

Contents

| | | |
|----------------------------------|--|-----------------|
| Acknowledgement | | ix |
| Table of Contents | | x |
| List of Figures | | xiv |
| List of Tables | | xix |
| Symbols and Abbreviations | | xx |
| Preface | | xxiii |
| Chapter 1 | Introduction | Page no. |
| | 1.1 General | 1 |
| | 1.2 Scouring | 4 |
| | 1.3 Effects of collar on scouring | 4 |
| | 1.4 Morphology of channel | 5 |
| | 1.5 Organization of thesis | 7 |
| Chapter 2 | Literature review | |
| | 2.1 General | 8 |
| | 2.2 Experiment work related to scouring around hydraulics structure | 8 |
| | 2.3 Analytical and Numerical Approach to study fluid flow characteristics around structure | 16 |
| | 2.4 Energy loss in channel | 23 |
| | 2.5 Preventive measurement of scouring | 27 |
| | 2.6 Critical Observation | 35 |
| | 2.7 Scope of the present investigation | 35 |
| Chapter 3 | Experimental investigation | |
| | 3.1 General | 36 |
| | 3.2 Description of Experimental flume | 37 |

| | | |
|---------|--|----|
| 3.2.1 | Flow Recirculating System | 38 |
| 3.2.2 | Measurement of Discharge and depth of Water | 39 |
| 3.2.3 | Measurement devices of Flow Velocity and Direction | 41 |
| 3.2.4 | Preparation of fume bed | 42 |
| 3.3 | Model of Slender Structure | 43 |
| 3.4 | Brief description of Experimental Procedures and Program of Test | 45 |
| 3.5 | Experimental study on scouring around slender structure | 47 |
| 3.5.1 | Scouring of sand bed of slender structure | 47 |
| 3.5.1.1 | Scour depth variation around cylindrical shape pier | 48 |
| 3.5.1.2 | Scour depth variation around rectangular shape pier | 55 |
| 3.5.1.3 | Scour depth variation around oval shape pier | 58 |
| 3.5.2 | Effect of shape and size of slender structure on scour depth | 61 |
| 3.5.2.1 | Contour of scour hole and schematic representation of development of scouring | 65 |
| 3.5.3 | Parametric study of Non-dimensional Scour depth around slender structure | 69 |
| 3.5.3.1 | Variation of Non-dimensional Scour depth around piers model | 72 |
| 3.5.4 | Visualization of vortex motion around pier model | 76 |

| | | |
|------------------|---|-----|
| | 3.5.5 Flow characteristics and sand bed formation in flume | 82 |
| | 3.5.6 Explanation on Development of scour hole | 84 |
| 3.6 | Experimental study on scouring around slender structure fitted with collar | 85 |
| | 3.6.1 Brief Description of experimental procedures | 86 |
| | 3.6.2 Test Program | 86 |
| | 3.6.3 Effect of collar size on scouring | 89 |
| | 3.6.4 Explanation on Development of scour hole with collar | 93 |
| Chapter 4 | Mathematical modelling | |
| 4.1 | General | 96 |
| 4.2 | Influence of Slender Structure in Channel Section | 97 |
| | 4.2.1 Efficiency of channel section with slender obstruction in flow path | 97 |
| | 4.2.1.1 Rectangular channel section with slender barrier | 98 |
| | 4.2.1.2 Trapezoidal channel section with slender barrier | 101 |
| | 4.2.2 Energy of flow in channel section with slender obstruction in flow path | 105 |
| | 4.2.2.1 Rectangular channel section with slender obstruction | 105 |
| 4.3 | Flow behavior around slender structure | 109 |
| | 4.3.1 Flow behavior around cylindrical obstruction | 111 |

| | | |
|------------------|--|-----|
| | 4.3.2 Flow characteristics around slender structure with multiple obstruction in flow path | 117 |
| | 4.4 Influence of slender structure in erodible channel section | 124 |
| | 4.4.1 Scouring of channel section around cylindrical pier | 124 |
| | 4.4.2 Bed shear stress | 128 |
| | 4.5 Bed shear stresses and pier shear stress | 129 |
| Chapter 5 | Study of Ganga river morphology at Varanasi | |
| | 5.1 General | 133 |
| | 5.2 Description of area selected for morphological study | 134 |
| | 5.3 Methodology adopted | 137 |
| | 5.4 Influence of Viswasundari Bridge piers on morphology | 138 |
| | 5.4.1 Morphological change of Ganga River at Varanasi | 145 |
| Chapter 6 | Conclusion | |
| | 6.1 General | 152 |
| | 6.2 Concluding remarks | 152 |
| | Scope of future study | 154 |
| | References | 155 |
| | Author's Biography | |
| | Reprint | |

List of Figures

| | | |
|-------------|--|-----------|
| Figure 3.1 | Photograph of Experimental Flume | 38 |
| Figure 3.2 | Schematic Sketch of Experimental setup | 38 |
| Figure 3.3 | Flow recirculating system | 39 |
| Figure 3.4 | Venturi Meter | 40 |
| Figure 3.5 | Point gauge on sliding platform | 41 |
| Figure 3.6 | Acoustic Doppler Velocity (ADV) setup | 42 |
| Figure 3.7 | View of sand bed | 43 |
| Figure 3.8 | Cylindrical pier model | 44 |
| Figure 3.9 | Rectangular pier model | 44 |
| Figure 3.10 | Oval shape pier | 45 |
| Figure 3.11 | Piers embedded in sand bed | 46 |
| Figure 3.12 | Scour depth variation for cylindrical pier (d= 2.25 cm) of different discharges with time | 48- 49 |
| Figure 3.13 | Scour depth variation for cylindrical pier (d= 3.18 cm) of different discharges with time | 50- 51 |
| Figure 3.14 | Scour depth variation for cylindrical pier (d= 3.86 cm) of different discharges with time | 52- 53 |
| Figure 3.15 | Scour depth variation for cylindrical pier (d= 4.38 cm) of different discharges with time | 54- 55 |
| Figure 3.16 | Scour depth variation for Rectangular pier (R1 = 3.38 X 3.04 cm) for different discharges with time | 55- 56 |
| Figure 3.17 | Scour depth variation for Rectangular pier (R2 = 4.38 X 4.04 mm) of different discharges with time | 57- 58 |
| Figure 3.18 | Scour depth variation for Oval pier (O1 = 2.9 X 1.5 cm) of different discharges with time | 58- 59 |
| Figure 3.19 | Scour depth variation for Oval pier (O2 = 4.7 X 3 cm) of different discharges with time | 60- 61 |

| | | |
|-------------|--|-----------|
| Figure 3.20 | Comparison of scour depth between Cylindrical (diameter 3.18 cm) and Rectangular (3.38 X 3.04 cm) pier with different discharges with time | 62 |
| Figure 3.21 | Comparison of scour depth between Cylindrical (diameter 2.25 cm) and Oval (2.9 X 1.5 cm) pier for different discharges with time | 62 |
| Figure 3.22 | Comparison of scour depth between Rectangular (3.38 X 3.04 cm) and Oval (4.7 X 3 cm) for different discharges with time | 63 |
| Figure 3.23 | Equilibrium scour depth around cylindrical pier | 63- 64 |
| Figure 3.24 | Contour of cylindrical pier for scouring, (b): Scouring sketch diagram of Contour for cylindrical pier | 66 |
| Figure 3.25 | Contour of rectangular pier for scouring, (b): Scouring sketch diagram of Contour for rectangular pier | 67 |
| Figure 3.26 | (a) Contour of Oval pier for scouring, (b): Scouring sketch diagram of Contour for oval pier | 68 |
| Figure 3.27 | Variation of (D_{se}/d) vs $(V_{av.}/V_{app.})$ of Cylindrical Piers with different discharges | 72 |
| Figure 3.28 | Variation of (D_{se}/d) vs $(V_{av.}/V_{app.})$ of Rectangular Piers (1 & 2) with different discharges | 72 |
| Figure 3.29 | Variation of (D_{se}/d) vs $(V_{av.}/V_{app.})$ of Oval Piers (1 & 2) with different discharges | 73 |
| Figure 3.30 | Variation of (D_{se}/d) with y/b of Cylindrical Piers with different discharges | 73 |
| Figure 3.31 | Variation of D_{se}/d with y/b of Rectangular Piers with different discharges | 74 |
| Figure 3.32 | Variation of D_{se}/d with y/b of oval piers for different discharges | 74 |

| | | |
|-------------|---|-----------|
| Figure 3.33 | Variation of (D_{se}/d) with Q/b of Cylindrical Piers with different discharges | 74 |
| Figure 3.34 | Variation of D_{se}/d with Q/b of Rectangular Piers (1 & 2) for different discharges | 75 |
| Figure 3.35 | Variation of D_{se}/d with Q/b of oval piers (1 & 2) for different discharges | 75 |
| Figure 3.36 | Visualization of vortex motion around cylindrical slender structure | 77- 78 |
| Figure 3.37 | Visualization of vortex motion around rectangular slender structure | 79- 80 |
| Figure 3.38 | Visualization of vortex motion around oval slender structure | 80- 81 |
| Figure 3.39 | Scour pattern with mounds (a), depressions and ripples (b, c) at the end of the channel | 82- 83 |
| Figure 3.40 | Schematic illustration of the scour hole development for the plain pier: (a) Scour pattern and (b) Sketches of the scour hole with time | 84 |
| Figure 3.41 | View of scour hole around circular pier fitted with collar | 86 |
| Figure 3.42 | Schematic diagram of pier with collar | 89 |
| Figure 3.43 | Variation of maximum scour depth upstream of the pier for different discharges | 89- 90 |
| Figure 3.44 | Logarithmic Variation of maximum scour depth with time for different discharges | 91- 92 |
| Figure 3.45 | Experimental picture of (a) a pier fitted with collar (b) a pier without collar | 45- 93 |
| Figure 3.46 | Schematic diagram of development of scour hole with time (a & b) | 93- 94 |
| Figure 4.1 | Cross section of rectangular shape open channel with n - number barriers | 98 |

| | | |
|-------------|--|-------------|
| Figure 4.2 | Economical Depth of flow with obstruction factor α in rectangular channel section | 101 |
| Figure 4.3 | Cross section of Trapezoidal shape open channel with n - number of barriers | 102 |
| Figure 4.4 | Economical depth for different obstruction factor | 105 |
| Figure 4.5 | Energy of flow with depth of flow for $\alpha=0.05$ | 108 |
| Figure 4.6 | Energy of flow with depth of flow for $\alpha=0.1$ | 108 |
| Figure 4.7 | Cylindrical structure inside the computational domain | 112 |
| Figure 4.8 | Flow field around cylindrical pier at a plane 0.1m from bed level | 114 |
| Figure 4.9 | Flow filed around cylindrical structure of diameter 0.1 m | 114- 115 |
| Figure 4.10 | Flow filed around cylindrical structure of diameter 0.2 m | 115- 116 |
| Figure 4.11 | Flow filed around cylindrical structure of diameter 0.3 m | 116- 117 |
| Figure 4.12 | Computational domain of piers | 118 |
| Figure 4.13 | Velocity contour around multiple slender structures | 119- 120 |
| Figure 4.14 | Pressure contour around multiple slender structures | 120- 121 |
| Figure 4.15 | Pressure variation at 0.2m downstream of the piers line | 122 |
| Figure 4.16 | Pressure variation at 0.2m upstream of the piers line | 123 |
| Figure 4.17 | Turbulence kinetic energy | 123 |
| Figure 4.18 | Pier embedded in sand bed in model | 125 |
| Figure 4.19 | Scour depth around pier model of diameter 2.25cm | 126 |
| Figure 4.20 | Scour hole for circular pier of diameter 3.18 cm | 127 |
| Figure 4.21 | Maximum scour depth with discharge | 128 |
| Figure 4.22 | Maximum bed shear stress with mean velocity | 129 |

| | | |
|-------------|---|---------|
| Figure 4.23 | Channel cross section with pier at the middle of the channel | 130 |
| Figure 4.24 | Bed shear stress at mid of rectangular channel with mean velocity of flow | 130 |
| Figure 4.25 | Maximum bed shear stress variation with mean flow velocity for rectangular channel section | 131 |
| Figure 4.26 | Maximum shear stress variation at pier surface with mean flow velocity in rectangular channel section | 131 |
| Figure 4.27 | Maximum bed shear stress variation with mean velocity | 132 |
| Figure 4.28 | Maximum pier shear stress variation with mean velocity | 132 |
| Figure 5.1 | The River Ganga basin | 135 |
| Figure 5.2 | Satellite image of River Ganga near Varanasi with meander bend | 136 |
| Figure 5.3 | Two Reverse bend near Varanasi Bend1 and Bend2 | 136 |
| Figure 5.4 | Determination of radius of curvature | 137 |
| Figure 5.5 | Satellite image of Viswasundari Bridge on Ganga River at Varanasi | 139 |
| Figure 5.6 | Photograph of Viswasundari Bridge with bridge piers | 139 |
| Figure 5.7 | Planform of the Ganga river in downstream of Viswasundari bridge | 140 |
| Figure 5.8 | Ganga river at four different cross section downstream of Viswasundari bridge | 141-144 |
| Figure 5.9 | Historical and recent courses of the River Ganga, 1988–2013. | 145 |
| Figure 5.10 | Movement of the meander bends of the River Ganga at Varanasi [2002-2013]. | 146 |
| Figure 5.11 | Sand deposition on Bend1 in year 2001 | 148 |
| Figure 5.12 | Sand deposition on Bend1 in year 2012 | 148 |
| Figure 5.13 | Comparison of sand deposition at both bends in bank of Ganga River at Varanasi. | 151 |

List of Tables

| | | |
|------------|--|-----|
| Table 3.1 | Analysis data for Pier 1 | 69 |
| Table 3.2 | Analysis data for Pier 2 | 69 |
| Table 3.3 | Analysis data for Pier 3 | 70 |
| Table 3.4 | Analysis data for Pier 4 | 70 |
| Table 3.5 | Analysis data for Pier 5 | 70 |
| Table 3.6 | Analysis data for Pier 6 | 71 |
| Table 3.7 | Analysis data for Pier 7 | 71 |
| Table 3.8 | Analysis data for Pier 8 | 71 |
| Table 3.9 | Summary of Test Program | 88 |
| Table 4.1: | Input parameters | 125 |
| Table 4.2: | Output Parameters for pier diameter 2.25cm | 126 |
| Table 4.3: | Output Parameters for pier diameter 3.18cm | 126 |
| Table 4.4: | Output Parameters for rectangular pier 3.38 x 3.04m | 127 |
| Table 4.5: | Comparative result of experimental study and HEC-RAS | 128 |
| Table 5.1: | Siltation on downstream and upstream side | 149 |
| Table 5.2: | Variation of sinuosity and sand deposition from 2002 to 2013. | 150 |

List of Symbols and Abbreviations

List of symbols

| | |
|--|-----------|
| Strouhal number | St |
| Drag coefficient , | C_D |
| RMS lift coefficient | C_L |
| multiple channel roughness coefficient Manning's | n |
| Chezy's | C |
| Darcy-Weisbatch coefficient | f |
| Scour depth | D_{sc} |
| Equilibrium Scour depth | D_{se} |
| Pier diameter | D |
| Discharge | Q |
| Depth of flow | Y |
| Channel width | B |
| Froude no. | F_r |
| Average velocity | V_{av} |
| Approach velocity | V_{app} |
| Per unit width of discharge | Q/b |
| Collar width | W |

| | |
|--|----------|
| Collar elevation relative to the channel bed | y_c |
| % Finer | N |
| Corresponds to 50% of the sample finer in weight on the grain size distribution curve. | D_{50} |
| Median particle size | d_{50} |
| Coefficient of uniformity | C_u |
| Coefficient of curvature | C_c |
| List of abbreviation | |
| Computational Fluid Dynamics | CFD |
| Acoustic-Doppler Velocity-Profilers | ADV |
| Shallow Water Equations | SWEs |
| Mean/Root-Mean-Square | RMS |
| Root Mean Squared Error | RMSE |
| Surface Gradient Upwind Method | SGUM |
| Generalised Likelihood Uncertainty Estimation | GLUE |
| Hydrologic Engineering Center's River Analysis System | HEC-RAS |
| Large-Eddy Simulation | LES |
| Shiono and Knight Method | SKM |

| | |
|---|------|
| Horseshoe Vortex | HV |
| Partially Averaged Navier–Stokes approach | PANS |
| Reynolds Averaged Navier–Stokes | RANS |
| Horse Power | HP |