Bridge Pier Flow Interaction and Its Effect on the Process of Scouring

By

Chij Kumar Shrestha

A thesis submitted in fulfilment of the requirement for the degree of

Doctor of Philosophy

Faculty of Engineering and Information Technology
University of Technology Sydney (UTS)
September 2015
CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Chij Kumar Shrestha
Sydney, September 2015
ABSTRACT

Previous investigations indicate that scour around bridge piers is a contributor in the failure of waterway bridges. Hence, it is essential to determine the accurate scour depth around the bridge piers. For this purpose, deep understanding of flow structures around bridge piers is very important. A number of studies on flow structures and local scour around bridge piers have been conducted in the past. Most of the studies, carried out to develop a design criterion, were based on a single column. However, in practice, bridge piers can comprise multiple columns that together support the bridge superstructure. Typically, the columns are aligned in the flow direction. The design criteria developed for a single column ignore the most important group effects for multiple columns cases such as sheltering, reinforcement and interference effects. These group effects can significantly be influenced by the variation of spacing between two columns. This is evident by the fact that insufficient investigations and development have been reported for the flow structure and maximum scour depth around bridge piers comprising multiple columns. It is therefore necessary to investigate the effects of multiple columns and spacing between them on the flow structure and local scour around bridge piers and develop a practical method to predict the maximum scour depth.

The main objectives of this research work are to analyse the effect of spacing between two in-line circular columns on the flow structure and to develop a reliable method for prediction of the maximum local scour depth around bridge piers. To meet the objectives this research, detailed experimental studies on three dimensional flow structures and local scour around two-column bridge piers were carried out. A series of laboratory experiments were conducted for no column, a single column and two in-line columns cases with different spacing. Two in-line columns were installed at the centre of the flume along the longitudinal axis. Three dimensional flow velocities in three different horizontal planes were measured at different grid points within the flow using a micro acoustic doppler velocimeter (ADV). The velocity was captured at a frequency of 50Hz. Additionally, in vertical planes, particle image velocimetry (PIV) technique was employed to measure the two dimensional instantaneous velocity components. All experiments on flow structures were conducted under no scouring and clear water flow.
conditions. Similarly, an array of experimental tests were conducted under different flow conditions for studying the temporal development of scour depth and the maximum local scour depth around a single column and two-column bridge piers.

The measured instantaneous three dimensional velocity components were analysed and the results for flow field and turbulence characteristics were presented in graphical forms using vector plots, streamline plots, contour plots and profile plots. The results indicated that the flow structures around two- columns bridge piers is more complex than that of a single column case. Furthermore, the spacing between two columns significantly affects the flow structures, particularly in the wake of the columns. It was observed that for the spacing-column diameter ratio \((L/D) < 3\), the vortex shedding occurred only behind the downstream column. Hence, the flow pattern was more or less similar to that of the single column case. However, the turbulence characteristics such as turbulence intensity, turbulent kinetic energy and Reynolds shear stresses were notably different from those of a single column case. When the spacing was in the range of \(2 \leq L/D \leq 3\), stronger turbulence structures were noticed behind the upstream column. Further increase in the spacing between two columns resulted in a decrease in the strength of turbulence characteristics.

The experimental results on temporal development of local scour depth reveal that approximately 90% of the maximum scour depth around the upstream column was achieved within the first 10 hours of the experiments. However, for the downstream column, 90% of the scour depth was achieved within 20 hours. Similarly, the results from the experiments on local scour indicated that the maximum scour depth occurred at the upstream column, when the spacing between two columns was \(2.5D\). The maximum value of local scour depth for the two-column case was observed about 18% higher than the value obtained for the single column case. The reasons for maximum scour depth at the spacing of \(2.5D\) were identified as the reinforcing effect of downstream column, the strong horseshoe vortex at upstream column, strong turbulence characteristics at the wake of upstream column, and the highest probability of occurrence of sweep events at upstream side of upstream column. Furthermore, a semi empirical equation was developed to predict the maximum scour depth as a function of the spacing between two
columns. The findings of this study can be used to facilitate the position of columns when scouring is a design concern.
ACKNOWLEDGMENT

This thesis could not be completed without the assistance, understanding and counselling of several people throughout the research work. I would like to express my sincere gratitude to my supervisors, Associate Professor Hadi Khabbaz and Professor Alireza Keshavarzi for their support and guidance during my PhD study. Apart from the academic supervision, inspiring suggestions for work-family life balance and future career development from my supervisors were the important factors for successful completion of my thesis.

I would like to express my sincere thanks to Dr. Behzad Fatahi for coordinating my Doctoral Assessment and for his valuable suggestions. I cannot forget external and internal assessors Dr. Farzad Meysami and Dr. Hamid Valipour, respectively for evaluating my Doctoral Assessment report and providing constructive recommendations. My sincere thanks also go to Professor Bruce W. Melville and Associate Professor James Ball for their great contributions and suggestions as co-authors for the publication of conference and Journal papers. Furthermore, I would like to thank Mr. Rami Haddad and Mr. David Hooper for their valuable support for smooth conduction of the experimental tests in the Hydraulics Laboratory. I would also like to thank my close friends Dr. Aslan Hokmabadi and Dr. Md. Mahbube Subhani for sharing their time and friendship to make a life more fun and easy.

I am greatly indebted to my parents, my brother Manoj and my sister Shanti for their love, support and encouragement. Without their many years of encouragement and support, I may never have reached where I am today. They always refuel me with courage and inspiration to overcome any hardship encountered in my life. Most importantly, I am extremely indebted to my wife Chandra Laxmi Shrestha for her great love, kind patience and invaluable support. Thank you very much for your sacrifice in shouldering far more than your fair share of parenting and for being a vital source of encouragement when I feel lack of faith and energy.

Finally, I would be remiss if I did not acknowledge my son Charchit and daughter Chaarvi for their understanding, love and affection throughout my PhD research.
LIST OF PUBLICATIONS BASED ON THIS RESEARCH

Peer-reviewed Conference Papers


CONTENTS

CERTIFICATE OF ORIGINAL AUTHORSHIP ........................................................ i

ABSTRACT .................................................................................................................. ii

ACKNOWLEDGMENT ................................................................................................ v

LIST OF PUBLICATIONS BASED ON THIS RESEARCH ................................. vi

CONTENTS ................................................................................................................... vii

LIST OF NOTATIONS ............................................................................................. xxiii

1. INTRODUCTION ..................................................................................................... 2

1.1 Background ............................................................................................................ 2

1.2 Research Objectives ............................................................................................. 5

1.3 Scope and Limitation of Research ...................................................................... 6

1.4 Research Significance and Innovation ............................................................... 6

1.5 Research Methodology ......................................................................................... 7

1.6 Synopsis of Thesis ............................................................................................... 8

2. LITERATURE REVIEW ......................................................................................... 11

2.1 Introduction .......................................................................................................... 11

2.2 Scour at Bridge Crossings .................................................................................... 11

  2.2.1 General Scour ................................................................................................... 12

  2.2.2 Localised Scour ................................................................................................ 13

2.3 Sediment Transport and Local Scour around Bridge Piers ................................ 13

  2.3.1 Basics of Sediment Transport ......................................................................... 13

  2.3.2 Local Scour around Bridge Piers ..................................................................... 24

Bridge Pier – Flow Interaction and Its Effect on the Process of Scouring
2.3.3 Mechanism of Local Scour ................................................................. 26
2.3.4 Parameters for Analysis of Pier Scour ............................................... 29
2.3.5 Factors Affecting the Local Scour at Bridge Site ................................. 31
2.3.6 Equilibrium Scour Depth ................................................................. 43
2.3.7 Temporal Variation of Scour Depth ..................................................... 44
2.3.8 Estimation of Equilibrium Scour Depth .............................................. 47
2.4 Open Channel Flow and Flow around Bridge Piers ................................. 58
  2.4.1 Hydraulics of Open Channel Flow ..................................................... 58
  2.4.2 Basic Equations for Flow in Open Channels ..................................... 60
  2.4.3 Boundary Layer in Open Channel Flow .......................................... 63
  2.4.4 Turbulence in Open Channel Flow .................................................. 65
  2.4.5 Flow around Bridge Piers ............................................................... 66
2.5 Summary and Identification of the Gap in Literature .............................. 78

3. EXPERIMENTAL SETUP AND METHODOLOGY ............................... 82
3.1 Introduction ............................................................................................. 82
3.2 Experimental Setup and Design ............................................................. 82
  3.2.1 Flume and its Components .............................................................. 82
  3.2.2 Electromagnetic Flow Meter ........................................................... 84
  3.2.3 Vernier Point Gauge ....................................................................... 84
  3.2.4 Model Columns of Bridge Piers ...................................................... 85
  3.2.5 Bed Materials ................................................................................ 86
3.2.6 Flow Conditions ........................................................................................................ 87

3.3 Velocity Measurement .................................................................................................. 89

3.3.1 Acoustic Doppler Velocimetry (ADV) .................................................................... 89

3.3.2 Particle Image Velocimetry (PIV) .......................................................................... 91

3.4 Experimental Procedure and Data Acquisition .......................................................... 94

3.4.1 Procedure for Fixed Bed Experiments in Flume 1 ................................................ 94

3.4.2 Procedure for Mobile Bed Experiments in Flume 1 ............................................. 97

3.4.3 Procedure for Fixed Bed Experiments in Flume 2 ............................................. 97

3.5 Summary ..................................................................................................................... 99

4. RESULTS AND DISCUSSION ON FLOW STRUCTURE ...................................... 102

4.1 Introduction ............................................................................................................... 102

4.2 Previous Investigations on Flow around Bridge Piers ........................................... 102

4.3 Flow around the Bridge Piers in Horizontal Plane .................................................. 106

4.3.1 Flow Pattern ....................................................................................................... 107

4.3.2 Three Dimensional Velocity Component ........................................................... 110

4.3.3 Turbulence Intensity ......................................................................................... 124

4.3.4 Turbulent Kinetic Energy .................................................................................. 132

4.3.5 Reynolds Shear Stresses .................................................................................. 135

4.4 Flow around the Bridge Piers in Vertical Plane ....................................................... 138

4.4.1 Flow Pattern ...................................................................................................... 140

4.4.2 Time Average Velocity Components ................................................................. 145
A.1 Plots of Velocity Components in Horizontal Plane ............................................... 243
A.2 Plots of Velocity Components for Vertical Plane ............................................... 274
A.3 Table of Results on Velocity Components ......................................................... 297

APPENDIX-B: PLOTS FOR TURBULENCE INTENSITIES ........................................ 303
B.1 Plots of Turbulence Intensity in Horizontal Plane ............................................... 303
B.2 Plots of Turbulence Intensity in Vertical Plane ..................................................... 324
B.3 Table of Results on Turbulence Intensity Components ........................................ 340

APPENDIX-C: PLOTS FOR TURBULENT KINETIC ENERGY .................................. 346
C.1 Plots of Turbulent Kinetic Energy in Horizontal Plane ....................................... 346
C.2 Plots of Turbulent Kinetic Energy in Vertical Plane ............................................. 355
C.3 Table of Results on Turbulent Kinetic Energy ..................................................... 363

APPENDIX-D: PLOTS FOR REYNOLDS STRESSES ........................................... 364
D.1 Profile Plots of Reynolds Stresses in Horizontal Plane ....................................... 364
D.2 Plots of Reynolds Stresses in Vertical Plane ....................................................... 368
D.3 Table of Results on Reynolds Shear Stresses ..................................................... 376

APPENDIX-E PLOTS FOR QUADRANT ANALYSIS .............................................. 378
E.1 Probability of Occurrence of the Events at Upstream and Downstream sides ...... 378
E.2 Profile Plots for Stress Fraction Contribution of the Events for the Production of
   Reynolds Stress ........................................................................................................ 388
LIST OF FIGURES

Figure 1.1 Bridge piers experiencing the flood events (USGS (2014)) ......................... 4
Figure 1.2 a) Scour around bridge piers on the Logan river, Australia; (Queensland Government (2013) ; and b) Scour around bridge piers on the Tinau river, Nepal, (KC (2014)) ................................................................................................................................ 4
Figure 1.3 A bridge over the Gaula river in India washed away by flood in July 2008, (Bhatia (2013)) ........................................................................................................................................ 5

Figure 2.1 Types of scour at a bridge, (after Melville and Coleman, 2000) ................. 11
Figure 2.2 Classification of scour (after Melville and Coleman, 2000) ......................... 12
Figure 2.3 Local scour at bridge piers; (Vasquz, 2006) .................................................. 13
Figure 2.4 Threshold condition for the sediment entrainment ..................................... 15
Figure 2.5 Shields diagram for incipient motion of sediment (after Simons and Senturk, 1992) ................................................................. 17
Figure 2.6 Shear velocity chart for quartz sediment in water at 20° C; (after Melville and Coleman, 2000) .................................................................................................................. 18
Figure 2.7 Definition sketch of suspended load transport; (after Van Rijn, 1993) ....... 22
Figure 2.8 Shape factor for different suspension numbers; (after Van Rijn, 1993) ....... 23
Figure 2.9 Local scour around bridge piers as a function of time; (after Richardson and Davis, 2001) ........................................................................................................ 25
Figure 2.10 Flow field around bridge piers, (Ettema et al., 2011) ................................. 27
Figure 2.11 Influence of flow shallowness on local scour depth, (after Melville and Coleman, 2000) ........................................................................................................ 33
Figure 2.12 Effect of sediment coarseness on local scour; (after Melville and Coleman, 2000) ........................................................................................................ 34
Figure 2.13 Effect of sediment non-uniformity on local scour at bridge piers under clear water condition; (after Melville and Coleman, 2000) ................................. 35
Figure 2.14 Variation of local scour depth with sediment non-uniformity, (after Melville and Coleman, 2000) ................................................................. 36
Figure 2.15 Basic pier shapes; (after Ettema et al., 2011) ........................................... 37
Figure 2.16 Variation of local scour depth with pier alignment; (after Melville and Coleman, 2000)..................................................................................... 38
Figure 2.17 Variation of local scour depth with flow intensity, V/Vc, (after Melville and Coleman, 2000)........................................................................... 39
Figure 2.18 Effect of flow intensity on local scour depth in uniform sediment (after Melville and Coleman, 2000)................................................................. 40
Figure 2.19 Effect of flow intensity on local scour depth in non-uniform sediment (after Melville and Coleman, 2000)........................................................................... 41
Figure 2.20 Variation of scour depth with Froude number; (after Ettema et al., 2006) 42
Figure 2.21 Time development of scour depth under clear water and live bed conditions; (after Ettema et al., 2011) ..................................................................... 43
Figure 2.22 Temporal development of scour depth; (after Melville and Chiew, 1999) 46
Figure 2.23 Notations for continuity equations; (after Chaudhry, 2007) ..................... 61
Figure 2.24 Notations for momentum equations and application; (after Chaudhry, 2007) ........................................................................................................ 61
Figure 2.25 Notations for energy equations ................................................................ 63
Figure 2.26 Development of boundary layer in open channel (Simons, 1992) .......... 64
Figure 2.27 Definition sketch of flow regions; (after Sumer and Fredsoe, 1997) ....... 69
Figure 2.28 Flow regimes around smooth circular cylinder in steady current, (Sumer and Fredsoe, 1997) ................................................................. 72
Figure 2.29 Definition sketch of flow interference region for two cylinders arrangements; (after Sumner, 2010) ................................................................. 73
Figure 2.30 Classification of flow regimes for two tandem cylinders; (after Sumner, 2010) ........................................................................................................ 73
Figure 2.31 Schematics of vortex shedding a) Prior to shedding of Vortex A, Vortex B is being drawn across the wake, b) Prior to shedding of Vortex B, Vortex C is being drawn across the wake (Sumer and Fredsoe, 1997) ........................................................ 77

Figure 2.32 Strouhal number as a function of Reynolds number; (Sumer and Fredsoe, 1997) ............................................................................................................................... 78

Figure 3.1 Schematic diagram of Flume 1 ................................................................. 83
Figure 3.2 Schematic diagram of Flume 2 ................................................................. 83
Figure 3.3 Electromagnetic flow meter (courtesy of Siemens)................................. 84
Figure 3.4 Vernier point gauge to measure the scour depth ..................................... 85
Figure 3.5 Model columns showing the spacing between them .............................. 85
Figure 3.6 Grain size distribution curve of the sand used ......................................... 87
Figure 3.7 Velocity measurement a) Acoustic Doppler Velocimeter (ADV) (SonTek (2012), and b) measuring velocity in laboratory ................................................................. 90
Figure 3.8 ADV probe and signal processor in splash proof housing (SonTek (2012)) 91
Figure 3.9 Schematic illustration of PIV system, (ILA-GmbH (2004)) ..................... 92
Figure 3.10 Digital charged coupled device (CCD) camera,(PCO-TECH (2008)) ...... 93
Figure 3.11 Laser source and the controlling system: a) laser head with mirrored arm (ILA-GmbH), and b) ICE450 power supply system (Quantel (2006)) ..................... 94
Figure 3.12 Measurement grid in horizontal plane (top view) ................................. 96
Figure 3.13 Different axes of PIV measurements (top view) .................................... 98

Figure 4.1 Definition sketch of the bridge piers arrangement ............................... 106
Figure 4.2 Schematic diagram of different axis of data analysis in horizontal planes 107
Figure 4.3 Flow pattern around a single column in horizontal plane at \( Z/h = 0.09 \) a) Vector plot, and b) Streamline plot ................................................................. 108
Figure 4.4 Flow pattern around two columns with $L/D = 3$ in horizontal plane at $Z/h = 0.09$ a) Vector plot, and b) Streamline plot................................................................. 109

Figure 4.5 Contour plots of streamwise velocity component for the single column case in different horizontal planes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ .. 111

Figure 4.6 Profile plots of streamwise velocity component for the single column case in different horizontal planes along three different longitudinal axes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ................................................................. 112

Figure 4.7 Contour plots of streamwise velocity component for two columns case with $L/D = 3$ in different horizontal planes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ........................................................................ 113

Figure 4.8 Profile plots of the streamwise velocity component for two-column case with $L/D = 3$ in different horizontal planes along three different longitudinal axes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ........................................................................ 113

Figure 4.9 Contour plots of transverse velocity component for the single column case in different horizontal planes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ..... 114

Figure 4.10 Profile plots of transverse velocity component for the single column case in different horizontal planes along three different longitudinal axes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ........................................................................ 115

Figure 4.11 Contour plots of transverse velocity component for the two-column case with $L/D = 3$ in different horizontal planes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ................................................................. 116

Figure 4.12 Profile plots of transverse velocity component for the two-column case with $L/D = 3$ in different horizontal planes along three different longitudinal axes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ........................................................................ 117

Figure 4.13 Contour plots of vertical velocity component for the single column case in different horizontal planes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ................................................................. 118

Figure 4.14 Profile plots of vertical velocity component for the single column case in different horizontal planes along three different longitudinal axes a) at $Z/h = 0.09$, b) at $Z/h = 0.26$ and c). at $Z/h = 0.54$ ................................................................. 119
Figure 4.15 Contour plots of vertical velocity component for the two-column case with L/D = 3 in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................. 122

Figure 4.16 Profile plots of vertical velocity component for the two-column case with L/D = 3 in different horizontal planes along three different longitudinal axes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................. 123

Figure 4.17 Contour plots of streamwise turbulence component for the single column case in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 124

Figure 4.18 Profile plots of streamwise turbulence intensity component for the single column case in different horizontal planes along three different longitudinal axes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 125

Figure 4.19 Contour plots of streamwise turbulence intensity component for the two-column case with L/D = 3 in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 126

Figure 4.20 Profile plots of streamwise turbulence intensity component for the two-column case with L/D = 3 in different horizontal planes along three different longitudinal axes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 127

Figure 4.21 Contour plots of transverse turbulence intensity component for the single column case in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 128

Figure 4.22 Contour plots of transverse turbulence intensity component for the two-column case with L/D = 3 in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 129

Figure 4.23 Contour plots of vertical turbulence intensity component for the single column case in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ................................................................................................. 130
Figure 4.24 Contour plots of vertical turbulence intensity component for the two-column case with L/D = 3 in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 .............................................................................................................................. 131

Figure 4.25 Contour plots of turbulent kinetic energy for the single column case in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ...... 134

Figure 4.26 Contour plots of turbulent kinetic energy for the two-column case with L/D = 3 in different horizontal planes a) at Z/h = 0.09, b) at Z/h = 0.26 and c). at Z/h = 0.54 ....................................................................................................................................... 135

Figure 4.27 Profile plots of Reynold shear stresses for the single column case in different horizontal planes along axis of symmetry a) in u-v plane, b) in u-w plane, and c) in v-w plane............................................................................................................... 136

Figure 4.28 Profile plots of Reynolds shear stresses for two-column case with L/D = 3 in different horizontal planes along axis of symmetry a) in u-v plane, b) in u-w plane, and c) in v-w plane ............................................................................................................................................... 137

Figure 4.29 Schematic diagram of different axis of data analysis at upstream and downstream side of the columns in vertical planes (US, B and DS stand for upstream side, between and downstream side of the columns, respectively) .............. 139

Figure 4.30 Vector plots for single column a) vertical plane at Y/D = 0, and b) vertical plane at Y/D = 1.25 ............................................................................................................................................................. 142

Figure 4.31 Vector plots for two columns cases with L/D = 3 a) vertical plane at Y/D = 0, and b) vertical plane at Y/D = 1.25 ............................................................................................................................................... 143

Figure 4.32 Streamline plots for single column a) vertical plane at Y/D = 0, and b) vertical plane at Y/D = 1.25 ............................................................................................................................................... 144

Figure 4.33 Streamline plots for two columns cases with L/D = 3 a) vertical plane at Y/D = 0, and b) vertical plane at Y/D = 1.25 ............................................................................................................................................... 145

Figure 4.34 Contour plots of streamwise velocity component for the single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ........................................................................................................ 146

Figure 4.35 Profile plots of streamwise velocity component for the single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side ......... 147

Bridge Pier – Flow Interaction and Its Effect on the Process of Scouring xvii
Figure 4.36 Contour plots of streamwise velocity component for the case of two in-line columns with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ................................................................. 149

Figure 4.37 Profile plots of streamwise velocity component for two columns case with L/D = 3 in vertical plane at axis of symmetry a) upstream side; b) downstream side . 150

Figure 4.38 Profile plots of velocity components between two columns with L/D = 3 in vertical plane at axis of symmetry a) streamwise component, b) vertical component . 150

Figure 4.39 Contour plots of vertical velocity component for single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ...................................................... 152

Figure 4.40 Profile plots of vertical velocity component for single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side ................. 153

Figure 4.41 Contour plots of vertical velocity component for the two-column case with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ..................... 154

Figure 4.42 Profile plots of vertical velocity component for the two-column case with L/D = 3 in vertical plane at axis of symmetry a) upstream side; b) downstream side . 155

Figure 4.43 Profile plots of velocity components between two columns with L/D = 3 in vertical plane at axis of symmetry a) streamwise component, b) vertical component . 156

Figure 4.44 Contour plots of streamwise turbulence intensity component for the single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 .............. 157

Figure 4.45 Profile plots of streamwise turbulence intensity component for the single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side ......................................................................................................................... 158

Figure 4.46 Contour plots of streamwise turbulence intensity component for two columns case with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ......................................................................................................................... 159

Figure 4.47 Profile plots of streamwise turbulence intensity component for two-column case with L/D = 3 in vertical plane at axis of symmetry a) upstream side, b) downstream side, and c) between two columns ......................................................................................... 161
Figure 4.48 Contour plots of vertical turbulence intensity component for the single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ........................................162

Figure 4.49 Profile plots of vertical turbulence intensity component for the single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side .................................................................163

Figure 4.50 Contour plots of vertical turbulence intensity component for two columns case with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25........164

Figure 4.51 Profile plots of vertical turbulence intensity component for the case of two in-line columns with L/D = 3 in vertical plane at axis of symmetry a) upstream side, b) downstream side, and c) between two columns.................................................................165

Figure 4.52 Contour plots of turbulent kinetic energy for the single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ........................................167

Figure 4.53 Profile plots of turbulent kinetic energy for the single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side.................................168

Figure 4.54 Contour plots of turbulent kinetic energy for the two-column case with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25.........................169

Figure 4.55 Profile plots of turbulent kinetic energy for the case of two in-line columns with L/D = 3 in vertical plane at axis of symmetry a) upstream side, b) downstream side, and c) between two columns.................................................................170

Figure 4.56 Contour plots of Reynolds shear stress for the single column case in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25 ........................................171

Figure 4.57 Profile plots of Reynolds shear stress for the single column case in vertical plane at axis of symmetry a) upstream side; b) downstream side.................................172

Figure 4.58 Contour plots of Reynolds shear stress for the case of two in-line columns with L/D = 3 in different vertical planes a) at Y/D = 0, and b) at Y/D = 1.25.............173

Figure 4.59 Profile plots of Reynolds shear stress for the two-column case with L/D = 3 in vertical plane at axis of symmetry a) upstream side, b) downstream side, and c) between two columns.................................................................174
Figure 4.60 Definition sketch of four quadrant zones in u-w plane..............................177

Figure 4.61 Profile plots of probability of occurrence of different quadrants at upstream side (US1) for single column case ........................................................................................................183

Figure 4.62 Profile plots of probability of occurrence of different quadrants at downstream side (DS1) for single column case ..........................................................................................183

Figure 4.63 Profile plots of probability of occurrence of different quadrants at upstream side (US1) of Column 1 for the twocolumn case with L/D = 3 .............................................185

Figure 4.64 Profile plots of probability of occurrence of different quadrants at downstream side (DS1) of Column 2 for two columns case with L/D = 3 ..............................186

Figure 4.65 Profile plots of probability of occurrence of different quadrants between two columns (at B1) with L/D = 3 ........................................................................................................186

Figure 4.66 Profile plots for contribution of stress fraction of different quadrants for the production of Reynolds stress at upstream side of single column ........................................188

Figure 4.67 Profile plots for contribution of stress fraction of different quadrants for the production of Reynolds stress at downstream side of single column ........................188

Figure 4.68 Profile plots for contribution of stress fraction of different quadrants for the production of Reynolds stress at upstream side of Column 1 for two columns case with L/D = 3 .............................................................190

Figure 4.69 Profile plots for contribution of stress fraction of different quadrants for the production of Reynolds stress at downstream side of Column 2 for two columns case with L/D = 3 .................................................................................................190

Figure 4.70 Profile plots for contribution of stress fraction of different quadrants for the production of Reynolds stress between two columns with L/D = 3 ..............................191

Figure 5.1 Temporal development of scour depth at Column 1 for a single column and two columns with L/D = 1, 2 & 3; Time, t = 72-75 hours and V/Vc = 0.74. .................200

Figure 5.2 Temporal development of scour depth at Column 2 for a single column and two columns with L/D = 2 & 3; Time, t = 72-75 hours and V/Vc = 0.74. .................201
Figure 5.3 Scour depths at upstream column (Column 1) for different spacing between two columns ........................................................................................................................................203

Figure 5.4 Scour depths at downstream column (Column 2) for different spacing between two columns ........................................................................................................................................204

Figure 5.5 Comparison of predicted and observed scour depths for two-column bridge piers ..................................................................................................................................................210

Figure 5.6 Length scale of scour profile (Ahmed (1995)) ........................................................................................................................................211

Figure 5.7 Scour profile for different column spacing ........................................................................................................................................212

Figure 5.8 Variation of width of the scour hole for different spacing between two columns ........................................................................................................................................214

Figure 5.9 Predicted and observed to width of the scour hole ........................................................................................................................................215
LIST OF TABLES

Table 2.1 Classification of local scour processes at bridge piers (after Melville and Coleman, 2000) ........................................................................................................................................................................32

Table 2.2 Shape factors for different nosed shape piers; (after Richardson and Davis, 2001) ........................................................................................................................................................................37

Table 2.3 List of previous equations for scour depth (after Ettema et al. 2011) ........48

Table 2.4 Different correction factors of Equation 2.38 (after Melville and Coleman, 2000) ........................................................................................................................................................................52

Table 2.5 Shape factor (K_a,K_a) for multiple columns aligned in a row (after Melville and Coleman, 2000) ........................................................................................................................................................................54

Table 2.6 Correction factor K1 for pier nose shape (after Richardson and Davis, 2001) ........................................................................................................................................................................55

Table 2.7 Correction factor K2 for angle of attack (after Richardson and Davis, 2001) 55

Table 2.8 Correction factor K3 for bed condition (after Richardson and Davis, 2001) . 56

Table 3.1 Specification of bed material .......................................................................... 86

Table 3.2 Flow conditions for experimental tests ........................................................... 88

Table 5.1 Time for equilibrium scour depth and time factor K_t ................................... 202

Table 5.2 Test results for different piers arrangements.................................................. 205

Table 5.3 Model constants ............................................................................................ 207
# LIST OF NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Edge of the bed layer at $z=a$</td>
</tr>
<tr>
<td>$C'$</td>
<td>Chezy coefficient related to sediment grain</td>
</tr>
<tr>
<td>$C_{1}$</td>
<td>Column at upstream side (Column 1)</td>
</tr>
<tr>
<td>$C_{2}$</td>
<td>Column at downstream side (Column 2)</td>
</tr>
<tr>
<td>$C_{c}$</td>
<td>Coefficient of curvature</td>
</tr>
<tr>
<td>$C_{d}$</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>$C_{u}$</td>
<td>Coefficient of uniformity</td>
</tr>
<tr>
<td>$c$</td>
<td>Sediment concentration</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of a pier</td>
</tr>
<tr>
<td>$D_{p}$</td>
<td>Projected width of a pier</td>
</tr>
<tr>
<td>$d$</td>
<td>Size of the sediment particle</td>
</tr>
<tr>
<td>$d^\ast$</td>
<td>Dimensionless particle parameter</td>
</tr>
<tr>
<td>$d_{1}$</td>
<td>Equilibrium depth for single column bridge pier</td>
</tr>
<tr>
<td>$d_{50}$</td>
<td>Mean grain size of the sediment</td>
</tr>
<tr>
<td>$d_{i}$</td>
<td>Depth of scour at any time</td>
</tr>
<tr>
<td>$d_{se1}$</td>
<td>Equilibrium depth of scour at Column 1</td>
</tr>
<tr>
<td>$d_{se2}$</td>
<td>Equilibrium depth of scour at Column 2</td>
</tr>
<tr>
<td>$F$</td>
<td>Dimensionless shape factor of sediment</td>
</tr>
</tbody>
</table>
\[ F_e = \text{Coulomb force of resistance} \]
\[ F_d = \text{Drag force} \]
\[ F_g = \text{Submerged weight of a particle} \]
\[ Fr = \text{Froude number} \]
\[ f = \text{Frequency of vortex shedding} \]
\[ G = \text{Parameter describing the effects of lateral distribution of flow in the approach channel and the cross sectional shape of the approach channel} \]
\[ g = \text{Acceleration due to gravity} \]
\[ H = \text{Hole size (threshold level for bursting process)} \]
\[ h = \text{Depth of flow} \]
\[ I_e = \text{Sorting function for ejection event} \]
\[ I_s = \text{Sorting function for sweep event} \]
\[ K_{Gmn} = \text{Correction factor proposed by Ataie-Ashtiani and Beheshti (2006)} \]
\[ K_I = \text{Flow intensity parameter} \]
\[ K_{s1} = \text{Column-spacing factor for Column 1} \]
\[ K_{s2} = \text{Column-spacing factor for Column 2} \]
\[ K_{sh} = \text{Shape parameter of a pier} \]
\[ K_t = \text{Time factor for equilibrium scour depth} \]
\[ K_w = \text{Adjustment factor for wide pier} \]
\( K_a \) = Angle of flow attack parameter of a pier

\( k_s \) = roughness height

\( L \) = Centre to centre distance between two columns

\( L' \) = Length of the pier / Distance between two-column measured outer to outer face of the columns.

\( m \) = Number of piles in line with flow as in Ataie-Ashtiani and Beheshti (2006)

\( n \) = Number of piles normal to the flow as in Ataie-Ashtiani and Beheshti (2006)

\( n_e, n_k \) = Dimensionless number to find the roughness height

\( P_i \) = Probability of occurrence of the events, where \( i = 1, 2, 3 \) and \( 4 \)

\( Q_i \) = Quadrant zones, where, \( i = 1, 2, 3 \) and \( 4 \)

\( q \) = The rate of local scour in volume per unit time

\( q_1 \) = The rate at which sediment is transported out from the scour hole in volume per unit time

\( q_2 \) = The rate at which sediment is supplied to the scour hole in volume per unit time

\( q_b \) = Rate of bed load transport

\( q_b^* \) = Dimensionless Einstein number to quantify bed load transport

\( q_s \) = Rate of suspended load transport

\( R \) = Radius of the vortex

\( Re \) = Reynolds number

\( Rel \) = Reynolds number with respect to length of boundary layer
\( S \) = Bed slope

\( S_i \) = Stress fraction, where \( i = 1, 2, 3 \) and \( 4 \)

\( St \) = Strouhal number

\( s \) = Specific gravity of the water

\( s' \) = Submerged specific gravity of sediment particle

\( s_s \) = Specific gravity of the sediment

\( T \) = Dimensionless transport stage parameter

\( TI_u \) = Turbulence intensity component in stream-wise direction (x-direction)

\( TI_v \) = Turbulence intensity component in transverse direction (y-direction)

\( TI_w \) = Turbulence intensity component in vertical direction (z-direction)

\( TKE \) = Turbulence kinetic energy

\( t_e \) = Time to develop equilibrium scour depth

\( u \) = Velocity component in stream-wise direction (x-direction)

\( u_* \) = Bed shear velocity

\( u_c \) = Critical shear velocity

\( u' \) = Fluctuating component of velocity in stream-wise direction (x-direction)

\( V \) = Mean approach flow velocity

\( \bar{V} \) = Depth averaged velocity of fluid
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_a$</td>
<td>Critical mean flow velocity for armour peak</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Critical mean flow velocity for sediment entrainment</td>
</tr>
<tr>
<td>$V_{lp}$</td>
<td>Live bed peak velocity of flow</td>
</tr>
<tr>
<td>$V_\theta$</td>
<td>Tangential vortex velocity = $\omega_0 R$</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity component in transverse direction (y-direction)</td>
</tr>
<tr>
<td>$v'$</td>
<td>Fluctuating component of velocity in transverse direction (y-direction)</td>
</tr>
<tr>
<td>$w$</td>
<td>Velocity component in vertical direction (z-direction)</td>
</tr>
<tr>
<td>$w'$</td>
<td>Fluctuating component of velocity in vertical direction (z-direction)</td>
</tr>
<tr>
<td>$w_s$</td>
<td>Top width of the scour hole</td>
</tr>
<tr>
<td>$x$</td>
<td>Distance measured in stream-wise direction</td>
</tr>
<tr>
<td>$y$</td>
<td>Distance measured in transverse direction</td>
</tr>
<tr>
<td>$Z, Z'$</td>
<td>Sediment number</td>
</tr>
<tr>
<td>$z$</td>
<td>Distance measured in vertical direction</td>
</tr>
<tr>
<td>$\Gamma'$</td>
<td>Vortex strength</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Thickness of boundary layer</td>
</tr>
<tr>
<td>$\mu_c$</td>
<td>Coulomb friction coefficient</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity of fluid</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of fluid</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Density of sediment material</td>
</tr>
<tr>
<td>( \sigma_g )</td>
<td>Geometric standard deviation of the sediment</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Bed shear stress</td>
</tr>
<tr>
<td>( \tau_* )</td>
<td>Dimensionless critical shear stress parameter (Shields parameter)</td>
</tr>
<tr>
<td>( \tau_c )</td>
<td>Critical shear stress</td>
</tr>
<tr>
<td>( \tau_{uv} )</td>
<td>Reynolds shear stress component in ( uv ) direction</td>
</tr>
<tr>
<td>( \tau_{uw} )</td>
<td>Reynolds shear stress component in ( uw ) direction</td>
</tr>
<tr>
<td>( \tau_{vw} )</td>
<td>Reynolds shear stress component in ( vw ) direction</td>
</tr>
<tr>
<td>( \psi )</td>
<td>Correction factor for stratification</td>
</tr>
<tr>
<td>( \omega_0 )</td>
<td>Angular velocity of revolution</td>
</tr>
</tbody>
</table>