78
	3.2.2 Area Velocity Module	80
	3.2.3 Current Meter	81
	3.3 Data Collection	83
	3.4 Experiments Procedure	85
	3.5 Test Duration	87
	3.6 Bed Materials	92
	3.7 Threshold Shear Stress and Velocity of the Bed Material	94
	3.8 Experiments	96
	3.8.1. Pile Group	96
	3.8.2. Complex piers	98
	3.8.3 Isolated Components of Complex Piers	105
	3.9 Evaluation of Published Equations	110
	3.10 Discussion of Equations	111
	3.10.1 FDOT Method	111
	3.10.2 HEC- 18 Method	112
	3.10.3 Coleman Method	113
	3.11 Statistical Analysis to Evaluate the Methodologies	114
<b>4</b>	<b>RESULTS AND DISCUSSIONS</b>	
	4.1 Introduction	117





4.2 Scour Test on Pile Groups	118
4.2.1 Results of Experiments for Unsubmerged Pile Groups	120
4.2.2 Results of Experiments for Submerged Pile Groups	127
4.2.3 Estimate of Scour Depth for Pile Group	131
4.2.3.1 Proposed Methodology	132
4.2.3.2 Comparison of Proposed Method with Existing Prediction Methods	133
4.3 Scour Test Results on Complex piers	137
4.3.1 Evaluation of Existing Methodologies	144
4.4 Scour at Isolated Components of Complex Piers	155
4.4.1 Results of Experiments for Isolated Column	155
4.4.2 Results of Experiments for Isolated Pile Cap	159
4.4.2.1 Proposed Methodology	161
4.4.2.2 Comparison of Proposed Method with Existing Prediction Methods	167
4.4.3 Scour Results for Column Mounted on Pile Cap	170
4.4.4 Results of Experiments for Complex Pier and Its Components	172
4.5 Evaluation of Superposition Method	179
<b>5</b>	
<b>SUMMARY, CONCLUSIONS AND RECOMMENDATIONS</b>	
5.1 Summary	183
5.2 Conclusions	184
5.2.1 Simulate Local Scour for Complex Piers	185
5.2.2 Pile Group	185
5.2.3 Evaluating the Existing Methodologies	185
5.2.4 Complex Piers and Its Isolated Components	186
5.3 Recommendations	187
<b>REFERENCES</b>	189
<b>APPENDICES</b>	198
<b>BIODATA OF STUDENT</b>	229
<b>LIST OF PUBLICATIONS</b>	230



## LIST OF TABLES

Table		Page
1.1	PWD Cases of Scouring at Bridge in Malaysia (Yee-Meng et al., 2000)	8
1.2	Statistical Description of Malaysian Bridges (Zawawi, 2007)	11
2.1	Classification of local scour processes at bridge pier foundations and flow depth (Melville and Coleman, 2000)	26
2.2	Most Commonly Used Equations for Pier Scour (Li et al., 2002)	42
3.1	Properties of Sand Used as Bed Material in Flume	93
3.2	Details of Pier Models Geometries Used in This Study	101
3.3	The Experiment Types, Models/Arrangements and Number of Experiments Carried Out in the Research	109
4.1	Characteristics of Pile Group arrangements and Obtained Regression Equations for the Experiments	127
4.2	Evaluation Performance of Proposed and Existing Methodologies	135
4.3	Dimensionless Parameters in Complex Piers Models Used in the Research	138
4.4	Evaluation Performance of Existing Methodologies	147
4.5	Details of Models Geometries Used In This Study	160
4.6	Evaluation Performance of Proposed and Existing Approaches	169



## LIST OF FIGURES

<b>Figure</b>	<b>Page</b>
1.1 Various Types of Scour (Cheremisinoff and Cheng, 1987)	3
1.2 Causes of Bridge Failure in the United States, New Zealand, and South Africa (Annandale, 1993).	4
1.3 Examples of Scour around Complex Piers (A) Local Scour and Bed Degradation at Kaoping Bridge, Taiwan, (B) Failure of Kaoping Bridge, Taiwan Due to Combination of General and Local Scour (Lin, 1998)	5
1.4 Bridge Failure Due to Scouring on Sungai Sembrong in 2006 (Zawawi, 2007).	9
1.5 Temporary Repairing for Failed Bridge on Sungai Sembrong in 2006 (Zawawi, 2007).	9
1.6 General and Local Scouring of River Bed at Sg. Jeniang (King and Mohammad, 2009)	10
2.1 Diagrammatic Flow Components at Cylindrical Pier (Raudkivi, 1986)	20
2.2 Pier Scour Depth in a Sand-bed Stream as a Function of Time (Richardson and Davis, 2001).	23
2.3 Development of Local Scour Depth with Time and Flow Velocity (Melville and Chiew, 1999).	38
2.4 Nonuniform Pier Configuration: (a) Zone 1; (b) Zone 2; (c) Zone 3 (Melville and Raudkivi, 1996)	46
2.5 Effect of Collar on Scour Depth in the Region of a Cylindrical Bridge Pier (Chiew, 1992)	50
2.6 Adjustment Factor for Pile Spacing (Salim and Jones, 1996).	58
2.7 Effect of Angle of Attack (Salim and Jones, 1996)	59
2.8 Pile Stub Component (Salim and Jones, 1996)	60
2.9 Pile Cap Component (Salim and Jones, 1996)	60
2.10 Local Scour Variations with Complex-Pier Pile-Cap Elevation (Coleman, 2005)	63
2.11 Complex-Pier Configuration (Coleman, 2005)	65



2.12	Conceptual Hypotheses for Superimposing Scour Components (Sheppard and Jones, 1998)	65
2.13	Pile Group Height Factor (Jones and Sheppard, 2000)	67
2.14	Suspended Pier Height Factor (Sheppard and Jones, 1998)	67
2.15	Pile Cap Equivalent Solid Pier Ratio (Sheppard and Jones, 1998)	68
2.16	Complex Piers Used in Sterling Jones' Experiments (Sheppard and Renna, 2005)	71
2.17	Plan and Elevation View of Models of Complex Piers used in Coleman's Experiments (Sheppard and Renna, 2005)	72
2.18	Position of the Piers in Sheppard's Experiments (Sheppard and Renna, 2005)	73
2.19	Definition Sketches for the Effective Diameters of the Column, Pile Cap and Pile Group (Sheppard and Renna, 2005)	74
2.20	Definition Sketch for Total Effective Diameter for a Complex Pier Using in Superposition Method (Sheppard and Renna, 2005)	75
3.1	Schematic Drawing of the Flume Test Facility	79
3.2	The Laboratory Flume Test Stated in National Hydraulic Research Institute of Malaysia (NAHRIM)	80
3.3	Velocity Measurement Devices: (a) Area Velocity Module and Its Sensor (b) Two Type of Current Meter Probes	82
3.4	Details of Model Installation and Its Support during Experiments	86
3.5	The Particle Size Distributions of the Bed Material	94
3.6	Definition Sketch for 3*4-Pile Group Arrangement	97
3.7	Pier Position Related To Undisturbed Stream Bed and Water Surface	99
3.8	A Schematic Illustration of Complex Pier Configuration (Coleman, 2005)	100
3.9	Plan and Elevation View of Complex Pier Models; (a) Model One; (b) Model Two; (c) Model Three (all dimensions are in cm)	102
3.10	Pier Models for the Experiments: (a) Kedah, Pier No.1 with 1:9 Scale; (b) Pahang, Pier No. 3 with 1:37 Scale; (c) Johor Pier No. 2 with 1:35 Scale; (d) Pahang Pier No. 6 with Scale 1:65; (e) Pahang Piers No. 1,2,7,8 with 1:27 Scale	105
3.11	Plane-Bed Formation at a Location Far Upstream of the Model	108
3.12	The Schematic Flowchart of the Overall Work	109

4.1	Variation of Local Scour Depth with Time for 2*2 Pile Group Arrangement	119
4.2	Local Scour Depth Plotted Versus Pile Spacing at Uniform Exposed Pile Groups Arrangements	121
4.3	Equilibrium Scour Depth Ratio Plotted Versus Normalized Pile Spacing with Uniform Spacing Arrangements ( $S_n=S_m$ )	123
4.4	Equilibrium Scour Depth Ratio Plotted Versus Normalized Pile Spacing with Nonuniform Spacing Arrangements ( $S_n \neq S_m$ )	123
4.5	Equilibrium Scour Hole Contours and Surface Plots for 2*4 Arrangement of Exposed Pile Group with $D = 0.06$ and $S/D=2$	124
4.6	Combined Scour Hole at 2*4 Arrangement of Exposed Pile Group with $D = 0.06$ and $S/D=2$ (a) Looking From Upstream (b) Looking From Downstream	125
4.7	Individual Scour Hole at Exposed Pile Groups with $D = 0.06$ and $S/D=4$ ; a) 2*2 Pile Group Arrangement b) 3*5 Pile Group Arrangements	126
4.8	The Scour Test on 4*4 Arrangement of Submerged Pile Group a) Model Installation b) Pre Test; c) Post Test	128
4.9	Variation of $K_h$ with Submergence Ratio, $S_r$ , for Different Pile Group Arrangements	130
4.10	Coefficient $\hat{K}_{S_{mn}}$ as Function of $S/D$ for the Experiments	130
4.11	Comparison of Observed and Predicted Scour Depth at: a) Unsubmerged Pile Groups; b) Submerged Pile Groups	134
4.12	Comparison of Obtained Results of Proposed Method and Observed Data at Unsubmerged Pile Groups	136
4.13	Variation of Local Scour Depth with Pile Cap Location	138
4.14	Local Scour Depth at Complex pier a) Complex Pier Exposed with Varying Pile Cap Location; b) Conceptual Variation of Local Scour with Pile Cap Location	140
4.15	Post Scour Test Indicated Case 1 in Model 7	141
4.16	Post Scour Test Indicated Case 2 in Model 5	141
4.17	Post Scour Test Indicated Case 3 (Curve DE) in Model 8 When the Pile Cap Is Not Undercutting (Photograph Taken From the Side)	143
4.18	Post Scour Test Indicated Case 3(Curve EF) in Model 8 When the	

	Pile Cap Is Undercutting (Photograph Taken from Downstream and side)	143
4.19	Post Scour Test Indicated Case 4 in Model 7 (Photograph Taken From Upstream and Side)	144
4.20	Comparison of Calculated versus Measured Pier Scour Depth a) the FDOT Method; b) the HEC-18 Method; c) Coleman (2005) Method	145
4.21	Distribution of Residual Depth of Pier Scour for Evaluated Methods	147
4.22	Measured and Predicted Scour Depth versus Pile Cap Elevation a) Model One; b) Model Two; c) Model Three; d) Pier Model in Kedah, Pier No.1; e) Pier Model in Pahang, Pier No. 3; f) Pier Model in Johor, Pier No. 2 g) Pier Model in Pahang, Pier No. 6; h) Pier Model Pahang Piers No. 1, 2, 7 and 8	148
4.23	Measured Scour Depth Variation with Column Elevation at Suspended Columns Used at Assessed Complex Piers	156
4.24	The Normalized Scour Depth Plotted Against Normalized Pile Elevation	157
4.25	Scour Test for Column at Model 7 a) Pre Scour Test; b) During Scour Test; c) Post Scour Test	158
4.26	Measured Scour Depth at Suspended Pile Cap Models	159
4.27	Local Scour Variation with Pile Cap Level: (a) Pile Cap Exposed at Various Levels; (b) Conceptual Distinction of Local Scour at Various Levels of Pile Cap	162
4.28	Scour Hole at Pile Cap for Model 5 a) before Removing the Model b) after Removing the Model	167
4.29	Comparison of Observed and Calculated Scour Depth at Pile Cap	169
4.30	Application of Proposed Method on Data Obtained by Sheppard and Jones (1998)	171
4.31	Measured Scour Depth Variation with Pile Cap Elevation at Column - Pile Cap Combination	171
4.32	Scour Test for Pile Cap-Column Combination at model 4 a) Pre Scour Test; b) During Scour Test; c) Post Scour Test	172
4.33	Measured Scour Depth Variation with Model Elevation at Complex Pier and Isolated Components of Pier 1	173
4.34	Measured Scour Depth Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 2	174



4.35	Measured Scour Depth Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 3	174
4.36	Measured Scour Depth at Complex Pier Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 4	175
4.37	Measured Scour Depth at Complex Pier Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 5	175
4.38	Measured Scour Depth Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 6	176
4.39	Measured Scour Depth Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 7	176
4.40	Measured Scour Depth at Complex Pier Variation with Pile Cap/Column Elevation at Complex Pier and Isolated Components of Model 8	177
4.41	Comparison of Measured Scour Depth at Complex Pier Models and Combination of Pile Cap-Column versus Superposition Results	181



## ABBREVIATIONS

A	constant number
a	pier width
$a_{pg}^*$	equivalent full depth pile group
Al	parameter describing the alignment
$a_{proj}$	sum of non-overlapping projected widths of piles
b	width of pile cap
B	pier projection width
$b_{pg}^*$	width of a full depth solid pier that would yield the same scour depth as the full depth pile group
$B_1$	approaching flow width
$b_c$	width of column component at complex pier
$b_e$	equivalent cylindrical pier diameter relative exposure of the column, pile-cap and pile-group elements
$b_{pc}$	width of pile cap component at complex pier
C	constant number
Comp	soil compact ratio
D	diameter of cylindrical pile
$D^*$	effective diameter for complex pier components
$D^*$	foundation diameter in nonuniform cylindrical pier
$d_{50}$	median sediment size
$D_e$	the equivalent diameter of the nonuniform pier
$d_{s(ES)}$	scour depth around an equivalent solid pier at the same skew angle to flow direction.
$f_{cb}$	extension length of pile cap face out from column face
$f_{cl}$	extension length of pile cap face out from column face
$f_{pb}$	extension length of pile cap face out from nearest pile centerline
$f_{pl}$	extension length of pile cap face out from nearest pile centerline
$Fr_1$	Froude Number directly upstream of the pier = $V_1/(gy_1)$
h	height of pile cap relative to undisturbed streambed





IWC	Initial Water Content
$k$	turbulent kinetic energy
$K$	correction factors for specific conditions
$K_1$	correction factor for pier nose shape
$K_2$	correction factor for angle of attack of flow
$K_3$	correction factor for bed condition
$K_4$	correction factor for armoring by bed material size
$K_{ci}$	correction factor for suspended pile cap in $i^{\text{th}}$ case
$K_D$	sediment size factor
$K_{Gmn}$	correction factor for pile group spacing and arrangements
$K_h$	pile group height adjustment factor
$K_{hpg}$	the height factor for pile group at complex piers
$K_I$	flow intensity factor
$K_m$	coefficient for number of aligned rows
$K_s$	foundation shape factor
$K_{Smn}$	correction factor for spacing at exposed pile group arrangements
$K_{sp}$	coefficient for pile spacing
$K_t$	time factor
$K_{yb}$	flow depth-pier size factor (dimension of length)
$K_\theta$	foundation alignment factor
$l_{pc}$	length of pile cap in line with flow
$L$	length of pier
$l_c$	length of column component at complex pier
$m$	number of pile in line with flow
MAE	mean absolute error
$n$	number of piles normal to the flow
$N$	number of data
$p$	represents predicted scour depth
PF	prediction factor
$q$	unit flow rate
$R$	correlation coefficient