

**EXPERIMENTAL INVESTIGATION OF LOCAL SCOUR AROUND TWO  
PIERS IN TANDEM ARRANGEMENTS FOR DIFFERENT NOSE SHAPES**

M.Sc. Engineering Thesis

By

**Md. Mukdiul Islam**

Student ID: 1018162013 P



**DEPARTMENT OF WATER RESOURCES ENGINEERING  
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY  
DHAKA-1000, BANGLADESH**

**JULY 2023**

**EXPERIMENTAL INVESTIGATION OF LOCAL SCOUR AROUND TWO  
PIERS IN TANDEM ARRANGEMENTS FOR DIFFERENT NOSE SHAPES**

Submitted by

**MD. MUKDIUL ISLAM**

Student ID: 1018162013 P

In Partial fulfillment of the requirements for the degree of  
**MASTER OF SCIENCE IN WATER RESOURCES ENGINEERING**



**DEPARTMENT OF WATER RESOURCES ENGINEERING  
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY  
DHAKA-1000, BANGLADESH**

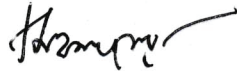
**JULY 2023**



## CERTIFICATION OF APPROVAL

The thesis titled “EXPERIMENTAL INVESTIGATION OF LOCAL SCOUR AROUND TWO PIERS IN TANDEM ARRANGEMENTS FOR DIFFERENT NOSE SHAPES” submitted by Md. Mukdiul Islam, Roll No. 1018162013 P, Session: October 2018, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Science in Water Resources Engineering** on **22<sup>nd</sup> July, 2023**.

## BOARD OF EXAMINERS



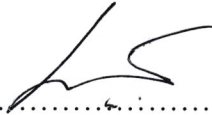
.....  
Dr. Badal Mahalder  
Associate Professor  
WRE, BUET, Dhaka

Chairman  
(Supervisor)



.....  
Dr. Nasreen Jahan  
Professor and Head  
WRE, BUET, Dhaka

Member  
(Ex-officio)



.....  
Dr. Md. Abdul Matin  
Professor  
WRE, BUET, Dhaka

Member



.....  
Dr. Aysha Akter  
Professor  
Department of Civil Engineering, Chittagong University of  
Engineering & Technology, Chittagong

Member  
(External)

## **CANDIDATE'S DECLARATION**

This is hereby declared that this thesis entitled “**Experimental Investigation of Local Scour Around Two Piers in Tandem Arrangements for Different Nose Shapes**” is the outcome of research carried out by me under the supervision of Dr. Badal Mahalder, Associate Professor, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology, Dhaka. I do hereby declare that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma from any other institution.

Signature of the Candidate



-----  
Md. Mukdiul Islam

*Dedicated to My Parents*

## **ACKNOWLEDGEMENT**

I would like to acknowledge and give my warmest thank to my supervisor, Dr. Badal Mahalder, Associate Professor, Department of Water Resources Engineering (WRE), Bangladesh University of Engineering and Technology (BUET), Dhaka, for his constant supervision, guidance, support and motivation throughout the entire research work.

I would like to express my gratitude to the members of the Board of Examination, Dr. Md. Abdul Matin, Professor, Department of WRE, BUET, Dr. Nasreen Jahan, Professor and Head, Department of WRE, BUET, and Dr. Aysha Akter, Professor, Department of Civil Engineering, CUET for their kind review and constructive suggestions regarding this thesis work.

I would like to express my gratitude to the Department of Water Resources Engineering at BUET for allowing me to perform this research in the "Hydraulics and River Engineering Laboratory".

## ABSTRACT

A popular configuration for studying complex flow characteristics and local scour around groups of piers by using piers arranged in tandem configurations or side-by-side. Alongside factors such as pier spacing and median sediment size, the nose configurations of piers play a key role in influencing scour patterns, and subsequently, the flow characteristics around the piers. In this thesis, an experimental investigation was conducted to analyze the effects of pier nose shape and pier spacing on turbulent characteristics and scour depths around the piers. Three different shapes namely, round nose,  $60^\circ$  nose angle, and  $90^\circ$  nose angle piers were placed in both single and tandem arrangements. In the tandem arrangements, two identical piers were positioned at center-to-center (C/C) spacings of  $3L$ ,  $6L$ , and  $9L$  (where  $L$  represents the pier length) within two different sediment beds: Sand-A ( $d_{50} = 0.23$  mm) and Sand-B ( $d_{50} = 0.89$  mm).

Three-dimensional instantaneous velocity was measured using an Acoustic Doppler Velocimeter (ADV). From the experiments, it was observed that the magnitude of turbulent intensity and turbulent kinetic energy between the piers was found to be higher for smaller center-to-center (C/C) spacing, attributed to increased interference from the rear pier. The turbulence structure was also influenced by the shape of the pier as the  $90^\circ$  nose angle piers exhibited the maximum turbulence intensity and turbulent kinetic energy. The Reynolds Shear Stress value near the bed was higher at the upstream of front pier. In contrast, at downstream of the pier, an oscillating (positive-negative) pattern was observed due to flow separation and vortex shedding.

Analyzing the measured scour depths data, it was observed that for a single pier, the maximum scour depth was 19.61% higher around the round nose pier compared to the  $60^\circ$  nose angle pier, and 5.89% higher compared to the  $90^\circ$  nose angle pier. This difference was attributed to the comparatively blunter nose of the round nose pier, which led to an increase in the magnitude of the downflow as well as the formation of a horse-shoe vortex. The position of maximum scour depths also varied as for round nose pier; it was formed at the front of the pier. However, for the  $60^\circ$  nose angle and  $90^\circ$  nose angle piers, the maximum scour was observed at the frontal edge. The pier shape factor was calculated as 0.88 for the round nose pier, 0.73 for the  $60^\circ$  nose angle

pier, and 0.775 for the  $90^\circ$  nose angle pier. The smaller shape factors for the  $60^\circ$  nose angle and  $90^\circ$  nose angle piers were a result of their sharp leading edges.

Experimental results also showed that the scour depth around the front pier always exceeded that around the rear pier. The highest scour depth around the front pier was recorded for 3 L C/C spacing compared with 6L and 9L C/C spacing attributed to the increased drag force of the front pier compared with other spacings. Notably, at a 9L C/C spacing, the scour depth around the front pier closely resembled that of a single pier configuration. Furthermore, it was observed that regardless of pier shape, the maximum scour depth was more pronounced for Sand-A in comparison to Sand-B. This observation was attributed to the formation of an armor layer at the base of the scour hole in Sand-A, which was influenced due to the accumulation of larger particles within the scour hole.

Four existing scour depth predicting equations were used to compare predicted and observed scour depths around piers of different shapes. The results showed that the predictive equations consistently overpredicted scour depths. Among the four equations, Lacey's equation exhibited close values to the experimental results compared to the others. Lastly, a correction factor was introduced for incorporating the spacing between two piers in the CSU single pier equation, enhancing its ability to predict scour depths in tandem pier arrangements.

Turbulence characteristics, as observed in the experimental results, were also compared with Computational Fluid Dynamics (CFD) model using ANSYS software. The simulated results exhibited patterns of turbulence characteristics similar to the experimental findings. However, the simulated results consistently overestimated the normalized streamwise velocity at mid-depth for all pier shapes. Furthermore, in all cases, the CFD simulations underestimated the normalized turbulent kinetic energy compared to the experimental findings.

The findings of this study would be helpful in enhancing our understanding of the effects of pier nose shapes and spacing on turbulent flow characteristics and scour development around tandem piers.

## TABLE OF CONTENTS

|                                                     |              |
|-----------------------------------------------------|--------------|
| <b>ACKNOWLEDGEMENT.....</b>                         | <b>V</b>     |
| <b>ABSTRACT.....</b>                                | <b>VI</b>    |
| <b>TABLE OF CONTENTS .....</b>                      | <b>VIII</b>  |
| <b>LIST OF FIGURES.....</b>                         | <b>XII</b>   |
| <b>LIST OF TABLES.....</b>                          | <b>XVII</b>  |
| <b>LIST OF SYMBOLS .....</b>                        | <b>XVIII</b> |
| <b>CHAPTER 1.....</b>                               | <b>1</b>     |
| <b>INTRODUCTION.....</b>                            | <b>1</b>     |
| 1.1 Background.....                                 | 1            |
| 1.2 Objectives of the Study.....                    | 3            |
| 1.3 Scope and Expected Outcome of the Study.....    | 3            |
| 1.4 Synopsis of Thesis .....                        | 4            |
| <b>CHAPTER 2.....</b>                               | <b>5</b>     |
| <b>LITERATURE REVIEW .....</b>                      | <b>5</b>     |
| 2.1 General Remarks on Scour .....                  | 5            |
| 2.2 Types of Scour .....                            | 5            |
| 2.2.1 General Scour.....                            | 5            |
| 2.2.2 Localized Scour .....                         | 5            |
| 2.3 Parameters Affecting Scour Depth .....          | 7            |
| 2.4 Mechanism of Local Scour .....                  | 9            |
| 2.4.1 Local Scour Mechanism around Single Pier..... | 9            |
| 2.4.2 Local Scour Mechanism around Pier Group.....  | 11           |
| 2.5 Turbulence Parameters.....                      | 12           |
| 2.5.1 Instantaneous Velocity.....                   | 12           |
| 2.5.2 Turbulent Intensity .....                     | 13           |

|                                                 |                                                                               |           |
|-------------------------------------------------|-------------------------------------------------------------------------------|-----------|
| 2.5.3                                           | Turbulent Kinetic Energy .....                                                | 13        |
| 2.5.4                                           | Reynolds Shear Stress.....                                                    | 14        |
| 2.6                                             | Effect of Pier Spacing on Scour Depth .....                                   | 14        |
| 2.7                                             | Local Scour Predictive Equations around Pier Group .....                      | 15        |
| 2.7.1                                           | HEC-18 Equation for a Single Pier.....                                        | 16        |
| 2.7.2                                           | CSU or HEC-18 Equation for Group of Piers .....                               | 18        |
| 2.7.3                                           | Correction Factor on CSU or HEC-18 Equation by Ashtiani and Beheshti<br>..... | 19        |
| 2.7.4                                           | Gao et al. (1993) .....                                                       | 19        |
| 2.7.5                                           | Melville and Coleman (2000) .....                                             | 20        |
| 2.7.6                                           | Sheppard equation.....                                                        | 22        |
| 2.7.7                                           | Lacey's Equation .....                                                        | 23        |
| 2.8                                             | Previous Studies.....                                                         | 24        |
| <b>CHAPTER 3 .....</b>                          |                                                                               | <b>30</b> |
| <b>EXPERIMENTAL SETUP AND METHODOLOGY .....</b> |                                                                               | <b>30</b> |
| 3.1                                             | General.....                                                                  | 30        |
| 3.2                                             | Laboratory Setup.....                                                         | 30        |
| 3.2.1                                           | Recirculating Tilting Flume .....                                             | 30        |
| 3.2.2                                           | Electromagnetic Flow Meter.....                                               | 30        |
| 3.2.3                                           | Vernier Point Gauge .....                                                     | 31        |
| 3.3                                             | Experimental Setup .....                                                      | 32        |
| 3.3.1                                           | Flume Modification .....                                                      | 32        |
| 3.3.2                                           | Pier Characteristics and Dimensions .....                                     | 33        |
| 3.3.3                                           | Bed Materials .....                                                           | 35        |
| 3.4                                             | Experimental Scenarios .....                                                  | 36        |
| 3.4.1                                           | Flow Condition during experimental study .....                                | 37        |



|                                      |                                                                                            |           |
|--------------------------------------|--------------------------------------------------------------------------------------------|-----------|
| 3.5                                  | Duration of the Run .....                                                                  | 40        |
| 3.6                                  | Velocity Measurement .....                                                                 | 41        |
| 3.6.1                                | Acoustic Doppler Velocimetry (ADV) .....                                                   | 41        |
| 3.7                                  | Data Acquisition .....                                                                     | 42        |
| 3.7.1                                | ADV Data Collection .....                                                                  | 43        |
| 3.7.2                                | Scour Data Collection .....                                                                | 46        |
| 3.8                                  | Experimental Procedure .....                                                               | 46        |
| 3.9                                  | Uncertainty Analysis .....                                                                 | 49        |
| <b>CHAPTER 4 .....</b>               |                                                                                            | <b>50</b> |
| <b>RESULTS AND DISCUSSIONS .....</b> |                                                                                            | <b>50</b> |
| 4.1                                  | General .....                                                                              | 50        |
| 4.2                                  | Normalized Streamwise Velocity Variations along the Centerline .....                       | 50        |
| 4.2.1                                | Single Pier .....                                                                          | 50        |
| 4.2.2                                | Tandem Pier .....                                                                          | 52        |
| 4.2.3                                | Maximum Normalized Streamwise Velocity Variation .....                                     | 54        |
| 4.2.4                                | Comparison Between Single and Tandem Pier .....                                            | 59        |
| 4.3                                  | Normalized Streamwise Turbulent Intensity Variations along the Centerline .....            | 60        |
| 4.3.1                                | Single Pier .....                                                                          | 60        |
| 4.3.2                                | Tandem Pier .....                                                                          | 60        |
| 4.3.3                                | Maximum Normalized Streamwise Turbulent Intensity Variation .....                          | 64        |
| 4.3.4                                | Comparison Between Single and Tandem Pier .....                                            | 68        |
| 4.4                                  | Normalized Streamwise Turbulent Kinetic Energy (TKE) Variations along the Centerline ..... | 70        |
| 4.4.1                                | Single Pier .....                                                                          | 70        |
| 4.4.2                                | Tandem Pier .....                                                                          | 71        |
| 4.4.3                                | Maximum Normalized Turbulent Kinetic Energy Variation .....                                | 73        |

|                                        |                                                                                      |            |
|----------------------------------------|--------------------------------------------------------------------------------------|------------|
| 4.4.4                                  | Comparison Between Single and Tandem Pier .....                                      | 78         |
| 4.5                                    | Normalized Streamwise Reynolds Shear Stress Variations along the Centerline .....    | 80         |
| 4.5.1                                  | Single Pier.....                                                                     | 80         |
| 4.5.2                                  | Tandem Pier .....                                                                    | 81         |
| 4.5.3                                  | Maximum Normalized Reynolds Shear Stress Variation .....                             | 83         |
| 4.6                                    | Comparison of Turbulent Characteristics between Circular and Non-circular pier. .... | 88         |
| 4.7                                    | Comparison between Computational Fluid Dynamics (CFD) Model and Observed Data.....   | 92         |
| 4.8                                    | Temporal Development of Scour Depth .....                                            | 100        |
| 4.9                                    | Spatial Variation of Scour Depth around Piers.....                                   | 101        |
| 4.10                                   | Development of Scour along the Centerline of the Flume .....                         | 104        |
| 4.11                                   | Effect of Pier's Nose Shape on Scour Depth .....                                     | 107        |
| 4.12                                   | Effect of Pier Spacing on Scour Depth .....                                          | 111        |
| 4.13                                   | Effect of Bed Material on Scour Depth .....                                          | 115        |
| 4.14                                   | Scour Summary.....                                                                   | 117        |
| 4.15                                   | Variation of Turbulence Parameters and Scour Depth .....                             | 118        |
| 4.16                                   | Comparison of Observed and Predicted Scour Depth .....                               | 120        |
| 4.17                                   | Development of Correction Factor on CSU Equation .....                               | 124        |
| <b>CHAPTER 5</b>                       | .....                                                                                | <b>126</b> |
| <b>CONCLUSIONS AND RECOMMENDATIONS</b> | .....                                                                                | <b>126</b> |
| 5.1                                    | Conclusions.....                                                                     | 126        |
| 5.2                                    | Recommendations for Future Work.....                                                 | 128        |
| <b>REFERENCES</b>                      | .....                                                                                | <b>129</b> |
| <b>APPENDICES</b>                      | .....                                                                                | <b>135</b> |

## LIST OF FIGURES

|                                                                                                                                                                     |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 2.1</b> Classification of scour (Melville and Coleman, 2000).....                                                                                         | 6  |
| <b>Figure 2.2</b> Local scour around pier as a function of time (Richardson and Davis, 2001).<br>.....                                                              | 7  |
| <b>Figure 2.3</b> Schematic of mechanism contributing to scour (Hannah, 1978).....                                                                                  | 10 |
| <b>Figure 2.4</b> Schematic diagram showing the reinforcing effect. (Redrawn from Nazariha (1996)).....                                                             | 12 |
| <b>Figure 2.5</b> Time variation of velocity in x direction. ....                                                                                                   | 13 |
| <b>Figure 2.6</b> Maximum normalized scour depths for different normalized spacing at the upstream of (a) Front Pier & (b) Rear Pier (Keshavarzi et al., 2018)..... | 15 |
| <b>Figure 3.1</b> Laboratory Flume (21.3 m long, 0.76 m wide, and 0.74 m deep) .....                                                                                | 31 |
| <b>Figure 3.2</b> Vernier point gauge that measures the scour depth .....                                                                                           | 31 |
| <b>Figure 3.3</b> Modification of the flume with geotextile material on top.....                                                                                    | 32 |
| <b>Figure 3.4</b> Flume details with false floor and experimental section. ....                                                                                     | 33 |
| <b>Figure 3.5</b> Piers with different nose shapes along with dimensions: (a) Round nose.                                                                           | 34 |
| <b>Figure 3.6</b> Particle size distribution curve of (a) Sand-A and (b) Sand-B .....                                                                               | 36 |
| <b>Figure 3.7</b> All the experimental scenarios of the study.....                                                                                                  | 37 |
| <b>Figure 3.8</b> Temporal development of scour depth during test runs of 24 hour duration.<br>.....                                                                | 41 |
| <b>Figure 3.9</b> Components of Acoustic Doppler Velocimeter Probe (Sontek, 2001) .....                                                                             | 42 |
| <b>Figure 3.10:</b> Schematic plan view of ADV data collection Points in the tandem pier arrangements (along the center line).....                                  | 43 |
| <b>Figure 3.11</b> Schematic plan view of ADV data collection points for single pier experiment (along the center line) .....                                       | 44 |
| <b>Figure 3.12</b> Processing of ADV data on Win-ADV. ....                                                                                                          | 46 |
| <b>Figure 3.13</b> Schematic view of the scour depth measuring grid in tandem arrangement.<br>.....                                                                 | 46 |

|                                                                                                                                                                                                                                                                    |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 3.14</b> Schematic diagram of the overall experimental procedures.....                                                                                                                                                                                   | 47 |
| <b>Figure 4.1</b> Normalized streamwise velocity variation ( $u/U_0$ vs $z/h$ ) around single pier:<br>(a) Sand-B (b) Sand-A. ....                                                                                                                                 | 51 |
| <b>Figure 4.2</b> Normalized streamwise velocity variation for piers placed in tandem<br>arrangements at Sand B ( $d_{50}=0.0.89$ mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c)<br>9L C/C Spacing.....                                                            | 53 |
| <b>Figure 4.3</b> Maximum normalized streamwise velocity variation along the centerline on<br>Sand-A (a, b & c) and Sand-B (d, e & f). ....                                                                                                                        | 56 |
| <b>Figure 4.4</b> Effect of pier nose shape on maximum streamwise velocity on Sand-B ( $d_{50}=$<br>0.89 mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.....                                                                                        | 58 |
| <b>Figure 4.5</b> Comparison of normalized streamwise velocity at the downstream of the<br>front pier (Section-2): (a) Sand-A (b) Sand-B. ....                                                                                                                     | 60 |
| <b>Figure 4.6</b> Normalized streamwise turbulent intensity variation ( $u, 2/U_0$ vs $z/h$ ) around<br>single pier: (a) Sand-A (b) Sand-B. ....                                                                                                                   | 62 |
| <b>Figure 4.7</b> Normalized streamwise turbulent intensity variation ( $u, 2/U_0$ vs $z/h$ ) for<br>piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$ mm): (a)<br>3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing .....        | 63 |
| <b>Figure 4.8</b> Maximum normalized streamwise turbulent intensity variation along the<br>centerline on Sand-A (a, b & c) and Sand-B (d, e & f).....                                                                                                              | 66 |
| <b>Figure 4.9</b> Effect of pier nose shape on maximum turbulent intensity on Sand-B ( $d_{50}=$<br>0.89 mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing .....                                                                                       | 68 |
| <b>Figure 4.10</b> Comparison of normalized streamwise turbulent intensity at the<br>downstream of the front pier (Section-2): (a) Sand-A (b) Sand-B. ....                                                                                                         | 69 |
| <b>Figure 4.11</b> Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$ vs<br>$z/h$ ) around single pier: (a) Sand-A (b) Sand-B. ....                                                                                                            | 71 |
| <b>Figure 4.12</b> Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$ vs<br>$z/h$ ) for piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$<br>mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing. .... | 73 |
| <b>Figure 4.13</b> Maximum normalized turbulent kinetic energy variation along the<br>centerline on Sand-A (a, b & c) and Sand-B (d, e & f).....                                                                                                                   | 76 |

|                                                                                                                                                                                                                                                              |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 4.14</b> Effect of pier nose shape on maximum turbulent kinetic energy on Sand-B ( $d_{50} = 0.89$ mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing .....                                                                             | 78 |
| <b>Figure 4.15</b> Comparison of normalized turbulent kinetic energy at the downstream of the front pier (Section-2): (a) Sand-A (b) Sand-B. ....                                                                                                            | 79 |
| <b>Figure 4.16</b> Normalized Reynolds shear stress variation ( $-u'w'/U_0^2$ vs $z/h$ ) around single pier on: (a) Sand-A (b) Sand-B .....                                                                                                                  | 81 |
| <b>Figure 4.17</b> Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$ vs $z/h$ ) for piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$ mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing ..... | 83 |
| <b>Figure 4.18</b> Maximum normalized Reynolds shear stress variation along the centerline on Sand-A (a, b & c) and Sand-B (d, e & f). ....                                                                                                                  | 85 |
| <b>Figure 4.19</b> Effect of pier nose shape on maximum Reynolds Shear Stress on Sand-B ( $d_{50} = 0.89$ mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.....                                                                                 | 88 |
| <b>Figure 4.20</b> Comparison of normalized streamwise velocity between circular and non-circular pier: (a) Sand-A (b) Sand-B.....                                                                                                                           | 90 |
| <b>Figure 4.21</b> Comparison of normalized turbulent intensity between circular and non-circular pier: (a) Sand-A (b) Sand-B.....                                                                                                                           | 91 |
| <b>Figure 4.22</b> Comparison of normalized turbulent kinetic energy between circular and non-circular pier: (a) Sand-A (b) Sand-B. ....                                                                                                                     | 92 |
| <b>Figure 4.23</b> Streamwise velocity variation around piers placed at 3L C/C spacing: (a) Round Nose (b) Pier with $60^\circ$ nose angle and (c) Pier with $90^\circ$ nose angle. ....                                                                     | 94 |
| <b>Figure 4.24</b> Comparison of normalized streamwise velocity variation between CFD simulation and experiments: (a) Round Nose (b) Pier with $60^\circ$ Nose Angle (c) Pier with $90^\circ$ Nose Angle. ....                                               | 96 |
| <b>Figure 4.25</b> Turbulent kinetic energy variation around piers placed at 3L C/C spacing: (a) Round Nose (b) Pier with $60^\circ$ nose angle and (c) Pier with $90^\circ$ nose angle.....                                                                 | 98 |
| <b>Figure 4.26</b> Comparison of normalized turbulent kinetic energy variation between CFD simulation and experiments: (a) Round Nose (b) Pier with $60^\circ$ Nose Angle (c) Pier with $90^\circ$ Nose Angle. ....                                          | 99 |

|                                                                                                                                                                                                                                                                                                      |     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Figure 4.27</b> Temporal Development of Scour Depth around Front Piers Placed at Different Spacing (a) Round Nose Pier on Sand-A ( $d_{50}=0.23$ mm) (b) Round Nose Pier on Sand-B ( $d_{50}=0.89$ mm).....                                                                                       | 101 |
| <b>Figure 4.28</b> Contours of bed surface elevation around single pier in Sand-B: (a) Round Nose (b) $60^\circ$ Nose Angle & (c) $90^\circ$ Nose Angle.....                                                                                                                                         | 102 |
| <b>Figure 4.29</b> Contours of bed surface elevation around tandem piers in Sand-B ( $S/L=3$ ): (a) Round Nose (b) $60^\circ$ Nose Angle & (c) $90^\circ$ Nose Angle. ....                                                                                                                           | 104 |
| <b>Figure 4.30</b> Development of scour along the centerline of the flume for round nose pier placed on Sand-A. (a) Single (b) $S/L=3$ (c) $S/L=6$ & (d) $S/L=9$ .....                                                                                                                               | 106 |
| <b>Figure 4.31</b> Effect of pier's nose shape on scour depth on Sand-A: (a) Front Pier & (b) Rear Pier.....                                                                                                                                                                                         | 108 |
| <b>Figure 4.32</b> Effect of pier's nose shape on scour depth on Sand-B: (a) Front Pier & (b) Rear Pier.....                                                                                                                                                                                         | 110 |
| <b>Figure 4.33</b> Effect of pier spacing on maximum 6-h scour depth on Sand-A: (a) Round Nose Pier (b) Pier with $60^\circ$ Nose Angle and (c) Pier with $90^\circ$ Nose Angle and on Sand-B: (d) Round Nose Pier (e) Pier with $60^\circ$ Nose Angle and (f) Pier with $90^\circ$ Nose Angle ..... | 113 |
| <b>Figure 4.34</b> Effect of pier spacing on maximum 6-h scour depth (a) Front Pier and (b) Rear Pier.....                                                                                                                                                                                           | 114 |
| <b>Figure 4.35</b> Effect of bed material on maximum 6-h scour depth around (a) Single Pier, (b) Piers placed at 3L C/C spacing, (c) Piers placed 6L C/C spacing and (d) Piers placed at 9L C/C spacing. ....                                                                                        | 117 |
| <b>Figure 4.36</b> Variation of normalized maximum turbulent intensity and turbulent kinetic energy along the centerline of the flume: (a) $S1:3L$ (b) $S1:6L$ and (c) $S1:9L$ ...                                                                                                                   | 120 |
| <b>Figure 4.37</b> Comparison of observed maximum 6-h scour depth with predicted equilibrium scour depth using single pier equation for 5.5 cm cylindrical pier on Sand-A: (a) Round Nose Pier (b) Pier with $60^\circ$ Nose Angle & (c) Pier with $90^\circ$ Nose Angle .....                       | 122 |
| <b>Figure 4.38</b> Comparison of observed maximum 6-h scour depth with predicted equilibrium scour depth using single pier equation for 5.5 cm cylindrical pier on Sand-                                                                                                                             |     |

|                                                                                    |     |
|------------------------------------------------------------------------------------|-----|
| B: (a) Round Nose Pier (b) Pier with 60° Nose Angle & (c) Pier with 90° Nose Angle | 123 |
|------------------------------------------------------------------------------------|-----|

|                                                                                                     |     |
|-----------------------------------------------------------------------------------------------------|-----|
| <b>Figure 4.39</b> Comparison of observed and predicted scour depth using the new CSU equation..... | 125 |
|-----------------------------------------------------------------------------------------------------|-----|

## LIST OF TABLES

|                                                                                                                              |     |
|------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>Table 2.1</b> Pier nose shape correction factor, $K_1$ (Richardson and Davis, 2001) .....                                 | 16  |
| <b>Table 2.2</b> Flow skew angle correction factor, $K_2$ (Richardson and Davis, 2001) .....                                 | 17  |
| <b>Table 2.3</b> Dune factor, $K_3$ (Richardson and Davis, 2001) .....                                                       | 17  |
| <b>Table 2.4</b> Multiplying Factor ( $K_s K_\alpha$ ) for Pier Groups (Melville and Coleman, 2000)<br>.....                 | 21  |
| <b>Table 3.1</b> Test scenarios of the experimental study .....                                                              | 39  |
| <b>Table 3.2</b> Details regarding the experimental study .....                                                              | 40  |
| <b>Table 3.3</b> Details of ADV data collection points .....                                                                 | 44  |
| <b>Table 3.4</b> ADV sample data collection at 50 Hz .....                                                                   | 45  |
| <b>Table 3.5</b> Uncertainty analysis of ADV measurements .....                                                              | 49  |
| <b>Table 4.1</b> Effect of Pier Spacing on Maximum Normalized Streamwise Velocity<br>( $u/U_0$ ) <sub>max</sub> . .....      | 57  |
| <b>Table 4.2</b> Effect of Pier's Nose Shape on Maximum Normalized Streamwise Velocity<br>( $u/U_0$ ) <sub>max</sub> . ..... | 58  |
| <b>Table 4.3</b> Effect of pier spacing on maximum normalized turbulent intensity .....                                      | 66  |
| <b>Table 4.4</b> Effect of pier's nose shape on maximum normalized turbulent intensity ...                                   | 68  |
| <b>Table 4.5</b> Effect of pier spacing on maximum normalized turbulent kinetic energy ..                                    | 76  |
| <b>Table 4.6</b> Effect of pier's nose shape on maximum normalized turbulent kinetic energy.<br>.....                        | 78  |
| <b>Table 4.7</b> Effect of pier spacing on maximum normalized Reynolds shear stress .....                                    | 86  |
| <b>Table 4.8</b> Effect of pier's nose shape on maximum normalized Reynolds shear stress.<br>.....                           | 88  |
| <b>Table 4.9</b> Summary of scour hole extent .....                                                                          | 107 |
| <b>Table 4.10</b> Calculation of pier's shape factor. ....                                                                   | 110 |
| <b>Table 4.11</b> Summary of maximum scour depth around front and rear pier. ....                                            | 118 |



## LIST OF SYMBOLS

|            |                                                          |
|------------|----------------------------------------------------------|
| $x$        | Distance measured in streamwise direction                |
| $y$        | Distance measured in transverse direction                |
| $z$        | Distance measured in vertical direction                  |
| $u$        | Instantaneous velocity component in streamwise direction |
| $v$        | Instantaneous velocity component in transverse direction |
| $w$        | Instantaneous velocity component in vertical direction   |
| $\rho$     | Density of water                                         |
| $\nu$      | Kinematic viscosity                                      |
| $g$        | Acceleration due to gravity                              |
| $h$        | Flow depth                                               |
| $D$        | Diameter of pier                                         |
| $U$        | Average velocity                                         |
| $U_0$      | Approach flow velocity                                   |
| $\sigma_g$ | Geometric standard deviation                             |
| $d_{50}$   | Median particle size of the sediment                     |
| $U_c$      | Critical velocity of sediment                            |
| $K_{sh}$   | Shape factor                                             |
| $A_l$      | Alignment factor                                         |
| $S$        | Center-to-center spacing between two tandem piers        |
| $K_m$      | Factor in the number of aligned rows                     |
| $m$        | Number of piers in line with the flow direction          |

|                             |                                                                |
|-----------------------------|----------------------------------------------------------------|
| $n$                         | Number of piers normal to the direction of flow                |
| $K_t$                       | Time factor for equilibrium scour depth                        |
| $D_s$                       | Equilibrium or Maximum scour depth (Using predictive equation) |
| $d_{sm}$                    | Observed maximum scour depth                                   |
| $t_e$                       | Time to reach equilibrium condition                            |
| $D^*$                       | Effective diameter of the pier group                           |
| $w_s$                       | Top width of the scour hole                                    |
| $F_r$                       | Froude number                                                  |
| $K_1$                       | Shape factor                                                   |
| $K_2$                       | Flow skew-angle factor                                         |
| $K_3$                       | Dune factor                                                    |
| $K_4$                       | Correction factor for armoring                                 |
| $S_r$                       | Submergence ratio                                              |
| $K_{sp}$                    | Correction factor for pier spacing                             |
| $K_{sp}$                    | Sum of non-overlapping projected pier widths                   |
| $K_{hD}$                    | Flow depth-pier size factor                                    |
| $K_I$                       | Flow intensity factor                                          |
| $K_d$                       | Sediment size factor                                           |
| $K_\alpha$                  | Foundation alignment factor                                    |
| $\bar{u}, \bar{v}, \bar{w}$ | Time-averaged velocity components in x, y, and z directions    |
| $u', v', w'$                | Velocity fluctuations in x, y, and z directions                |
| TI                          | Turbulence intensity                                           |

|                              |                                               |
|------------------------------|-----------------------------------------------|
| $TI_u$                       | Turbulence intensity in streamwise directions |
| $TI_v$                       | Turbulence intensity in transverse directions |
| $TI_w$                       | Turbulence intensity in vertical directions   |
| TKE                          | Turbulent kinetic energy                      |
| $-\overline{u'w'}$ or<br>RSS | Reynolds shear stress in x-z plane            |
| $-\overline{v'w'}$           | Reynolds shear stress in y-z plane            |
| POS                          | Plane of symmetry                             |
| ADV                          | Acoustic Doppler Velocimeter                  |
| B                            | Width of the flume                            |
| $u^*$                        | Shear velocity                                |
| $u_c^*$                      | Critical shear velocity                       |
| $\tau_b$                     | Resultant Reynolds shear stress               |
| $\tau_b^*$                   | Normalized near-bed shear stress              |
| $Re$                         | Reynolds number                               |
| Q                            | Flow rate                                     |
| $d_s$                        | Maximum scour depth in single pier            |
| $d_{s1}$                     | Maximum scour depth at the front pier         |
| $d_{s2}$                     | Maximum scour depth at the rear pier          |

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Numerous issues such as sediment transport, riverbed and bank deformation, flooding, scouring, etc. are associated with flowing water through a watershed, which is critical in the field of hydraulic engineering (Chavan, 2018). Riverbed deformation around bridge foundation (e.g., piers and abutments) is caused by the flow hydraulics and sediment properties. The aggradation and degradation processes of riverbed due to the flow obstruction leads to scouring around those foundations, has been the subject of interest for hydraulic engineers over past few decades (Melville, 1975).

One of the major causes of bridge failure is the scouring around bridge piers, which occurs due to the development of high shear stress caused by flow separation at boundary layer around pier (Kothyari and Kumar, 2012). So, the prediction of maximum scour depth around bridge pier is a crucial issue in bridge design. Different parameters which affect scour depth are: flow properties, pier geometry, pier alignment, sediment properties, scouring duration, etc. To predict scour depth, several studies have been conducted around single piers or circular piers in tandem arrangements (Breusers et al., 1977a; Breusers and Raudkivi, 1991; Kothyari and Kumar, 2012; Zhao et al., 2022); Basir, 2022). Semi-empirical equations have been developed based on those studies, most of which over-predict scour depth around bridge piers (Dargahi, 1990a; Coleman and Melville, 2001; Ataie-Ashtiani et al., 2010). Understanding the complex turbulent flow field around piers is critical for precise scour depth prediction (Beheshti et al., 2013). The interaction between approach flow and bridge piers generates various flow characteristics such as down flow, horse-shoe vortex, wake vortices, and bow waves resulting a complex flow field around the piers (Vijayasree et al., 2019). The horseshoe vortex increases the sediment transport capacity of the flow, whereas the wake vortices keep the sediment in suspension (Keshavarzi et al., 2018). Extensive research has been conducted to better comprehend the flow field around a single circular pier. Melville (1975) conducted laboratory experiments to study the mean flow and turbulence characteristics around a circular pier. He noticed that as the scour hole developed, the velocity at the bottom of the scour hole decreased. Graf and Istiarto (2002) investigated the three-dimensional turbulent flow field around a circular pier.

They observed a robust vortex system termed horseshoe vortex system at the foot upstream of the pier and a flow reversal downstream towards the water surface.

Recently, pile groups and complex piers becoming popular in bridge design due to geotechnical and economic considerations (Zhou and Yiu, 2006; Nowrin, 2020; Zobeyer et al., 2021). Furthermore, rapid urbanization has resulted in the construction of wider or new bridges near the previous ones, making it even more important to use a group of piers rather than a single pier. It has been reported that the flow field around pier groups differs significantly from that of a single pier. For piers in tandem arrangements, several phenomena, such as sheltering, reinforcement, and shed vortices occur (C. Hannah, 1978). As a result, applying the results obtained from single circular piers to pier groups may be challenging. Very few studies have been conducted using group of circular piers to investigate the effect of pier spacing on scour depth. It was observed that when the ratio of the spacing between two piers and the pier diameter is less than 3, the vortex shedding occurred only behind the downstream pier making the flow pattern similar to a single pier (Shrestha, 2015a). Ataie-Ashtiani and Beheshti (2006) studied the clear water local scour at circular pile groups. They observed that scour around the front pier was higher than the rear pier, and maximum scour depth around the front pier was obtained when the spacing ( $S/D$ ) between the two piers was 3.

Besides, the flow field around a non-circular pier differs from a circular pier (Vijayasree et al., 2019). A few researchers have studied the scour depth and flow field around a single non-circular pier and developed shape factors (ratio of scour depth for non-circular pier to a circular pier) for different shapes of piers (Al-Shukur and Obeid, 2016; Fael et al., 2016; Funde et al., 2018; Jalal and Hassan, 2020; Shahhosseini and Guoliang, 2019; Vijayasree et al., 2019). Vijayasree et al. (2019) investigated the influence of bridge pier shape on the flow field and scour depth. They observed that turbulence intensity and scour depth were higher for piers with a blunt frontal edge (rectangular, circular) than those with sharp frontal edges (sharp nose, lenticular).

Along with experimental investigations, many researchers used Computational Fluid Dynamics (CFD) simulation, to predict local scour and to analyze the turbulent characteristics around pier. Ghasemi and Soltani-Gerdefaramarzi (2017) performed CFD simulation using Flow-3D to investigate the scour depth and turbulent characteristics around single circular piers at different flow rates and observed that Flow-3D

underestimated scour depth by 20%-30%, compared to experimental data. SVSNDL and Kumar (2018) simulated the flow behaviour around bridge pier using ANSYS-CFD model and used Finite Volume Method (FVM) by k-epsilon and k-omega turbulence model for analysing turbulent characteristics.

Though various researchers have done extensive studies to predict local scour to understand the turbulent flow field around single piers or circular piers in tandem arrangements, studies around non-circular piers in tandem arrangements are still lacking. As a result, a laboratory setup was developed in this study to assess the effect of pier spacing and the pier's nose shape on scour development in tandem arrangements using two different sediment beds for three different pier nose shapes (round nose, piers with  $60^\circ$  nose angle and piers with  $90^\circ$  nose angle).

## **1.2 Objectives of the Study**

In this experimental study, piers with different nose shapes will be carried out for different pier spacing in ent sediment bed conditions (e.g., fine sand and coarse sand). The specific objectives of this study are:

- i. To investigate the effect of pier's nose shapes on maximum scour depths and propagation of scour patterns for different spacing in fine and coarse sediment beds.
- ii. To study the variation of maximum scour depths between experimental data with available scour depth predicting equations for cylindrical piers and develop correction factors.
- iii. To investigate the variations of velocity profile and turbulence parameters at various locations and along the centerline of the tandem pier arrangements.

## **1.3 Scope and Expected Outcome of the Study**

The findings of this study will assist in understanding the variations of turbulence parameters along the centerline of the tandem arrangements and the effect of sediment size on scour development. The study findings will also help to enhance the current understanding of the effect of pier nose shapes in tandem arrangements on scour development. In addition, the experimental results will also help to investigate the applicability of the existing scour depth predictive equations around piers with different nose shapes in tandem arrangements.

## 1.4 Synopsis of Thesis

This thesis contains five chapters. A brief outline of each chapter is as follows:

**Chapter 1** contains the study's background, objective, scope and expected outcome.

**Chapter 2** concentrates on gathering existing information in the area of local scour. It also identifies the scientific gaps that need to be filled to achieve this study's objectives. This chapter begins with a brief overview of local scour (definition, factors affecting local scour, and local scour mechanism) followed by turbulence flow field around the pier. Several widely used scour depth predicting equations, both for a single pier and tandem pier arrangements, are also discussed in this chapter. Finally, some previous studies are discussed regarding scour depth and flow field around single non-circular and circular piers in tandem arrangements.

**Chapter 3** contains a details description of the 24 experimental runs carried out in this study. Details regarding flume preparation, pier geometry, pier spacing, bed materials, hydraulic conditions, and data collection procedures are presented with appropriate sketches where necessary.

**Chapter 4** describes the analysis of the experimental results. Turbulent flow fields around the piers in tandem arrangements are analyzed. The effect of pier spacing, the pier's nose shape, and bed materials on maximum scour depth and comparing the experimental data with scour depth predictive equations are discussed. Besides, some correction factors for different pier's nose shapes are proposed.

**Chapter 5** presents a summary of the significant findings of this study and makes recommendations for research.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 General Remarks on Scour**

Scour is the removal of sediment particles due to the erosive action of the flowing water. The removal of the bed materials lowers the bed level and can be attributed to the three-dimensional flow separation (Garde and Raju, 2000). Due to scouring, the foundation of structure exposes as it removes the bed materials around the foundations, consequently, structural collapse may occur. When the flow interacts with the pier, it creates a horseshoe vortex near the bed upstream of the pier. The horseshoe vortex is the primary scour-generating flow structure. Trailing vortices and wake vortices are produced at side and downstream of pier, which also influence the scouring processes and sediment transportation (Ettema et al., 2011).

#### **2.2 Types of Scour**

Scour can be divided into two major types: (i) general scour and (ii) localized scour. **Figure 2.1** represents the classification of scour

##### **2.2.1 General Scour**

The general removal of the bed material due to the natural process is termed as general scour, which contributes to the change in river characteristics. No structural obstruction is necessary for this scour to occur. General scour can be further classified as short-term scour and long-term scour. During a single or sequential floods (daily, weekly, or seasonally), short-term scour occurred. Some examples of short-term scour include scour at channel confluences, scour at bends, scour arising from a shift in the channel thalweg, and bedform migration (Coleman and Melville, 2001).

Due to some modification of the watershed and the stream, long-term general scour occurs over the years and has a relatively long-time scale. Human activities such as channel alterations, streambed mining, and dam construction contribute to long-term general scour.

##### **2.2.2 Localized Scour**

Contraction scour and local scour combinedly are referred to as localized scour (Coleman and Melville, 2001). Construction of piers or other hydraulic structures



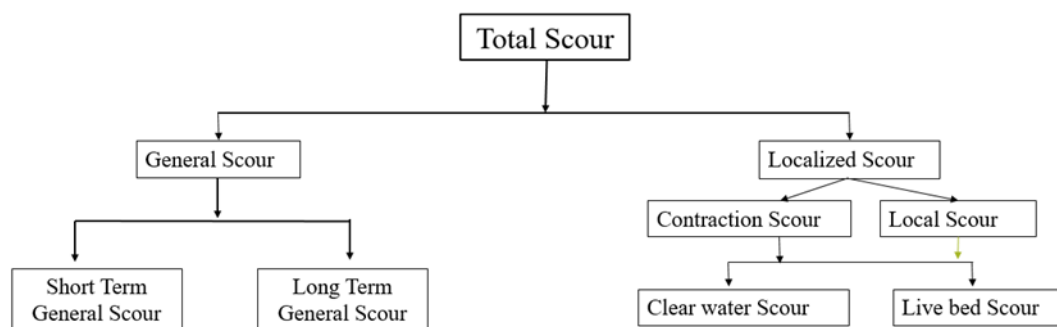
causes a reduction of the channel flow area, which causes an increase in flow velocity and shear stress, subsequently increasing the erosive forces. The removal of bed material from the confined reach will be further triggered in reaction to the mentioned operations, which may decrease the bed level and continue until an equilibrium state is reached.

Local scour occurs when an obstruction is introduced into the flow (Coleman, 2005). Construction of structures such as bridge piers and abutments change the flow pattern, which causes flow acceleration around the structures, consequently erodes the bed materials around the structure.

Local scour can be classified as (i) clear water scour and (ii) live bed scour. **Figure 2.2** represents local scour as a function of time.

### 2.2.2.1 Clear Water Scour

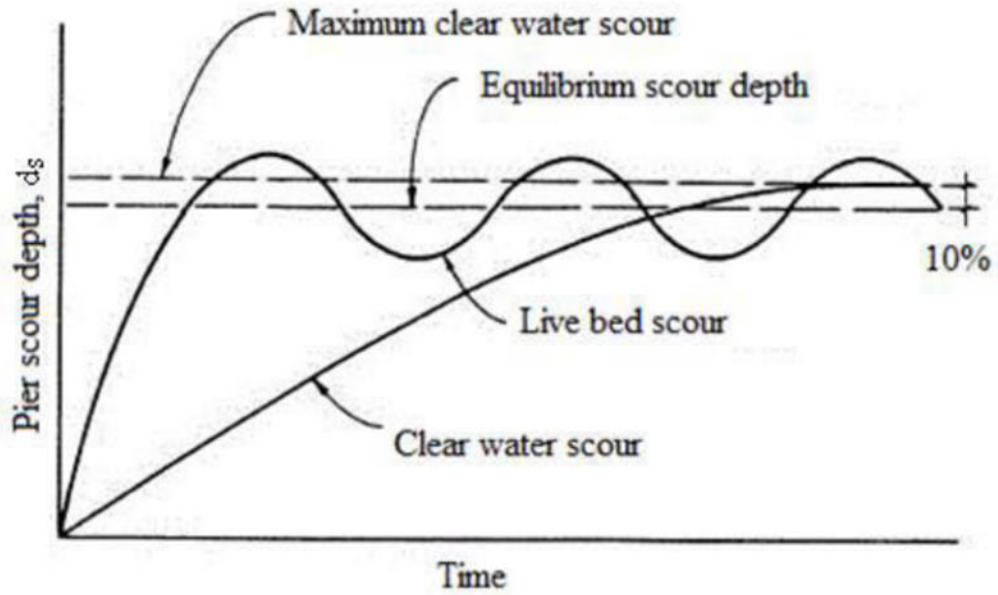
In clear water scour, bed material upstream of the structure do not mover, and the net transported sediment is zero. In the clear-water scour condition, the ratio between the approach flow velocity and the sediment critical velocity is less than unity ( $U_0/U_C < 1$ ). Under clear water conditions, bed material is eroded rapidly during the early stages. Equilibrium scour depth is obtained when the sediment in the scour hole cannot be removed anymore. When the critical shear stress of the bed material at the bottom of the scour hole equals the shear stress produced by the horseshoe vortex, equilibrium is achieved for the clear water scour conditions. Equilibrium scour depth is reached over several days or even weeks in clearwater conditions (Chiew and Lim, 2000).



**Figure 2.1** Classification of scour (Melville and Coleman, 2000).

### 2.2.2.2 Live Bed Scour

Live bed scour occurs when bed material is transported from the upstream reach of the channel. The ratio between the approach flow velocity and the sediment's critical velocity is greater than unity ( $U_0/U_C > 1$ ). In the case of live bed scour, the scour hole is continuously supplied with the sediment transported from upstream reach. When the rate of sediment supplied into the scour hole equals the rate of sediment transported out from the scour whole, equilibrium is achieved.



**Figure 2.2** Local scour around pier as a function of time (Richardson and Davis, 2001).

### 2.3 Parameters Affecting Scour Depth

Various parameters which affect scour depth are the flow, pier and sediment characteristics. According to Coleman and Melville (2001), the functional form of scour depth can be stated as follows:

$$d_s = f \{ \text{fluid } (\rho, \nu, g), \text{ flow } (h, U, ), \text{ sediment properties } (\sigma_g, d_{50}, U_C), \text{ pier geometry } (D^*, K_{sh}, Al) \} \quad (2.1)$$

where,  $d_s$  is the scour depth around piers,  $\rho$  is the density of water,  $\nu$  is the kinematic viscosity of water,  $g$  is the gravitational acceleration,  $h$  is the depth of flow,  $U$  is average velocity,  $\sigma_g$  is the geometric standard deviation,  $d_{50}$  is the median grain size,  $U_C$  is the critical velocity of the sediment,  $D^*$  is the effective diameter of the pier,  $K_{sh}$  is the pier

shape factor, and  $A_1$  is the pier alignment factors. Most scour depth estimation approaches use non-dimensional variables shown by:

$$\frac{d_s}{D^*} = f \left\{ Fr, \frac{Uh}{\nu}, \frac{U}{U_c}, \frac{h}{D^*}, \frac{D^*}{d_{50}}, \sigma_g \right\} \quad (2.2)$$

where,  $Fr$  is the Froude number, which includes the effect of gravity,  $\frac{Uh}{\nu}$  is the Reynolds number that includes the effect of viscosity,  $\frac{U}{U_c}$  is the ratio of flow velocity and critical velocity of the sediment,  $\frac{h}{D^*}$  is the ratio of flow depth and the effective diameter of the pier,  $\frac{D^*}{d_{50}}$  is the ratio of the effective diameter of the pier and median particle size, and  $\sigma_g$  is the geometric standard deviation.

Flow shallowness factor ( $h/D^*$ ) was used to classify the flow field by Coleman and Melville (2001). If the flow shallowness factor is greater than 1.4, the pier is referred to as a narrow pier; in this case, only the effective diameter of the pier affects scour depth. In the case of an intermediate pier ( $0.2 \leq h/D^* \leq 1.4$ ), both pier effective diameter and water depth affect scour depth. When  $h/D^* < 0.2$ , scour depth is independent of the water depth only (Coleman and Melville, 2001).

Furthermore, using the flow velocity ratio ( $U/U_c$ ), scour can be classified as either clear water scour or live bed scour. When  $U/U_c < 1$ , clear water scour condition exists, and the upstream sediment bed will not be in motion. The live bed scour conditions occur when the flow velocity ratio ( $U/U_c$ ) exceeds 1. In this case, sediment will be transported to the scour hole from upstream (Coleman and Melville, 2001).

Previous studies also suggested that relative coarseness ( $D^*/d_{50}$ ) affects scour depth. The influence of the median particle size of the sediment is negligible if the value of the relative coarseness ( $D^*/d_{50}$ ) is greater than 50 (Coleman and Melville, 2001). Lee and Sturm (2009) suggest if  $D^*/d_{50} > 100$ , due to the scaling, sediment size ( $d_{50}$ ) has a negligible effect on scour depth.

The effect of sediment non-uniformity or the geometric standard deviation of the sediment ( $\sigma_g$ ) on scour depth can be described in several different ways. A sand is said to be uniform if ( $\sigma_g$ )  $< 1.5$  (Lee and Sturm, 2009). Presence of larger particle significantly reduces scour depth which is called the armoring effect. If the erosive force increases due to the increased flow intensity, the armoring effect is reduced as

well as the effect of sediment non uniformity on scour depth is also reduced (Ettema et al., 2011)

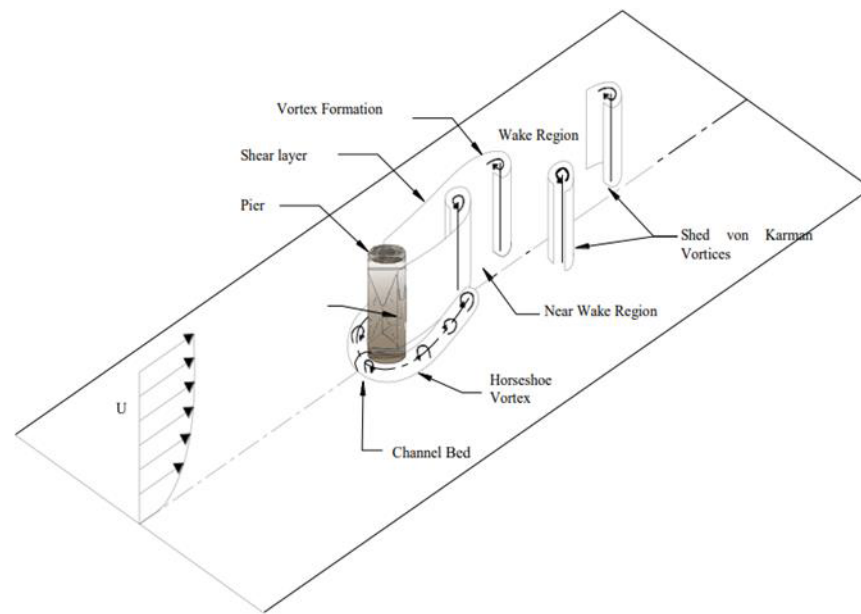
Pier shape factor ( $K_{sh}$ ) has a significant effect on scour depth. Many researchers developed shape factors for calculating scour depth of non-circular piers using the equations developed for the circular pier. Al-Shukur and Obeid (2016) studied the effect of pier shape on scour depth using ten different pier shapes. The shape factor for a circular pier is 1. For rectangular, oblong, elliptical, and sharp nose piers, the shape factor was 1.11, 0.85, 0.8, and 0.7 respectively. Shahhosseini and Yu (2019) also studied the effect of pier shape on scour depth in single pier arrangements using three different shapes of pier and shape factors for oblong, rhombus30 (inner-angle  $30^\circ$ ), and rhombus60 (inner-angle  $60^\circ$ ) were obtained as 1, 0.9, and 0.9 respectively.

## **2.4 Mechanism of Local Scour**

The flow hydrodynamics and scour mechanism around a single pier differ significantly from the flow hydrodynamics around the pier group in tandem or side-by-side arrangements. Scour mechanisms around the pier group are more complex than single pier (Ataie-Ashtiani et al., 2010). The details mechanism of scour around single pier and piers in the tandem arrangement is described below.

### **2.4.1 Local Scour Mechanism around Single Pier**

The flow structure contributing to the formation of scour around a pier has been described by many researchers (Melville, 1975; Breusers et al., 1977; Dargahi, 1990; Dey et al., 1995; Ozturk et al., 2008; Ettema et al., 2011). Breusers et al. (1977) identified several vortices systems: downflow in front of the pier, the horseshoe vortex system, the near wake vortex system, and the trailing vortex system as being crucial to the creation of local scour. The combined or separate operation of these systems might result in scour, depending on the type of pier and the free stream conditions. The horseshoe vortex is the main contributor to the scouring process caused by the flow separation upstream of the pier. The Horseshoe vortex moves sediment into the wake region by carrying it from upstream of the pier, wrapping it around the edges, and combining it with the incoming flow. The Karman vortex shedding then causes wake vortices to transport sediment from the wake zone and deposit sediment downstream. **Figure 2.3** shows a schematic diagram of scour process around bridge piers.



**Figure 2.3** Schematic of mechanism contributing to scour (Hannah, 1978)

#### 2.4.1.1 Flow Field at the Upstream Region of Pier

Since the horseshoe vortex controls the local scouring around bridge piers, there has been a lot of research on the area upstream of the pier. This area of the scouring process was given a lot of attention as the largest scour depth also occurs at the upstream face of the pier. At various stages of scour development, Melville (1975) made some groundbreaking measurements of the velocity, turbulence, shear stress at the bed, and vortex shedding. He was able to figure out the size of the horseshoe vortex, the magnitude of the vertical downward flow upstream of the pier, and their relationship to the rate of scour. A stagnation line forms at the upstream face of the pier for a fully turbulent flow, with a decreasing pressure moving toward the bed (Sturm, 2001). The approaching flow velocity profile is much slower closer to the bed, which causes the pressure gradient to decrease. A horseshoe-shaped vortex forms at the bed around the pier due to the interaction of the incoming flow and the downstream flow around the pier. Due to accelerated flow around the pier, scour begins at the sides of the pier and in the wake before the horseshoe vortex upstream takes control (Kirkil et al., 2008). When the flow enters the scour hole, the horseshoe vortex becomes more prevalent (Dey et al., 1995). The horseshoe vortex keeps moving downstream until it is shed to the side of the scour hole, which increases shear forces and causes sediment to be

removed (Kirkil et al., 2008). In the region of the primary horseshoe vortex, secondary vortices are created.

#### **2.4.1.2 Flow Field at the Downstream Region of Pier**

The separation of flow at the pier's sides and being carried downstream by the approach flow form wake vortices. The wake vortices' low-pressure center acts as a "vacuum cleaner," connecting with the arms of the horseshoe vortex and pulling fluid and sediment up and out of the pier's wake region, depositing the sediment downstream as the wake vortices are shed and combine with the flow. The shedding of these Karman vortices occurs with regularity at a stable state, and the strength of these vortices depends on the pier shape and fluid velocity. The shed vortices' direction coincides with sediment deposition from the scour hole.

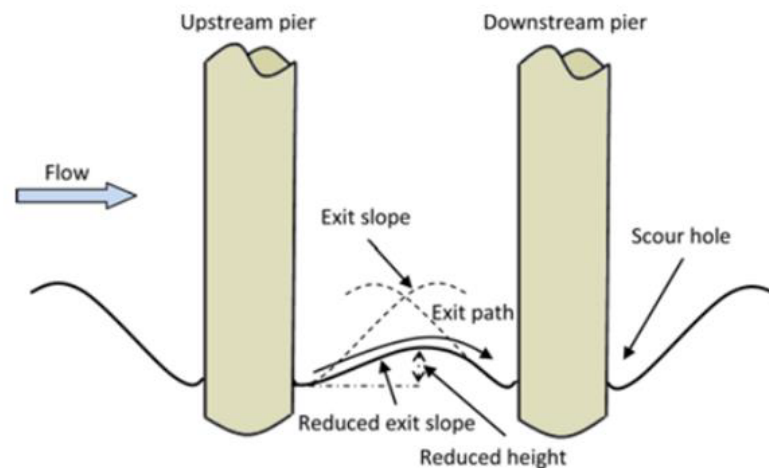
#### **2.4.2 Local Scour Mechanism around Pier Group**

In addition to the mechanism at the single pier, scour at piling groups is aided by four more processes. According to Hannah (1978) these mechanisms include reinforcing, sheltering, shed vortices, and compressed horseshoe vortex.

**Reinforcing:** When two piers are placed very close to each other, the scour hole of the individual pier overlaps. This overlapping reduces the exit slope and the bed level in the scour hole around the upstream pier. Thus, the energy required to move the bed materials is reduced; subsequently, the movement of the bed materials near the upstream pier is increased. This effect is referred to as the reinforcing effect. When the distance between two piers is increased or the flow skew angle is increased (from  $0^\circ$  to  $90^\circ$ ), the strength of the reinforcing effect is reduced (Hannah, 1978). **Figure 2.4** shows the impact of reinforcement in the scour hole elevation and exit slope for piers in tandem designs. The solid line represents the exit slope when there is a downstream pier present, while the dotted line represents the exit slope for a single pier.

**Sheltering:** Due to sheltering effect scour depth of the downstream pier is reduced. As the flow hits the upstream pier, the intensity of flow velocity reduces for the downstream pier. Besides, the bed materials scoured from the upstream pier were deposited near the downstream pier. By forcing the flow upward in front of the downstream pier, it weakens the horseshoe vortex. Thus, the horse-shoe vortex's strength and decreased velocity decrease the downstream pier's scour depth (Hannah, 1978).





**Figure 2.4** Schematic diagram showing the reinforcing effect. (Redrawn from Nazariha (1996)).

**Shed vortices:** When the vortices generated by the upstream and downstream piers collide, shed vortices are generated. The materials from the bed are lifted onto a pier downstream by these vortices. The speed of the shed vortex's convection and the distance between it and the affected pier have an impact on the strength of this lifting. The downstream pier is not in the path that the shed vortices trace in a tandem arrangement. Therefore, compared to staggered designs, the strength of shed vortices in moving material is lower.

**Compressed horseshoe vortex:** Each pier will have its own horseshoe vortex, except when they are situated very closely together or transverse to the flow. The compressed horseshoe vortex and reinforcing effects are strengthened by the interaction between the piers (Hannah, 1978).

## 2.5 Turbulence Parameters

### 2.5.1 Instantaneous Velocity

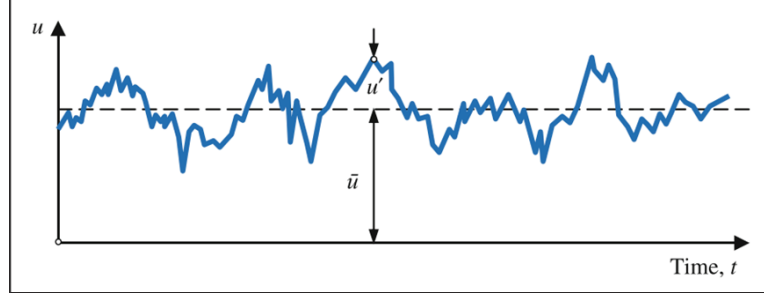
The velocity of an object at any specific moment is termed as instantaneous velocity. It can be considered as the average velocity for a very small time interval. Instantaneous velocity has two components named time average velocity and fluctuating components.

$$\text{Instantaneous Velocity} = \text{Time average velocity} + \text{Fluctuating component.}$$

The three-dimensional instantaneous velocities ( $u$ ,  $v$  and  $w$ ) in  $x$ ,  $y$  and  $z$  direction respectively can be represented by.

$$\left. \begin{aligned} u &= \bar{u} + u' \\ v &= \bar{v} + v' \\ w &= \bar{w} + w' \end{aligned} \right\} \quad (2.3)$$

**Figure 2.5** schematically shows the time variation of the velocity component in the streamwise direction (x-direction), denoted by  $u$ .



**Figure 2.5** Time variation of velocity in x direction.

### 2.5.2 Turbulent Intensity

The standard deviation of the fluctuation in the instantaneous flow velocity over a flowing fluid's mean average flow velocity can be used to define turbulent intensity. It represents the degree of flow velocity fluctuation. Turbulence intensity in x, y and z direction are shown in Eq (2.4).

$$\begin{aligned} \text{Turbulent intensity in x direction: } u^+ &= \sqrt{\overline{u'^2}}, \\ \text{Turbulent intensity in y direction: } v^+ &= \sqrt{\overline{v'^2}}, \\ \text{Turbulent intensity in z direction: } w^+ &= \sqrt{\overline{w'^2}} \end{aligned} \quad (2.4)$$

### 2.5.3 Turbulent Kinetic Energy

Turbulent kinetic energy represents the total turbulent intensity of the stream irrespective of direction. This indicates the mean kinetic energy per unit mass due to the generated eddy in turbulent flow. Turbulent kinetic energy is measured by the RMS (root mean square) of the velocity fluctuations. Usually, turbulent kinetic energy is defined by the following:



$$\text{Turbulent kinetic energy: TKE} = \frac{1}{2} (u'^2 + v'^2 + w'^2) \quad (2.5)$$

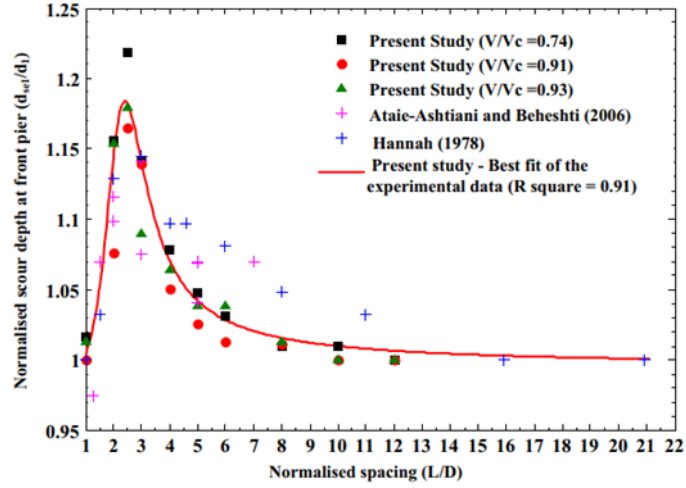
#### 2.5.4 Reynolds Shear Stress

Reynolds shear stresses are related to a stream's ability to transport sediments. It also indicates the exchange of turbulent momentum between layers of a stream. The correlations between velocity components parallel to and perpendicular to the background flow are represented by Reynolds shear stress (RSS). In the case of isotropic turbulence, this correlation will be disappeared. Reynolds shear stress can be defined by the following:

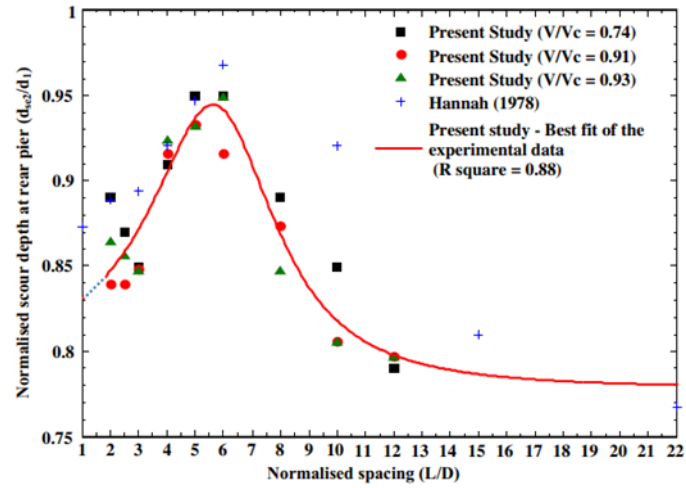
$$\text{Reynolds shear stresses: } -\rho \overline{u'v'}, -\rho \overline{u'w'}, -\rho \overline{v'w'} \quad (2.6)$$

#### 2.6 Effect of Pier Spacing on Scour Depth

One of the most important factors affecting the scour characteristics around pier groups is the spacings (S) between two piers. Keshavarzi et al. (2018) investigated the effect of pier spacing on scour depth by placing two identical cylinders in tandem arrangements at various C/C pier spacing (S). The scour at the rear pier is always less than the front pier due to the sheltering effect. At S/D=1, when two piers touched each other, the maximum scour depth equaled the scour depth obtained for a single pier. The maximum scour depth was obtained when the C/C spacing between two piers was 2.5D, and it was 22% higher compared to the single pier case. With the increase of spacing (S) between two piers (S/D>2.5), scour depth around the front pier was decreased, and at S/D>11-12, the scour depth around the front pier was equaled to a single pier. In the case of a rear pier, the maximum scour depth was obtained when S/D=6.5; with a further increase of S/D, scour depth decreased. **Figure 2.6** shows the effect of pier spacing on scour depth for two identical piers in tandem arrangement where C/C spacing between two piers is denoted by L.



(a)



(b)

**Figure 2.6** Maximum normalized scour depths for different normalized spacing at the upstream of (a) Front Pier & (b) Rear Pier (Keshavarzi et al., 2018).

## 2.7 Local Scour Predictive Equations around Pier Group

Various researchers have done numerous studies to estimate scour depth around a single pier and introduced several equations (Hosseini and Amini, 2015). These equations are used with some correction for a group of piers, typically assuming an effective diameter for a group of piers (Salim and Jones, 1998; Sheppard et al., 2004). Colorado State University Equation (CSU) or HEC-18 equation is the basis for most of the scour depth predictive equations developed for the pier group. The following section describes some widely used single-pier scour depth predictive equations, along with correction procedures for a group of piers.

### 2.7.1 HEC-18 Equation for a Single Pier

Federal Highway Administration recommended Colorado State University Equation (CSU) or HEC-18 equation. This equation is considered the most reliable and widely used one for calculating scour depth around a single pier. Eq (2.7) represents the CUS or HEC-18 equation.

$$\frac{D_s}{h} = 2.0K_1K_2K_3K_4 \left(\frac{D}{h}\right)^{0.65} F_r^{0.43} \quad (2.7)$$

where,

$D_s$ = Scour Depth

$K_3$ = Dune Factor

$h$ = Flow Depth

$K_4$ = Correction Factor for Armoring

$K_1$ = Shape Factor

$F_r$ = Froude Numer

$K_2$ = Flow Skew Angle Factor

The correction factors  $K_1$ ,  $K_2$ , and  $K_3$  can be obtained from **Table 2.1**, **Table 2.2**, and **Table 2.3** respectively.

The bed material size correction factor for armoring ( $K_4$ ) is equal to 1 ( $K_4=1$ ) if  $d_{50} < 2$  mm or  $d_{95} < 20$  mm. The correction factor for flow skew angle can be calculated by using Eq (2.8). Where,  $\alpha$  is the flow skew angle,  $l$  is the length of the pier and  $D$  is the pier diameter. If  $l/D$  is greater than 12,  $l/D$  is set to 12 for calculation  $K_2$ .

$$K_2 = \left( \cos\alpha + \frac{l}{D} \sin\alpha \right)^{0.65} \quad (2.8)$$

**Table 2.1** Pier nose shape correction factor,  $K_1$  (Richardson and Davis, 2001)

| Shape of pier nose | $K_1$ |
|--------------------|-------|
| Square nose        | 1.1   |
| Round nose         | 1.0   |
| Circular cylinder  | 1.0   |
| Group of cylinders | 1.0   |
| Sharp nose         | 0.9   |

**Table 2.2** Flow skew angle correction factor,  $K_2$  (Richardson and Davis, 2001)

| Angle | l/D=4 | l/D=8 | l/D=12 |
|-------|-------|-------|--------|
| 0     | 1.0   | 1.0   | 1.0    |
| 15    | 1.5   | 2.0   | 2.5    |
| 30    | 2.0   | 2.75  | 3.5    |
| 45    | 2.3   | 3.3   | 4.3    |
| 90    | 1.5   | 3.9   | 5.0    |

**Table 2.3** Dune factor,  $K_3$  (Richardson and Davis, 2001)

| Bed condition             | Dune height (m)      | $K_a$   |
|---------------------------|----------------------|---------|
| Clear-water scour         | N/A                  | 1.1     |
| Plane bed & antidune flow | N/A                  | 1.1     |
| Small dunes               | $0.06 \leq H \leq 3$ | 1.1     |
| Medium dunes              | $3 \leq H \leq 9$    | 1.1-1.2 |
| Large dunes               | $H \geq 9$           | 1.3     |

If the median particle size  $d_{50}$  is less than 2 mm or  $d_{95} < 20$  mm,  $K_4$  which is the correction factor for armoring is equal to 1. Where is if  $d_{50} > 2$  mm or  $d_{95} > 20$  mm,  $K_4$  is calculated by:

$$K_4 = 0.4 \frac{V_i - V_{icD_{50}}}{V_{cD_{50}} - V_{icD_{50}}} \quad (2.9)$$

$V_i$  is the flow velocity in the upstream of the pier,  $V_{icD}$  is the threshold velocity for initiating scour at the pile for the grain size  $D_x$ , which can be estimated by:

$$V_{icD_x} = 0.645 \left( \frac{D_x}{D} \right)^{0.053} V_{cD_x} \quad (2.10)$$

where,  $V_{cD_x}$  is the critical velocity that starts the movement of the sediment particle of size  $D_x$ .

The Froude number ( $F_r$ ) can be determined by:

$$F_r = \frac{U}{\sqrt{gh}} \quad (2.11)$$

where, U is the approach flow velocity, g is the acceleration due to gravity, and h is the flow depth.

### 2.7.2 CSU or HEC-18 Equation for Group of Piers

In order to use the CSU or HEC-18 equation of single pier for pier groups, Federal Highway Administration introduced effective pier width ( $D^*$ ) to replace pier diameter (D). Using CSU or HEC-18 equation for group of pier, scour depth can be estimated by the following equation

$$\frac{Ds}{h} = 2.0K_1K_2K_3K_4 \left( \frac{D^*}{h} \right)^{0.65} F_r^{0.43} \quad (2.12)$$

where  $D^*$  is the effective diameter of the pier group. Other parameters of the Eq (2.12) have been discussed in the previous article 2.7.1.

Effective width of an equivalent pier group can be calculated by the following equation:

$$D^* = D_p K_{sp} K_m \quad (2.13)$$

Where,

$D^*$  = Effective width of an equivalent full-depth pier

$K_{sp}$  = Correction factor for the pier spacing

$K_m$  = Correction factor for the number of piers in line with the flow

$D_p$  = Sum of non-overlapping projected pier widths onto a plane normal to the flow direction

The correction factor for pier spacing ( $K_{sp}$ ) can be calculated by:

$$K_{sp} = 1 - \frac{4}{3} \left( 1 - \frac{1}{\frac{D_p}{D}} \right) \left( 1 - \left( \frac{S}{D} \right)^{-0.6} \right) \quad (2.14)$$

The correction factor for the number of piers in line with the flow ( $K_m$ ) can be computed by the following equation

$$K_m = 0.9 + 0.1m - 0.0714(m - 1) \left[ 2.4 - 1.1 \frac{S}{D} + 0.1 \left( \frac{S}{D} \right)^2 \right] \quad (2.15)$$

where,  $m$  = Number of aligned piers or rows and  $S$  is the spacing between two piers.

This applies for pile groups with flow skew angle varying from  $0^\circ$  to  $90^\circ$ .  $K_m$  increases with the increase of  $m$ , and attained a maximum value for  $m = 6$ . For  $m > 6$ ,  $K_m$  is calculated using  $m = 6$ .

### 2.7.3 Correction Factor on CSU or HEC-18 Equation by Ashtiani and Beheshti

To use Eq. (2.12) (CSU or HEC-18) of single pier for pier group, Ataie-Ashtiani and Beheshti (2006) suggested a correction factor ( $K_{smn}$ ) as follows:

$$K_{smn} = 1.11 \frac{(m)^{0.0396}}{\left[ (n)^{0.5225} \left( \frac{S}{D} - 1 \right)^{0.1153} \right]} \quad (2.16)$$

where,  $m$  is the number of piers in-line with the flow, and  $n$  is the number of piers normal to the direction of flow. Multiplying the Eq (2.7) with this correction factor, scour depth around pier group can be estimated.

### 2.7.4 Gao et al. (1993)

A different correction factor for pier spacing was introduced by Gao et al. (1993) for the equation used for estimating scour depth in China. Clear water scour depth predictive equation used in China is given by Gao et al. (1993):

$$D_s = 0.46 K_{sh} D^{0.6} y^{0.15} d_{50}^{-0.07} \left( \frac{v - v'_c}{v_c - v'_c} \right) \quad (2.17)$$

where,  $D_s$  is the maximum scour depth,  $K_{sh}$  is the pier shape factor,  $y$  is the flow depth,  $v$  is the flow velocity and  $v'_c$  is the initial velocity of the local scour.

The correction factor introduced by Gao et al. (1993) is as follows:

$$K_s = 1 + 5 \left[ \frac{1}{1 + \left( \frac{S}{D} \right)} \right]^2 \quad (2.18)$$

Multiplying the scour depth obtained for single pier by using Eq (2.17) with the factor obtained from Eq (2.18), scour depth for pier group can be estimated.

### 2.7.5 Melville and Coleman (2000)

To estimate the scour depth around a single pier Melville and Coleman (2000) developed an equation. This equation is defined by:

$$D_s = K_{yD} K_I K_d K_s K_\alpha K_t \quad (2.19)$$

where,  $D_s$  is the equilibrium scour depth,  $K_{yD}$  denotes flow depth-pier size factor,  $K_I$  denotes flow intensity factor,  $K_d$  denotes sediment size factor,  $K_s$  is the foundation shape factor,  $K_\alpha$  denotes foundation alignment factor, and  $K_t$  for the time factor.

To calculate  $K_{yD}$ , following equation can be used:

$$K_{yD} = \begin{cases} 2.4D & \frac{D}{y} < 0.7 \\ 2\sqrt{yD} & 0.7 < \frac{D}{y} < 5 \\ 4.5y & \frac{D}{y} > 5 \end{cases} \quad (2.20)$$

where,  $y$  denotes flow depth and  $D$  is the pier diameter.

The flow intensity factor ( $K_I$ ) is given by:

$$K_I = \begin{cases} \frac{U - (U_a - U_c)}{U_c} & \frac{U - (U_a - U_c)}{U_c} < 1 \\ 1 & \frac{U - (U_a - U_c)}{U_c} \geq 1 \end{cases} \quad (2.21)$$

For uniform sand  
 $U_a = U_c$   
For non-uniform sand  
 $U_a = U$

The sediment size factor ( $K_d$ ) is given by:

$$K_d = \begin{cases} 1 & \frac{D}{d_{50}} > 25 \\ 0.57 \log \left( 2.24 \frac{D}{d_{50}} \right) & \frac{D}{d_{50}} \leq 25 \end{cases} \quad (2.22)$$

The foundation alignment factor ( $K_\alpha$ ) is given by:

$$(2.23)$$

$$K_{\alpha} = \begin{cases} 1 & \text{Circular Pier} \\ \left(\frac{1}{D} \sin \alpha + \cos \alpha\right)^{0.65} & \text{Non – circular Pier} \end{cases}$$

where, length of the pier is denoted by  $l$ .

The time factor ( $K_t$ ) is given by:

$$K_t = \begin{cases} 1 & \frac{U}{U_c} > 1 \\ \exp\left(-0.03 \left|\frac{U}{U_c} \ln\left(\frac{t}{t_e}\right)\right|^{1.6}\right) & \frac{U}{U_c} \leq 1 \end{cases} \quad (2.24)$$

where,  $t_e$  (days) is the development time for the equilibrium scour that is defined by:

$$t_e = \begin{cases} 48.26 \frac{D}{U} \left(\frac{U}{U_c} - 0.04\right) & \frac{h}{D} > 6, \frac{U}{U_c} > 0.4 \\ 30.89 \frac{D}{U} \left(\frac{U}{U_c} - 0.04\right) \left(\frac{h}{D}\right)^{0.25} & \frac{h}{D} \leq 6, \frac{U}{U_c} > 0.4 \end{cases} \quad (2.25)$$

Melville and Coleman (2000) recommended to replace the correction factor  $K_s K_{\alpha}$  in Eq (2.19) with the values given **Table 2.4**, for calculating scour depth around pier group which was only provided for pier groups with single row and double row arrangements.

**Table 2.4** Multiplying Factor ( $K_s K_{\alpha}$ ) for Pier Groups (Melville and Coleman, 2000)

| Type       | S/D | $K_s K_{\alpha}$ |                          |                 |
|------------|-----|------------------|--------------------------|-----------------|
|            |     | $\alpha < 5^0$   | $\alpha < 5^0$ to $45^0$ | $\alpha = 90^0$ |
| Single row | 2   | 1.12             | 1.4                      | 1.2             |
|            | 4   | 1.12             | 1.2                      | 1.1             |
|            | 6   | 1.07             | 1.16                     | 1.08            |
|            | 8   | 1.04             | 1.12                     | 1.02            |
|            | 10  | 1.0              | 1                        | 1               |
| Double row | 2   | 1.5              | 1.8                      | -               |
|            | 4   | 1.35             | 1.5                      | -               |



## 2.7.6 Sheppard equation

### 2.7.6.1 Single pier equation, according to Sheppard

To calculate the scour depth around single pier, Sheppard et al. (2004) developed an equation for clear water conditions ( $0.47 < U/U_c < 1$ ).

$$\frac{D_s}{D} = 2.5f_1\left(\frac{h}{D}\right)f_2\left(\frac{U}{U_c}\right)f_3\left(\frac{D}{d_{50}}\right) \quad (2.26)$$

where,  $D_s$  is the equilibrium scour depth.

$f_1\left(\frac{h}{D}\right)$ ,  $f_2\left(\frac{U}{U_c}\right)$  and  $f_3\left(\frac{D}{d_{50}}\right)$  can be calculated by the following equations:

$$f_1\left(\frac{h}{D}\right) = \tanh\left[\left(\frac{h}{D}\right)^{0.4}\right] \quad (2.27)$$

$$f_2\left(\frac{U}{U_c}\right) = 1 - 1.75\left[\ln\left(\frac{U}{U_c}\right)\right]^2 \quad (2.28)$$

$$f_3\left(\frac{D}{d_{50}}\right) = \left[\frac{\left(\frac{D}{d_{50}}\right)}{0.4\left(\frac{D}{d_{50}}\right)^{1.2} + 10.6\left(\frac{D}{d_{50}}\right)^{-0.13}}\right] \quad (2.29)$$

### 2.7.6.2 Pier group equation, according to Sheppard

To estimate scour depth around pier groups, Sheppard et al. (2004) introduced effective width ( $D^*$ ) to replace pier diameter ( $D$ ) in Eq (2.26). Effective width can be calculated using the following equation.

$$D^* = K_m K_{sp} K_H K_{sh} D_p \quad (2.30)$$

where  $D^*$  is the effective width,  $K_m$  is the correction factor for the number of piers in-line with the flow (m),  $K_{sp}$  is the correction factor for the pier spacing,  $K_H$  is the pier group height adjustment factor,  $K_{sh}$  is the shape factor, and  $D_p$  is the sum of projected width (calculated using HEC-18 technique). The pier spacing correction factor ( $K_{sp}$ ) was calculated using Eq. (2.14). The following equation may determine the shape factor:

$$K_{sh} = \frac{K_{sh(pile)} - K_{sh(pilegroup)}}{9} \left( \frac{S}{D_{pi}} \right) + K_{sh(pile)} - \frac{10}{9} (K_{sh(pile)} - K_{sh(pilegroup)}) \quad (2.31)$$

where  $K_{sh(pile)}$  for circular piers and  $K_{sh(pilegroup)}$  for pier groups are both equal to 1.

The following formula can be used to get the correction factor for the number of piers parallel to the flow:

$$K_m = \begin{cases} 0.045(m) + 0.96 & |\alpha| < 5^0, m \leq 5 \\ 1.19 & |\alpha| < 5^0, m > 5 \\ 1 & |\alpha| > 5^0 \end{cases} \quad (2.32)$$

For the pier group, the height adjustment factor was defined by the following equation:

$$K_H = \begin{cases} 1.5 \tanh \left( 0.8 \sqrt{\frac{H}{y_{max}}} \right) & 0 \leq \frac{H}{y_{max}} \leq 1 \\ 1 & \frac{H}{y_{max}} > 1 \\ 0 & \frac{H}{y_{max}} < 0 \end{cases} \quad (2.33)$$

$D_s$  can be estimated by the following equation:

$$D_s = \begin{cases} h & h \leq 2K_s D_p K_{sp} K_m \\ 2K_s D_p K_{sp} K_m & h > 2K_s D_p K_{sp} K_m \end{cases} \quad (2.34)$$

Where,  $D_s$  is the maximum scour depth.

### 2.7.7 Lacey's Equation

Lacey (1930) introduced the formula for the prediction of the maximum scour depth around piers show in Eq (2.35)

$$\frac{ds}{h} = 1.35 \times \left( \frac{q^2}{f} \right)^{1/3} - 1 \quad (2.35)$$

where,

$D_s$ =scour depth

$h$  = depth of flow

$f$  = silt factor calculated

$q$  = discharge per unit weight

Silt factor  $f$  can be calculated by the following equation.

$$f = 1.76 \times \sqrt{d_{50}} \quad (2.36)$$

where,

$d_{50}$  = median sediment size in mm.

Maximum scour depth using Lacey's equation can be computed by the following formula.

$$D_{smax} = 1.5 \times D \quad (2.37)$$

where,  $D_{smax}$  is the maximum scour depth.

## 2.8 Previous Studies

Due to rapid urbanization, traffic volume is increasing day by day. So, it has become essential to construct wider bridge or to create new one next to the existing one. This has led to the pier interreference. Besides, twin piers are favored for safety and economic consideration (Khaple et al., 2017). Prediction of scour depth around pier groups is much more complex compare to the single pier. Besides, the shape of the pier also affects the scour depth significantly. As pier scour is one of the main reasons for bridge failure around the world. So, for safe and economical design, an accurate prediction of scour depth around piers is essential.

Elliott and Baker (1985) investigated the effect of pier spacing on scour around bridge pier in clear water condition. Wooden rectangular piers with semicircular nose were placed at varying spacing. From their experiments, they concluded that when the spacing ( $S/D$ ) between the piers increases up to  $S/D=2$ . With further increase in spacing, scour depth decreases. For  $S/D>20$ , the spacing between the pier didn't affect scour depth.

Ataie-Ashtiani and Beheshti (2006) investigated local scour around pier groups. They considered a variety of conditions i.e., spacing, flow rates and sediment grain size. They

concluded that, scour depth around the upstream pier always exceeds that around at the downstream pier. Besides, in tandem arrangements, with the increase in spacing, maximum scour depth increased and reached a maximum value at  $S/D$  equals to 2. With further increase in pier spacing, maximum scour depth decreased and eventually became equal to that at a single pier.

Ataie-Ashtiani and Aslani-Kordkandi (2013) investigated the flow field around both single and tandem pier arrangements in fixed bed condition. They observed a decreased approach velocity near the bed towards the rear pier due to the sheltering effect of the upstream pier. Compared to the single pier arrangements, the values of turbulent intensity and turbulent kinetic showed a considerable decrease in the tandem pier arrangements. In tandem pier arrangements, turbulent intensity and turbulent kinetic energy was higher near the rear pier than that of the front pier.

Shrestha (2015) investigated the flow interaction and its effect on scour process for two circular piers in tandem arrangements. They observed the occurrence of vortex shedding behind the rear pier for  $S/D < 3$ . For  $2 \leq S/D \leq 3$ , he observed stronger turbulence behind the front pier, and as the spacing increased, he noticed a decrease in the strength of the turbulence characteristics.

Fael et al. (2016) investigated the effect of pier shape and alignment on the equilibrium scour depth around single piers. Using five pier shapes, a total of 55 long duration (minimum 168 h) experimental runs were conducted. From those experiments, shape factor (ratio of the scour depth around non-circular pier to the scour depth around circular pier) for rectangular round nose pier, oblong pier, rectangular square nosed pier and pile group cross section pier were obtained as 1.0, 1.0, 1.2 and 1.2 respectively. Besides, they concluded that, shape factor doesn't depend on the duration of the tests and the effect of pier shape also present in skewed piers.

Al-Shukur and Obeid (2016) conducted several experiments using ten different shapes of pier in single pier arrangement. In their experiments, they used three different velocities (0.18, 0.25 and 0.3 m/s). From their experiments, they concluded that, scour depth increases with increase in velocity. The shape factor for circular, rectangular, octagonal, chamfered, oblong and sharp nose piers were obtained as 1.0, 1.1, 0.9, 0.98, 0.85 and 0.733 respectively.

Khaple et al. (2017) investigated the effect of upstream pier on local scour at downstream pier. He conducted the experiment using multiple circular piers of the same diameter in three pier configurations at varying spacing (two piers in both tandem and staggered arrangements and three piers in staggered arrangements). The minimum duration of each of the experiment was 36h. From those experimental runs, it was found that in tandem arrangement, scour depth at the downstream pier varies from 0.8 to 0.87 time the scour depth of the single pier. The minimum scour depth at the downstream pier was obtained when  $S/D$  was 8. The scour depth around the upstream pier was always higher than the downstream pier. For, two piers in staggered arrangement, the minimum scour depth around the downstream pier was obtained at  $S/D=4$ .

Keshavarzi et al. (2018) conducted laboratory experiments to estimate the maximum scour depth at upstream of front and rear pier for two in-line circular piers. In their experiments, they placed two cylindrical shaped pier at varying spacing in tandem arrangements. They concluded that, scour depth at the upstream pier always exceed that at the downstream pier. The maximum scour depth was obtained at the upstream pier at  $S/D=2.5$ . For  $S/D>2.5$ , scour depth around the upstream pier decreased and became equal to that at a single pier at  $S/D=10$  (approximately).

Funde et al. (2018) conducted several laboratory experiments using three different shapes of pier to analyze scour depth around single pier. Circular, elliptical and diamond shape piers were used in their experiment. Besides, they also used two different sediment sample ( $d_{50} = 1.18$  mm and  $d_{50} = 2.36$  mm). The geometric standard deviation of sand with  $d_{50} = 1.18$  mm and  $d_{50} = 2.36$  mm were 1.6 and 2.0, respectively. Each of the experimental duration was 6h. Those experiments showed that, pier shape factor for circular, elliptical and diamond shaped piers were obtained as 1.0, 0.77 and 1.19 respectively. Besides, they also concluded that, for sediment with higher geometric standard deviation had a lower scour depth, for a given flow condition.

Shahhosseini and Guoliang (2019) conducted several experiments to analyze the effect of pier shape on local scour. In those experiments, piers of four different shapes named (cylindrical, rhombus with  $60^\circ$  inner angle, rhombus with  $30^\circ$  inner angle and oblong) were used. The shape factor for cylindrical, rhombus with  $60^\circ$  inner angle, rhombus with  $30^\circ$  inner angle and oblong piers were obtained as 1.0, 1.0, 0.9 and 0.9, respectively.

Vijayasree et al. (2019) performed laboratory experiments to investigate the influence of bridge pier shape on flow field and scour geometry. Several experiments were carried out using single piers of oblong, rectangular, trapezoidal, triangular and lenticular shapes with a common pier's length to width ratio of 5. The vertical instantaneous velocity was collected for 180 seconds along the centerline of the flume at several locations over the flat sand bed using Micro-ADV. From those experiments, they concluded that, scour formation around the piers with frontal sharp edge (triangular and lenticular) was less than the others (piers with frontal blunt edge i.e., oblong, rectangular and trapezoidal) as they sharply bifurcated the flow. They also stated that, the turbulent intensity at the downstream of the pier was higher than of the upstream of the pier for all shapes of pier except for lenticular pier (sharpest frontal edge). The higher turbulent intensity at the upstream of the pier indicated the higher potential for erosion and suspension, whereas the low intensity indicated the potential for sedimentation. Besides, turbulent intensity for frontal sharp-edged pier was less than that of frontal blunt edged pier. In case of Reynolds shear stress (RSS), they concluded that at the downstream of the frontal blunt edged pier, RSS showed oscillatory nature due to flow separation and vortex shedding, whereas at the upstream of the pier, the shear stress was negative due to reversal of the flow. For piers with frontal shape edge, RSS was almost constant because of sharp leading edge and smooth boundary. They identified three basic forms of scour that took place around the piers, the first one was at the upstream of the pier due horse-shoe vortices causing frontal scour, the second one was at the side of the piers due to flow separation and the last one was at the downstream of the pier due to vortices and turbulent wakes. Besides, they found that, along with maximum scour depth, occurrence of location of maximum scour depth depended on pier geometry. Maximum scour depth around frontal blunt edged piers was higher than that of frontal sharp edged pier.

Nowrin (2020) carried experimental study to investigate the turbulent flow around a pair of cylinders placed along the centerline in a rectangular open channel. Cylinders were placed at various C/C spacings and using ADV. Three-dimensional instantaneous velocity was collected at several locations. She observed that, upstream cylinder had great influence on both near and far wake of the downstream cylinder. Additionally, the recirculation in the midstream's near wake is stronger towards the surface than at the bottom.

Bento et al. (2021) investigated the flow field around oblong pier both in fixed bed (before the beginning of the scour) and in eroded bed (at the final stage of experiments) conditions. According to their investigation, at the upstream region of the pier, the stream-wise component of the velocity increases with the distance from the bed, whereas at the downstream of the pier a general increase of stream-wise velocity profile was observed as the vertical profile moved away from the oblong pier. Immediately at the upstream of the pier in eroded bed condition, the stream-wise velocity was negative near the bed due to flow separation and recirculation. Immediately at the downstream of the pier, alternate negative and positive values of the stream-wise velocity was observed due to the developed shedding and vortices.

Zobeyer et al. (2021) investigated the impact of the interactions between two tandem cylindrical piers on mean and turbulent flow characteristics. The experiments were done in fixed bed condition using two tandem cylindrical piers placed at varying spacings. Three-dimensional instantaneous velocity was measure using ADV to analyze the turbulent characteristics around the piers. They concluded that, the flow recirculation zone between the two piers was larger than that of the downstream of the rear pier. They observed the increase length of the recirculation zone with increase of pier spacing. They also observed maximum kinetic energy near the end of the recirculation zone.

Zhao et al. (2022) performed numerical simulation to analyze the effect of gap in local scour around two tandem piers. From the numerical simulations, the found that scour depth around front pier was higher than that of rear pier.

Basir (2022) conducted laboratory experiment to investigate local scour around two cylinder-shaped piers in tandem arrangements. The experiments were done on two different sediment bed using two different sizes of cylindrical pier. He found that maximum scour depths occurred around the larger pier due to greater obstruction to the flow. He also found that maximum scour depth occurred when the C/C spacing between the to in-line pier is  $2D$  ( $S/D=2$ ). Besides he developed a correction factor so that the CSU equation for predicting scour depth around single pier can be used for two cylindrical pier placed in tandem arrangements.

Literature review on the previous studies shows that local scour analysis around piers in tandem arrangements are carried out mainly for cylindrical piers. A very few



attempts were made to analyse the turbulent flow field around the cylindrical piers in tandem arrangements. The effect of pier nose shape on flow characteristics were studied by a few researchers for single pier configuration. Several researchers tried to develop pier shape factor in single pier arrangements. These studies have increased our understanding on the effect of pier nose shape on scour depth or the impact of front pier on rear pier for scour development and the associated turbulent characteristics for cylindrical piers. There is a lack of understanding in scour development when two in-line non circular piers are placed at varying spacing. Besides, turbulent flow characteristics around two non-circular piers in tandem arrangements also need to be focused. The effect of pier nose shapes in tandem arrangements, along with different pier spacing and different sediment beds has not been studied yet. Therefore, in this study, an attempt has been made to develop a laboratory set-up using two piers in tandem arrangements to investigate the effect of nose shape, spacing and median grain size on scour development. Besides, the flow characteristics around those arrangements were also studied



## CHAPTER 3

### EXPERIMENTAL SETUP AND METHODOLOGY

#### 3.1 General

The experimental study was conducted in a 21.3 m long recirculating tilting rectangular flume in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering, Bangladesh University of Engineering and Technology (BUET). A total 24 experimental runs were carried out using wooden piers of 13.75 cm long and 5.5 cm wide with the three different nose shapes (Round Nose, 60<sup>0</sup> Nose Angle and 90<sup>0</sup> Degree Nose Angle). Piers were placed both in single pier arrangement and two piers in tandem arrangements. For tandem arrangements, two identical piers were used. A downward-facing Acoustic Doppler Velocimeter (ADV) was used to measure three-dimensional instantaneous velocity components around the tandem cylinders in order to examine the turbulence parameters. A point gauge mounted at the top of the flume was used to measure the scoured bed profile. This chapter describes the experimental setup and methodology used for the experiments.

#### 3.2 Laboratory Setup

##### 3.2.1 Recirculating Tilting Flume

Recirculating tilting rectangular flume (21.3 m long, 0.76 m wide, and 0.74 m deep) was used for the experiments (**Figure 3.1**). The side walls of flume are vertical and made of clear plexiglass for visual inspection. The bottom of flume is made of steel. The flume is supported by an elevated steel truss. Water was supplied by external pipes, and the flume water depth was kept at the desired level. The necessary steps were taken to avoid any unnecessary leakage in the flume. A tailgate was installed at the end of the flume, which was used to control the depth of flow and thus the flow velocity. A reservoir is equipped with the recirculating tilting flume. Water was stored in the reservoir during the experiment. The reservoir existing facilities can regulate the reservoir water supply during the experimental runs.

##### 3.2.2 Electromagnetic Flow Meter

An electromagnetic flow meter was used to measure the flow rate through the flume. As the water passes through the flume, the flow rate is displayed on the digital screen at the external supply pipeline junction.



**Figure 3.1** Laboratory Flume (21.3 m long, 0.76 m wide, and 0.74 m deep)

### 3.2.3 Vernier Point Gauge

The scoured bed profile was measured using a Vernier point gauge with a minimum count of 0.05 mm. At the top of the flume, this Vernier point gauge has been installed to move in all three directions (longitudinal, transverse, and vertical). **Figure 3.2** shows the photograph of the Vernier point gauge used in the laboratory flume.



**Figure 3.2** Vernier point gauge that measures the scour depth

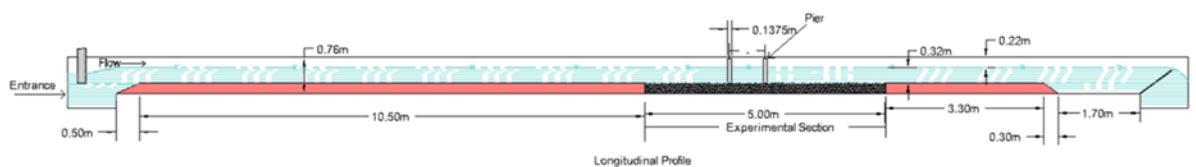
### 3.3 Experimental Setup

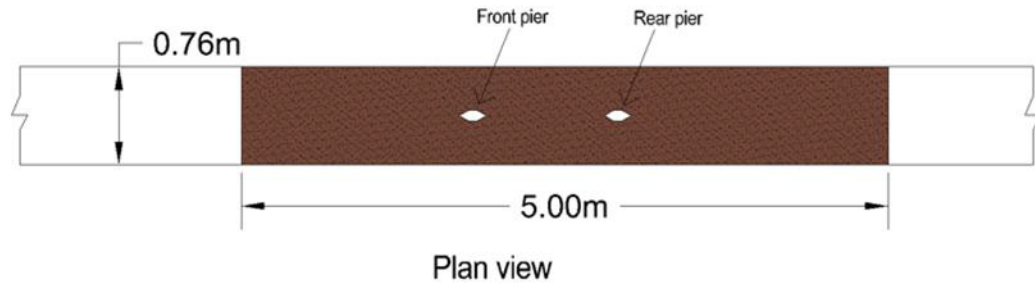
#### 3.3.1 Flume Modification

Existing flume bed was raised by 0.22 m using a wooden structure to conduct the experiment. Geotextile material was placed on the top of the raised bed to ensure uniform roughness during experiments. An experimental section (5.0 m x 0.76 m x 0.22 m) was constructed at about 11.0 m downstream from the entrance of the flume to ensure fully developed flow. The longitudinal slope of the flume bed has been maintained as 0.00187. **Figure 3.3** shows the experimental set up with geotextile embedded on the top of raised floor. **Figure 3.4** shows the full-length flume to the scale. Other pictures collected during the experiments are shown in **Figure A. 1** to **Figure A. 2** of **Appendix-A**.



**Figure 3.3** Modification of the flume with geotextile material on top.



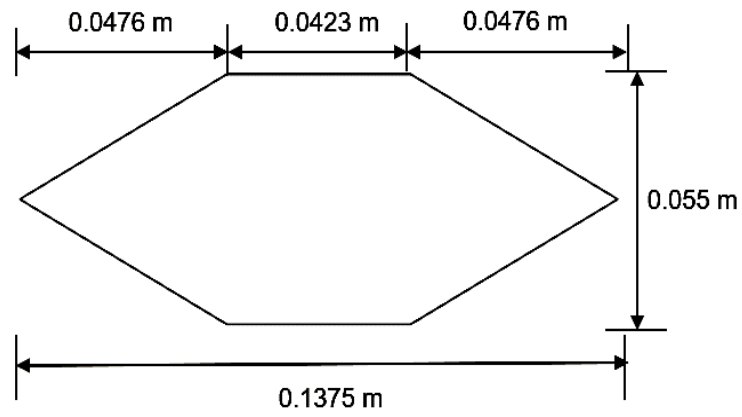


**Figure 3.4** Flume details with false floor and experimental section.

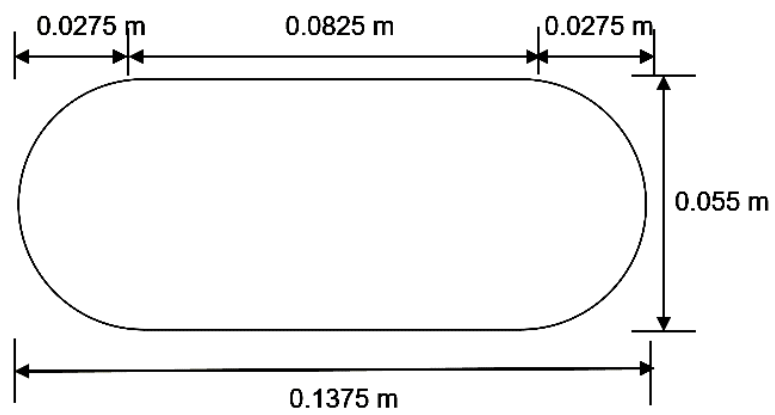
### 3.3.2 Pier Characteristics and Dimensions

Piers with three different types of nose shapes were used in this experimental study named round nose pier, pier with  $90^\circ$  nose angle and pier with  $60^\circ$  nose angle. All those piers were made of wood with a length ( $L$ ) of 13.75 cm and width ( $B$ ) of 5.5 cm. All the piers were painted to provide a smooth finishing. The width of the pier was chosen as 5.5 cm to develop shape factor comparing with scour depth data around circular pier of 5.5cm diameter obtained from Basir's study (Basir, 2022). And the ratio of the pier length to pier width ( $L/B$ ) was chosen as 2.5 based on literature review and considering the length of the experimental section and pier spacing (Al-Shukur and Obeid, 2016; Jalal and Hassan, 2020; Shahhosseini and Guoliang, 2019). Besides, according to Bridge Scour Manual of Florida Department of Transportation, the value of  $L/B$  affect scour depth up to 2, with further increase in the value of  $L/B$ , there is no effect on scour depth.

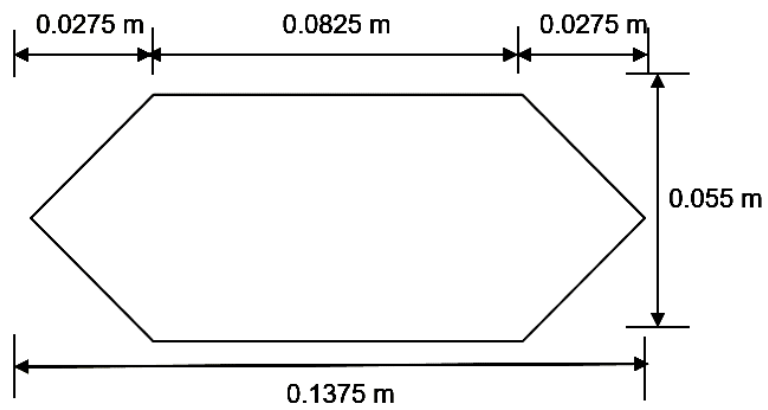
In this experiment, the ratio of the flume width to pier width was 13.81 which is grater then 6.5 to avoid wall effect of the flume. The ratio of the flow depth to the pier diameter was 5.81 which is greater than 3-4 so that the scour depth is independent of the flow depth (Omara et al., 2019). **Figure 3.5** shows the details dimension and shape of the piers used in these experiments.



(a)



(b)



(c)

**Figure 3.5** Piers with different nose shapes along with dimensions: (a) Round nose  
(b) 60° nose angle (c) 90° nose angle

### 3.3.3 Bed Materials

In this experiments, two locally available sands of different median particle size named Sand-A and Sand-B have been used. After sieve analysis the median particle size ( $d_{50}$ ) of Sand-A and Sand-B were found as 0.23 mm and 0.89 mm respectively. The geometric standard deviation ( $\sigma_g$ ) of Sand-A and Sand-B were 1.35 and 2.10.

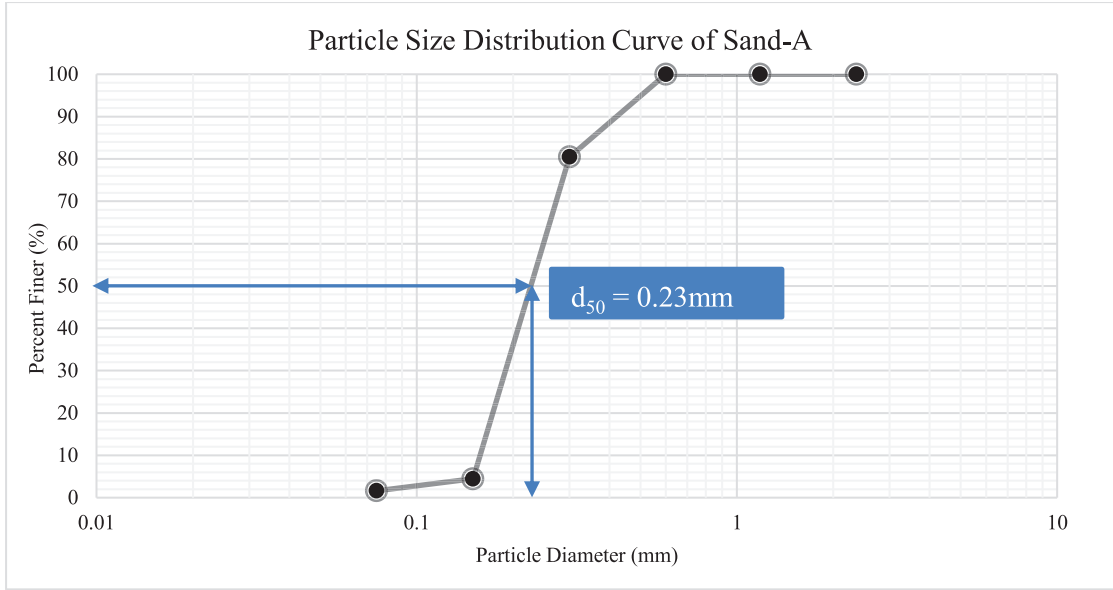
The selection of the bed materials was based on three factors, local availability, literature review and larger ranger of geometric standard deviation so that the effect of geometric standard deviation on scour depth can be observed. Rahul and Baldev (2020) conducted laboratory experiments with three different sediments with median particle size of 0.23 mm, 0.33 mm and 0.50 mm. Fael et al. (2016) conducted laboratory experiments to predict local scour with median particle size of 0.86 mm.

Sand is considered uniformly graded if  $\sigma_g \leq 1.4$  (Marsh et al., 2004). Thus, Sand-A ( $d_{50}= 0.23\text{mm}$ ) is uniformly graded and Sand-B ( $d_{50}= 0.89\text{mm}$ ) is considered non-uniformly graded. Before conducting each experiment, sand was placed in the experimental section following standard compaction procedure.

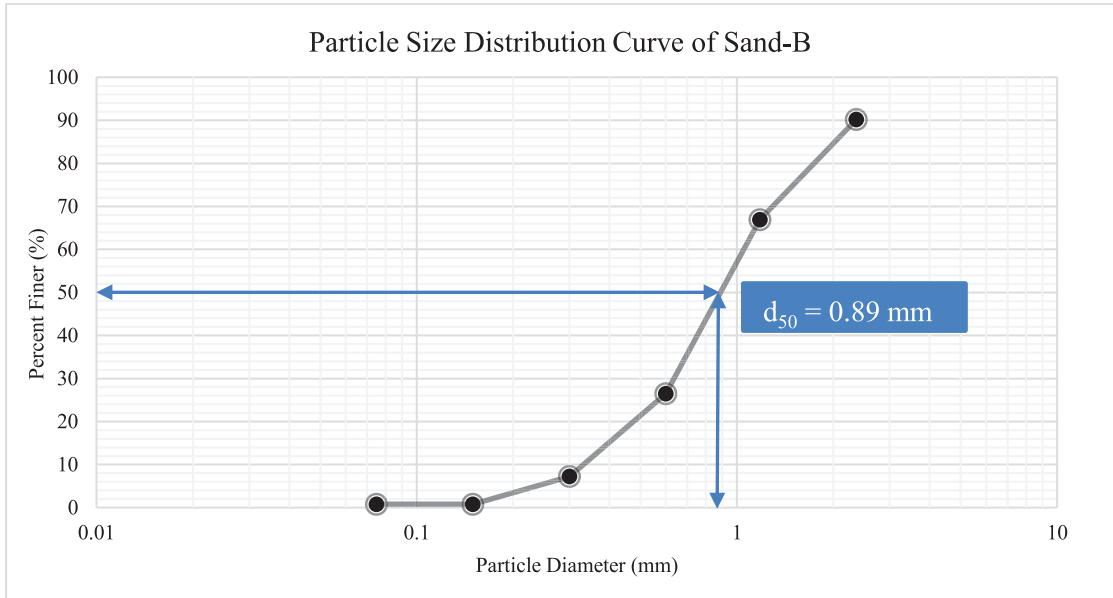
The geometric standard deviation was calculated as shown in Eq (3.1):

$$\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} \quad (3.1)$$

where,  $d_{84}$ , and  $d_{16}$  can be defined as the grain size of the sample, which is finer by weight of 84%, and 16%, respectively. **Figure 3.6** shows the particle size distribution curve of Sand-A and Sand-B.



(a)



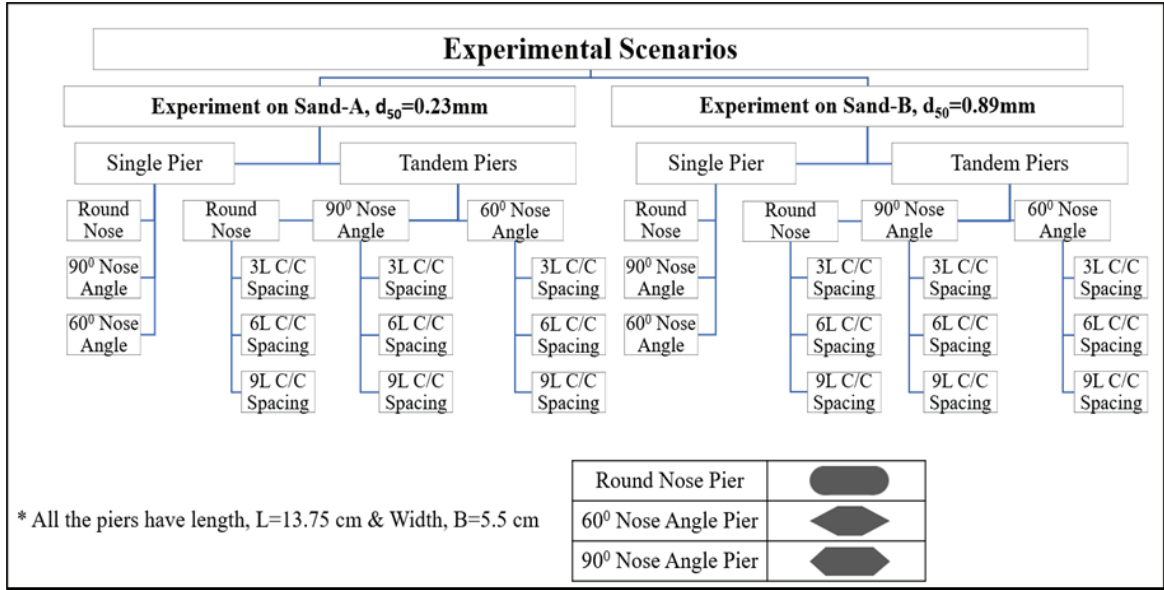
(b)

**Figure 3.6** Particle size distribution curve of (a) Sand-A and (b) Sand-B

### 3.4 Experimental Scenarios

Using three different shapes of pier, experiments were conducted both in single pier arrangement and tandem pier arrangements on both Sand-A and Sand-B. A total of 24 experiments were conducted in this study. The details of the experimental set up is shown in **Figure 3.7**.





**Figure 3.7** All the experimental scenarios of the study

All the experimental setup was arranged in six sets i.e., S1, S2, S3, S4, S5 and S6 (**Table 3.1**) for the convenience. S1, S2 and S3 consists of experiments on Sand-A with round nose pier, piers with 60° nose angle and piers with 90° nose angle, respectively. Whereas S4, S5 and S6 consists of experiments on Sand-B with round nose pier, piers with 60° nose angle and piers with 90° nose angle, respectively. Each set consists of four experimental runs (one single pier arrangements and three tandem piers arrangements with center to center spacing 3L, 6L and 9L, where L is the length of the pier). In tandem arrangements, two identical piers were used in this study.

#### 3.4.1 Flow Condition during experimental study

Clear water scour condition ( $U_0/U_c < 1$ ) was ensured for all the experimental runs. Experiments on Sand-A had a flow rate of  $0.0625\text{ m}^3/\text{s}$  and on Sand-B, flow rate was  $0.08\text{ m}^3/\text{s}$ . The flow depth was kept fixed to 32 cm during all the experimental runs. The hydraulic conditions for each experimental program are presented in **Table 3.2**. The approach shear velocity  $u^*$  was estimated by the methods of Reynolds shear stress ( $\tau = \rho u^{*2}(1 - z/\sigma) \cong -\rho \overline{u'w'}$ ) by Nezu and Nakagawa (1993). They measured Reynolds shear stress very close to the bed (10% depth from the bed), where  $\tau$  is the total shear stress,  $\sigma$  is the distance from the bottom to the point of the maximum velocity,  $\rho$  is the density of water,  $u'$  and  $w'$  are the streamwise and vertical velocity fluctuations, respectively. The critical shear velocity ( $u_c^*$ ) was calculated using the empirical formula as suggested by Chien and Wan (1983). Reynolds numbers ( $Re$ ) and



Froude number ( $F_r$ ) were estimated based on the flow depth. The critical velocity of sediment ( $U_C$ ) was calculated by the empirical formula provided by Zhang (2007), as shown in Eq.(3.3):

$$\tau = \rho u'^2 (1 - z/\sigma) \cong -\rho \overline{u'w'} \quad (3.2)$$

where,  $\tau$  = Total shear stress

$\sigma$  = Distance from the bottom to the point of the maximum velocity

$\rho$  = Density of water

$u'$  = Streamwise velocity fluctuations

$w'$  = Vertical velocity fluctuations.

$$U_C = \left( \frac{h}{d_{50}} \right)^{0.14} \sqrt{17.6 \frac{\gamma_s - \gamma}{\gamma} d_{50} + 0.000000605 \frac{10 + h}{d_{50}^{0.72}}} \quad (3.3)$$

where,  $U_C$ = critical velocity of sediment (m/s);  $h$ = approach flow depth (m);  $\gamma_s$  and  $\gamma$  are the unit weight of sand and water, respectively ( $\text{kN/m}^3$ );  $d_{50}$ = median particle size of the sediment (m).

In this study, approach flow velocity was measured at 2.0 m upstream of the front pier. Approach shear velocity for Sand-A and Sand-B were calculated as 1.38 cm/s and 1.90 cm/s respectively whereas the critical shear velocity were calculated as 1.4 cm/s and 2.0 cm/s respectively. Approach shear velocity was calculated by Reynolds shear stress method proposed by Nezu and Nakagawa (1993) and critical shear velocity was calculated by using equation suggested by Chien and Wan (1983). To calculate the approach shear velocity and the critical shear velocity Eq (3.2) and Eq (3.3) have been used.

**Table 3.1** Test scenarios of the experimental study

| Run ID | Pier Length(L) and Width (B) | Set No | Pier's Nose Shape                                                                                | C/C Spacing | Sediment Type | Mean Particle Size ( $d_{50}$ ) | Flow Rate Q         | Approach Flow Depth (h) | Approach Flow Velocity ( $U_0$ ) |
|--------|------------------------------|--------|--------------------------------------------------------------------------------------------------|-------------|---------------|---------------------------------|---------------------|-------------------------|----------------------------------|
|        | (cm)                         |        |                                                                                                  |             |               | (mm)                            | (m <sup>3</sup> /s) | (m)                     | (cm/s)                           |
| 1      | 13.75 and 5.5                | S1     | Round Nose      | Single      | Sand-A        | 0.23                            | 0.0625              | 0.32                    | 26.1                             |
| 2      |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 3      |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 4      |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |
| 5      |                              | S2     | 60° Nose Angle  | Single      |               |                                 |                     |                         |                                  |
| 6      |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 7      |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 8      |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |
| 9      |                              | S3     | 90° Nose Angle  | Single      |               |                                 |                     |                         |                                  |
| 10     |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 11     |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 12     |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |
| 13     |                              | S4     | Round Nose      | Single      | Sand-B        | 0.89                            | 0.08                | 0.32                    | 36.3                             |
| 14     |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 15     |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 16     |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |
| 17     |                              | S5     | 60° Nose Angle  | Single      |               |                                 |                     |                         |                                  |
| 18     |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 19     |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 20     |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |
| 21     |                              | S6     | 90° Nose Angle  | Single      |               |                                 |                     |                         |                                  |
| 22     |                              |        |                                                                                                  | 3 L         |               |                                 |                     |                         |                                  |
| 23     |                              |        |                                                                                                  | 6 L         |               |                                 |                     |                         |                                  |
| 24     |                              |        |                                                                                                  | 9 L         |               |                                 |                     |                         |                                  |

The approach shear velocity  $u^*$  was estimated by the methods of Reynolds shear stress ( $\tau = \rho u^{*2}(1 - z/\sigma) \cong -\rho \overline{u'w'}$ ) by Nezu and Nakagawa (1993). They measured Reynolds shear stress very close to the bed (10% depth from the bed), where  $\tau$  is the total shear stress,  $\sigma$  is the distance from the bottom to the point of the maximum velocity,  $\rho$  is the density of water,  $u'$  and  $w'$  are the streamwise and vertical velocity fluctuations, respectively. The critical shear velocity ( $u_c^*$ ) was calculated using the empirical formula as suggested by Chien and Wan (1983). Reynolds numbers ( $Re$ ) and Froude number ( $Fr$ ) were estimated based on the flow depth. The critical velocity of sediment ( $U_C$ ) was calculated by the empirical formula provided by Zhang (2007), as shown in Eq.(3.3):

$$\tau = \rho u^{*2}(1 - z/\sigma) \cong -\rho \overline{u'w'} \quad (3.2)$$

where,  $\tau$  = Total shear stress

$\sigma$  = Distance from the bottom to the point of the maximum velocity

$\rho$  = Density of water

$u'$  = Streamwise velocity fluctuations

$w'$ = Vertical velocity fluctuations.

$$U_C = \left( \frac{h}{d_{50}} \right)^{0.14} \sqrt{17.6 \frac{\gamma_s - \gamma}{\gamma} d_{50} + 0.000000605 \frac{10 + h}{d_{50}^{0.72}}} \quad (3.3)$$

where,  $U_C$ = critical velocity of sediment (m/s);  $h$ = approach flow depth (m);  $\gamma_s$  and  $\gamma$  are the unit weight of sand and water, respectively ( $\text{kN/m}^3$ );  $d_{50}$ = median particle size of the sediment (m).

**Table 3.2** Details regarding the experimental study

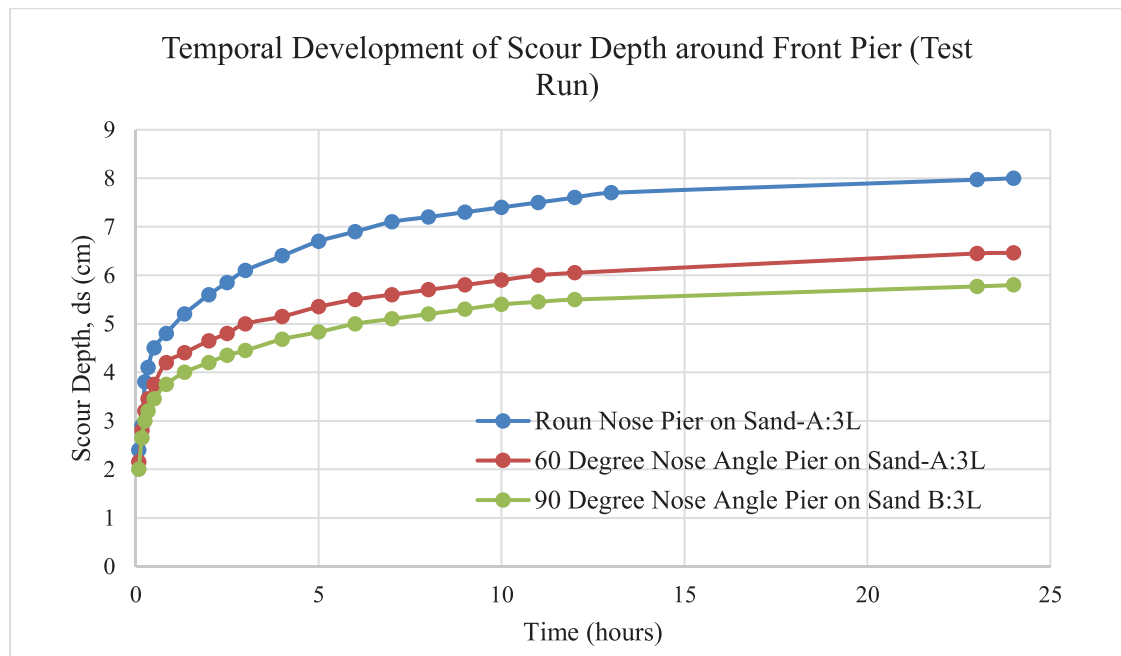
| Set No. | Pier's Nose Shape | Sediment type | Approach flow velocity ( $U_0$ ) | Critical velocity of sediment ( $U_C$ ) | Shear velocity ( $u^*$ ) | Critical shear velocity ( $u_c^*$ ) | Reynolds number ( $Re$ ) | Froude number ( $Fr$ ) |
|---------|-------------------|---------------|----------------------------------|-----------------------------------------|--------------------------|-------------------------------------|--------------------------|------------------------|
|         |                   |               | (cm/s)                           | (cm/s)                                  | (cm/s)                   | (cm/s)                              |                          |                        |
| S1      | Round Nose        | Sand-A        | 26.1                             | 26.54                                   | 1.38                     | 1.4                                 | 83520                    | 0.147                  |
| S2      | 60° Nose Angle    |               |                                  |                                         |                          |                                     |                          |                        |
| S3      | 90° Nose Angle    |               |                                  |                                         |                          |                                     |                          |                        |
| S4      | Round Nose        | Sand-B        | 36.3                             | 37.33                                   | 1.90                     | 2.0                                 | 116160                   | 0.205                  |
| S5      | 60° Nose Angle    |               |                                  |                                         |                          |                                     |                          |                        |
| S6      | 90° Nose Angle    |               |                                  |                                         |                          |                                     |                          |                        |

Where  $U_C$ = critical velocity of sediment (m/s);  $h$ = approach flow depth (m);  $\gamma_s$  and  $\gamma$  are the unit weight of sand and water, respectively ( $\text{kN/m}^3$ );  $d_{50}$ = mean particle size of the sediment (m).

### 3.5 Duration of the Run

The maximum local scour depth under clear water scour conditions is attained asymptotically with time, and as a result, the time to establish equilibrium scour depth may be indefinite (Breusers et al., 1977b). To fix the duration of each run, a numbers

of test runs lasting for about 24 hours were conducted to understand the development of maximum scour depth. Which showed that, around 80% of maximum scour depth was obtained within first 6 hours. Therefore, considering the number of test runs and the laboratory facilities, the duration of the each of the experimental run was chosen as 6 hours. Vittal et al. (1994) conducted an experimental investigation around pier groups for 6 hours. Salim and Jones (1998) tested exposed pile foundations for 4 hours. Other researchers also (Mia and Nago, 2003; Yanmaz and Altinbilek, 1991) reported similar duration for experimental runs. **Figure 3.8** represents the temporal development of scour depth during test runs of 24-hour duration.



**Figure 3.8** Temporal development of scour depth during test runs of 24 hour duration.

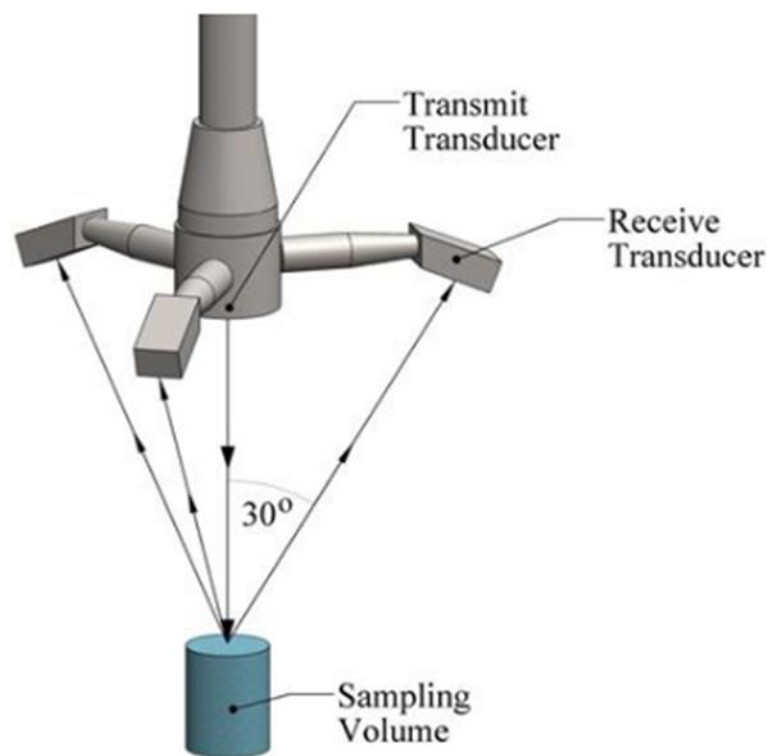
### 3.6 Velocity Measurement

Three-dimensional velocity components served as the primary measurement throughout the experiments. This study used a downward-facing ADV to measure the velocity components.

#### 3.6.1 Acoustic Doppler Velocimetry (ADV)

Velocimeters are a particular type of high-resolution 3D equipment used to examine rapid velocity fluctuations in a lab or ocean. These instruments can measure with high sampling rates in a small point using three or more focused beams. On the basis of the

Doppler shift effect, measurements are made by determining the velocity of particles in a remote sampling volume. **Figure 3.9** shows the components of the probe. The signal processing hardware, which handles the signal generation and processing necessary for the ADV to conduct velocity measurements, is another essential measuring equipment. Sontek (2001) asserts that the processor generates the electrical signals that are afterwards converted at the transducers into acoustic energy. In order to determine velocity, it additionally digitizes the return signal and applies Doppler processing. The signal processor is protected from accidental water contact by being contained in a splash-proof casing. ADV mounting must be 5 cm from the volume being sampled to the transducer's center. To avoid data errors, all acoustic transducers must be submerged during data collecting.



**Figure 3.9** Components of Acoustic Doppler Velocimeter Probe (Sontek, 2001)

The Horizon ADV software package was used to collect data using the ADV instrument. This software can be used to put together ADV systems and display data files that come from them. For processing of ADV data, WinADV was used.

### 3.7 Data Acquisition

In each of the experimental run, three-dimensional instantaneous velocity measurement was done by ADV and scour depth data was collected using vernier point gauge.

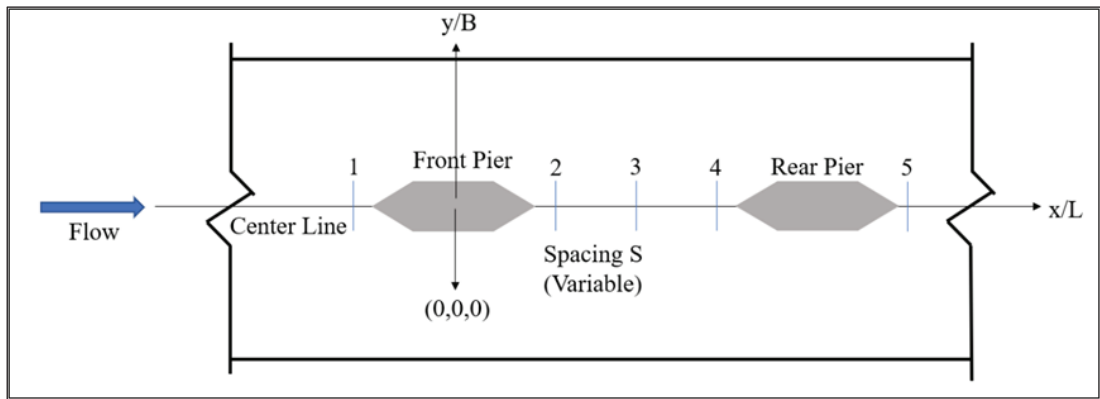
### 3.7.1 ADV Data Collection

In tandem pier arrangement, ADV data was collected along the centerline ( $y/B=0$ ) at 5 sections. Section 1 and Section 2 were at just upstream and downstream of the front pier. Section 2 was at the middle of the 2 piers and Section 4 and Section 5 were at just upstream and downstream of the rear pier. ADV data collection points for single pier and tandem pier arrangements are shown in **Figure 3.10** and **Figure 3.11** respectively.

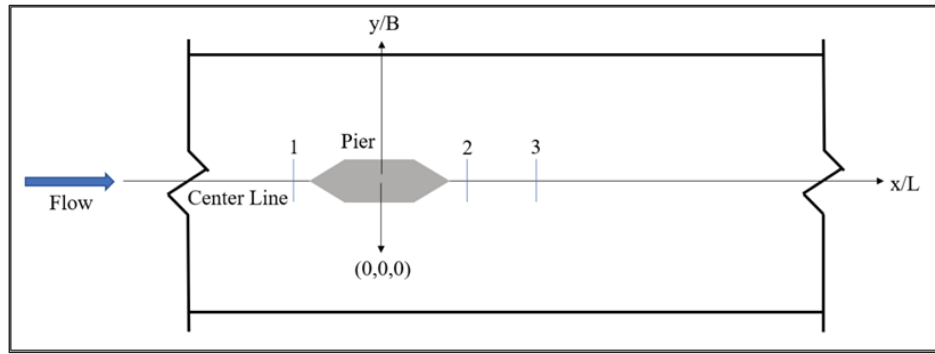
**Table 3.3** shows the data collection point of the tandem pier arrangement along the center line. **Table 3.4** represents a sample of unfiltered instantaneous velocity data collected using ADV at a sampling rate 50Hz. **Figure 3.12** represents ADV data processing on Win-ADV software.

In single pier arrangement, ADV data was collected along the centerline ( $y/B=0$ ) at 3 sections. Section 1 was located at the upstream of the pier and Section 2 and Section 3 were located at the downstream of the pier.

The Cartesian coordinate system ( $x, y, z$ ) was taken in the streamwise, transverse, and vertical directions. The origin of the single pier and tandem piers was centered at the base of the front pier.



**Figure 3.10:** Schematic plan view of ADV data collection Points in the tandem pier arrangements (along the center line)



**Figure 3.11** Schematic plan view of ADV data collection points for single pier experiment (along the center line)

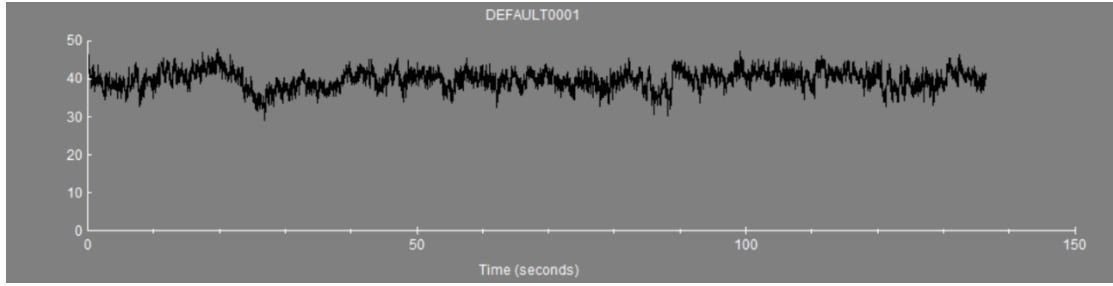
**Table 3.3** Details of ADV data collection points

| Run ID | Pier's Nose Shape | C/C Spacing Between Two Piers(S) | Number of Measured sections | Sections Streamwise Location (x/L) |     |     |     |     | Sediment Type |
|--------|-------------------|----------------------------------|-----------------------------|------------------------------------|-----|-----|-----|-----|---------------|
|        |                   |                                  |                             | 1                                  | 2   | 3   | 4   | 5   |               |
| 1      | Round Nose        | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     | Sand-A        |
| 2      |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 3      |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 4      |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |
| 5      | 60° Nose Angle    | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     |               |
| 6      |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 7      |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 8      |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |
| 9      | 90° Nose Angle    | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     |               |
| 10     |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 11     |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 12     |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |
| 13     | Round Nose        | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     | Sand-B        |
| 14     |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 15     |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 16     |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |
| 17     | 60° Nose Angle    | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     |               |
| 18     |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 19     |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 20     |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |
| 21     | 90° Nose Angle    | Single                           | 3                           | -0.9                               | 0.7 | 1.7 |     |     |               |
| 22     |                   | 3L                               | 5                           | -0.9                               | 0.7 | 1.5 | 2.1 | 3.7 |               |
| 23     |                   | 6L                               | 5                           | -0.9                               | 0.7 | 3.0 | 5.1 | 6.7 |               |
| 24     |                   | 9L                               | 5                           | -0.9                               | 0.7 | 4.5 | 8.1 | 9.7 |               |

**Table 3.4** ADV sample data collection at 50 Hz

| <b>Unfiltered ADV Data Sample</b> |                      |                      |                      |                |                |
|-----------------------------------|----------------------|----------------------|----------------------|----------------|----------------|
| <b>Time, seconds</b>              | <b>V<sub>x</sub></b> | <b>V<sub>y</sub></b> | <b>V<sub>z</sub></b> | <b>Avg COR</b> | <b>Avg SNR</b> |
| 0.01                              | 33.31                | 5.06                 | 0.7                  | 95             | 17.9           |
| 0.03                              | 33.7                 | 3.92                 | 1.68                 | 95.3           | 19.1           |
| 0.05                              | 34.29                | 5.56                 | 2.23                 | 96.3           | 19.9           |
| 0.07                              | 36.27                | 2.73                 | 1.25                 | 96             | 21.1           |
| 0.09                              | 37.76                | 1.96                 | 3.08                 | 95.7           | 27.7           |
| 0.11                              | 37.04                | 2.75                 | 2.54                 | 96.3           | 33.4           |
| 0.13                              | 39.61                | 0.35                 | 0.47                 | 95             | 32.4           |
| 0.15                              | 38.08                | -0.22                | 2.61                 | 95.7           | 21.9           |
| 0.17                              | 39.66                | -0.74                | 3.29                 | 96.7           | 30.4           |
| 0.19                              | 41.04                | -0.17                | 1.85                 | 96             | 18.9           |
| 0.21                              | 42.85                | -0.32                | 1.92                 | 96.3           | 25.9           |
| 0.23                              | 40.82                | -0.29                | 2.35                 | 96             | 25.1           |
| 0.25                              | 40.52                | -2.71                | 2.53                 | 96.3           | 22.2           |
| 0.27                              | 40.35                | -0.34                | 3.11                 | 96             | 27.7           |
| 0.29                              | 38.81                | -0.25                | 2.8                  | 96.3           | 33.4           |
| 0.31                              | 40.29                | -1.45                | 4.92                 | 93.7           | 32.6           |
| 0.33                              | 39.13                | -0.59                | 2.17                 | 93.7           | 20.5           |
| 0.35                              | 38.02                | -0.52                | 1.94                 | 93.3           | 26.6           |
| 0.37                              | 39.04                | 3.02                 | 3.1                  | 95             | 25.1           |
| 0.39                              | 36.68                | 0.69                 | 4.24                 | 95.3           | 28.9           |
| 0.41                              | 38.26                | -2.09                | 2.62                 | 94.7           | 22.2           |
| 0.43                              | 38.11                | -2.27                | 3.65                 | 95             | 29.4           |
| 0.45                              | 37.35                | 0.22                 | 3.14                 | 95             | 26             |
| 0.47                              | 38.17                | 1.61                 | 1.67                 | 95             | 20.5           |
| 0.49                              | 37.58                | 3.75                 | 1.9                  | 96             | 26.7           |
| 0.51                              | 37.83                | 2.26                 | 2.72                 | 94.7           | 20.9           |
| 0.53                              | 35.51                | -0.78                | 3.3                  | 95.3           | 18.1           |
| 0.55                              | 36.13                | -0.54                | 3.44                 | 95             | 19.1           |

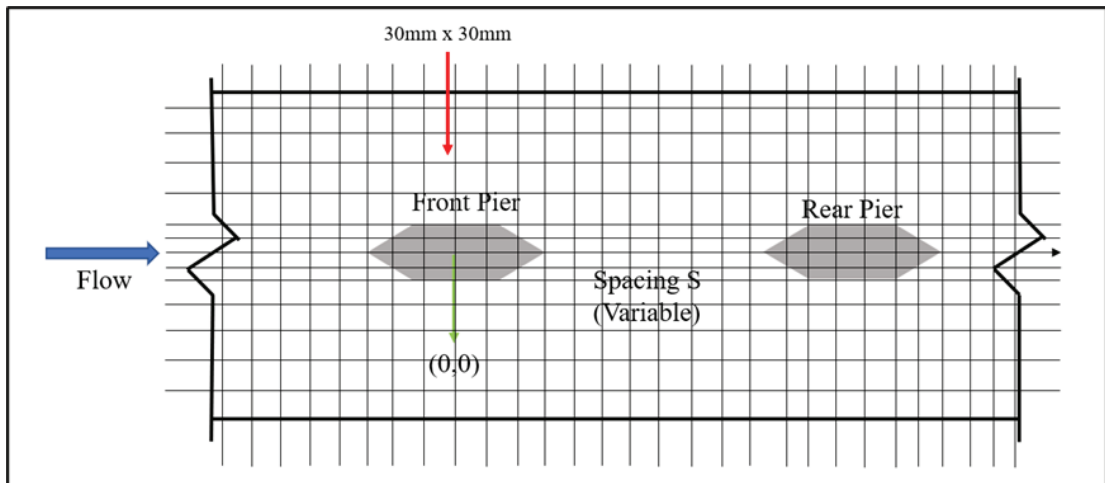




**Figure 3.12** Processing of ADV data on Win-ADV.

### 3.7.2 Scour Data Collection

During the experiment, to obtain temporal variation of scour depth both at front and rear pier, measuring tape was attached and scour depth was recorded at several time intervals. At the beginning of the experiment, scour data was recorded at 10 minutes interval for the first hour. 20 minutes intervals were chosen for the remaining 5 hours. At the end of the experiment, maximum scour depth around the piers and the scour profile was measured using vertically mounted point gauge. **Figure 3.13** shows the schematic plan view of the scour depth measuring grid (30mm x 30mm) around the tandem piers. Similarly, the scoured bed profile around the single pier was also measured.

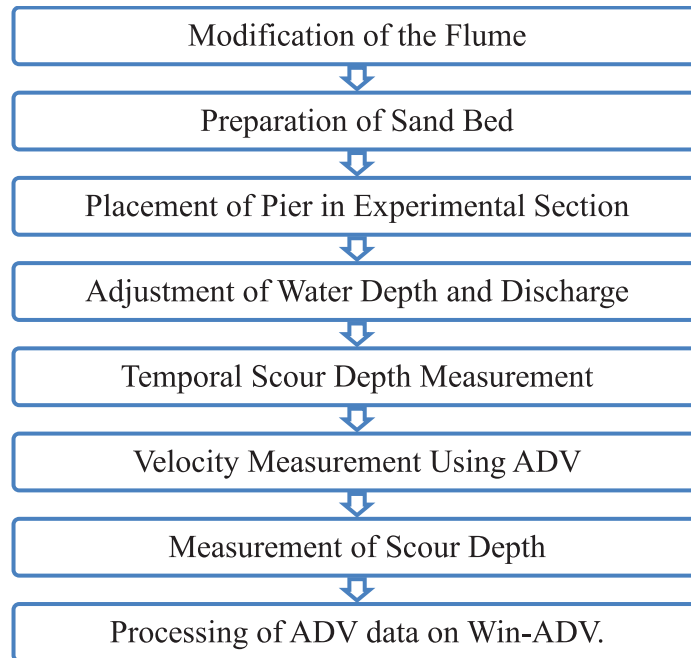


**Figure 3.13** Schematic view of the scour depth measuring grid in tandem arrangement.

### 3.8 Experimental Procedure

In this study, as stated earlier total of 24 experimental runs were conducted using both single pier and tandem pier arrangements. Piers were placed on the test sediment bed section which was 5m long and 0.76m wide and 0.22m deep. Two types of sediment

beds were prepared using Sand-A ( $d_{50} = 0.23$  mm) and Sand-B ( $d_{50} = 0.89$  mm). Piers were placed both in single pier and tandem pier arrangements. In tandem pier arrangements, two identical piers were used. The schematic diagram of the overall experimental procedures is shown in **Figure 3.14**.



**Figure 3.14** Schematic diagram of the overall experimental procedures.

The details procedure of each of the experiments are presented below:

- ❖ **Modification of the Flume:** Existing flume bed was raised by 0.22 m using a wooden structure to conduct the experiment. Geotextile material was placed on the top of the raised bed to ensure uniform roughness during experiments. An experimental section (5.0 m x 0.76 m x 0.22 m) was constructed at about 11.0 m downstream from the entrance of the flume to ensure fully developed flow.
- ❖ **Preparation of Sand Bed:** The experimental section was filled with sand in layers. In each layer compaction was done to ensure uniform compaction for all the experimental runs. At the starting of the test section geotextile material was placed above the sand bed for some distance and then inserted into the sand bed to prevent washing out of the sand due to incoming flow. The sand bed was leveled with a straight wooden bar and using the vertically mounted point gauge, it was ensured that the sand bed was properly leveled.
- ❖ **Placement of the Pier in the Experimental Section:** In single pier arrangement, an individual pier was placed along the centerline of the

experimental section (at the middle) . In case of tandem pier arrangements two identical piers were placed along the centerline of the experimental section in such a manner so that the front pier was located at the middle of the experimental section. Proper precaution was taken to so that the pier was fully vertical, which was checked using a level. To avoid unnecessary movement of the pier due to the action of the flowing water, weight was placed above the pier. To measure the temporal scour depth, measuring tape was attached with the pier.

- ❖ **Adjustment of Water Depth and Discharge:** At first, the pump placed at the downstream of the flume was started slowly and the flume was filled with water to a certain level. Then the main pump was started and the discharge was increased gradually to achieve desired discharge. Using the tail gate, the design water level (0.32 m) was achieved.
- ❖ **Temporal Scour Depth Measurement:** Throughout the studies, tape fastened to the pier was used to measure the temporal evolution of scour depth at various time intervals. For the first 30 minutes, scour depth was measured at 5 minutes interval. Scour depth was then measured every ten minutes for the following hour. Following that, scour depth was monitored every 30 minutes.
- ❖ **Velocity Measurement:** To avoid the disturbance of the flow due to the pier, approach flow velocity was measure along the centerline of the channel at 2 m upstream of the front pier. Using ADV velocity was measured at several vertical location (9 points) , so that the logarithmic velocity profile can be obtained. To analyze different turbulence parameters, ADV measurement was done at several location along the centerline of the channel. In each location, ADV measurement was done at several vertical location (9 points). At each point, the duration of the ADV measurement was 2 minutes at 50 Hz so that the turbulence characteristics can be fully described (Strom and Papanicolaou, 2007).
- ❖ **Measurement of Scour Depth:** After the completion of the experimental run, the flume was fully drained out. The scour depth was measured at different points shown in **Figure 3.13** using vertically mounted point gauge. Besides, the extent of scour depth in longitudinal and transverse direction were also measured.

❖ **Processing of ADV Data on WinADV:** Using Win-ADV, the collected ADV data was processed.

### 3.9 Uncertainty Analysis

Using 12 sets of ADV data, uncertainty of ADV measurement was computed. These data were collected at three different vertical depths ( $z/h=0.2, 0.6$  and  $0.8$ ). At each point, data was collected for 2 minutes at 50 Hz. Data used for uncertainty analysis was collected at different day. **Table 3.5** shows the uncertainty analysis of the measured ADV data. Where,  $u$ ,  $v$ , and  $w$  are the velocity components of streamwise, transverse, and vertical directions, respectively.  $TI_u$ , TKE, and RSS is the turbulence intensity in the streamwise direction, turbulent kinetic energy, and Reynolds shear stress, respectively.

**Table 3.5** Uncertainty analysis of ADV measurements

| <b>z/h</b> | <b>u</b>   | <b>v</b>   | <b>w</b>   | <b><math>TI_u</math></b> | <b>TKE</b>                   | <b>RSS</b>                   |
|------------|------------|------------|------------|--------------------------|------------------------------|------------------------------|
|            | (cm/s)     | (cm/s)     | (cm/s)     | (cm/s)                   | ( $\text{cm}^2/\text{s}^2$ ) | ( $\text{cm}^2/\text{s}^2$ ) |
| 0.2        | $\pm 0.36$ | $\pm 0.18$ | $\pm 0.19$ | $\pm 0.06$               | $\pm 0.36$                   | $\pm 0.15$                   |
| 0.6        | $\pm 0.31$ | $\pm 0.05$ | $\pm 0.09$ | $\pm 0.05$               | $\pm 0.22$                   | $\pm 0.20$                   |
| 0.8        | $\pm 0.19$ | $\pm 0.21$ | $\pm 0.02$ | $\pm 0.05$               | $\pm 0.13$                   | $\pm 0.33$                   |

## CHAPTER 4

### RESULTS AND DISCUSSIONS

#### 4.1 General

In this study, a total of 24 experimental runs were conducted to investigate the turbulence parameters and scour characteristics around single piers and two identical piers in tandem arrangements at varying C/C spacing (3L, 6L and 9L) on two different sediment bed (Sand-A and Sand-B) using three different shapes of pier (round nose, pier with 60° nose angle and pier with 90° nose angle). To understand the turbulence characteristics around piers, ADV data was collected along the centerline at different locations (both upstream and downstream of piers). Using a vertically mounted point gauge, scour depth were measured. The details procedure of each experimental scenario was described in Chapter 3. Obtained results from the experiments are presented in this chapter which includes the variation of streamwise velocity, turbulence characteristics (turbulence intensity, turbulence kinetic energy and Reynolds shear stress), temporal development of scour hole around front and rear pier and effect of pier spacing on maximum scour depth etc. Besides, a comparison between the obtained maximum scour depth around the piers, with the widely used maximum scour depth predicting equation has been presented. Also, pier shape factors (ratio of scour depth around non-circular pier to the scour depth around circular pier) have been calculated and correction to the CSU equation (for single circular) pier has been introduced to incorporate the effect of pier spacing on scour depth for identical piers placed in tandem arrangement.

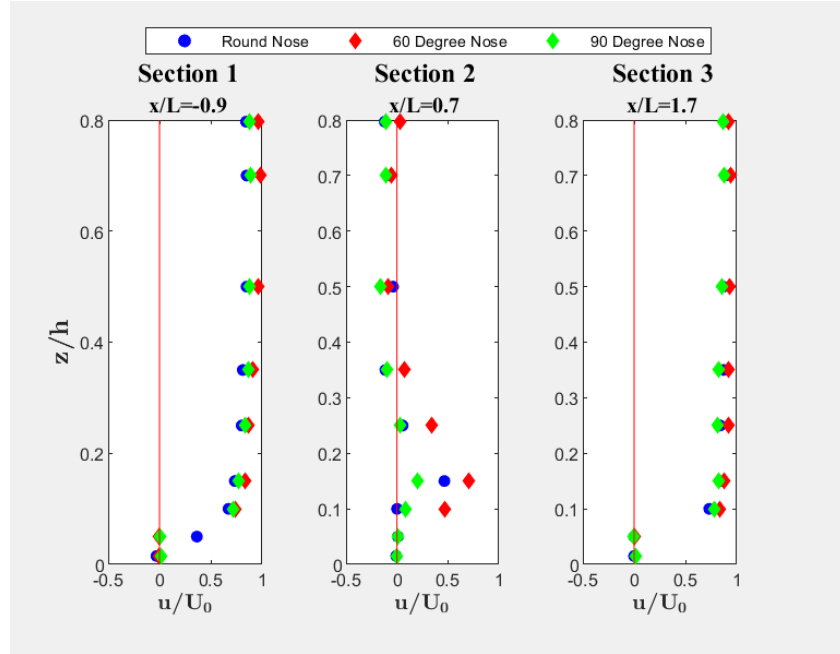
#### 4.2 Normalized Streamwise Velocity Variations along the Centerline

Using ADV point velocity measurement were conducted at nine different vertical depth at five and three locations for single pier and tandem pier arrangement respectively along the centerline. In tandem pier arrangement, two identical piers were placed at 3L, 6L and 9L C/C pier spacing.

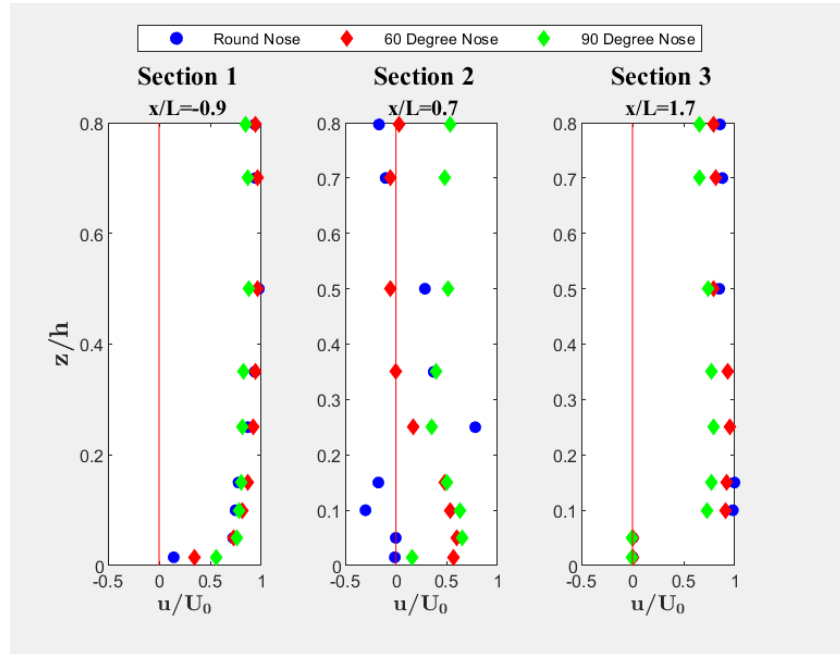
##### 4.2.1 Single Pier

Normalized streamwise velocity profile ( $u/U_0$  vs  $z/h$ ) around three different nose shapes pier on Sand-B ( $d_{50}=0.89$  mm) are plotted in **Figure 4.1**, which shows that, at Section-1 (just upstream of the pier) near the bed, streamwise velocity is lowest and with increase distance from the bed, streamwise velocity increases (logarithmic velocity

profile). At Section-2 (wake of the pier), maximum velocity occurs at  $z/h=0.15$ , then decreased and became negative due to flow reversal at  $z/h=0.25-0.35$ .



(a)



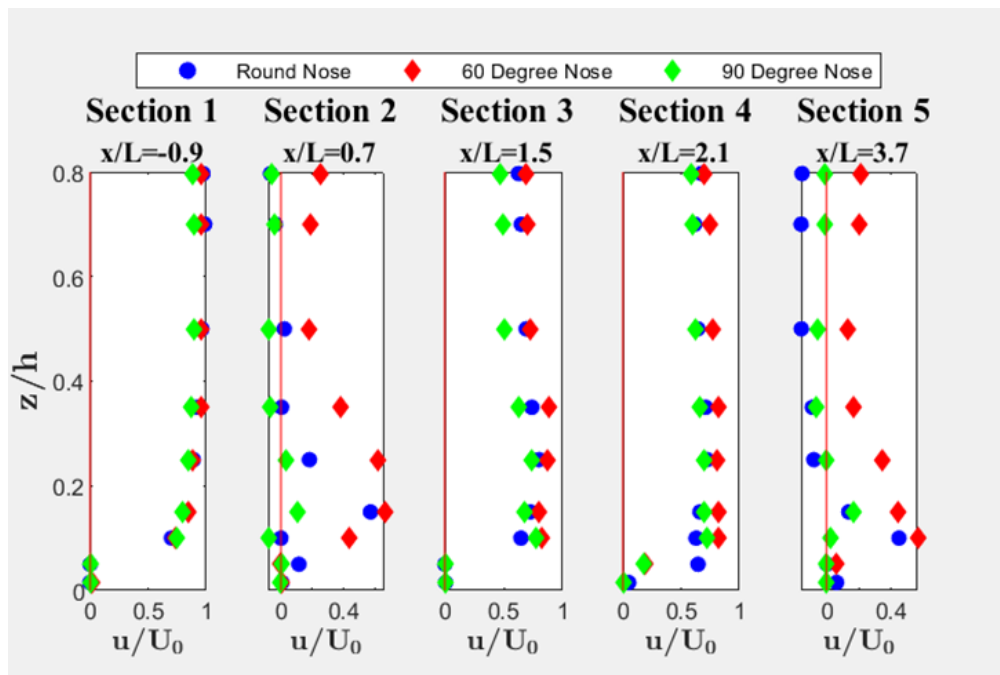
(b)

**Figure 4.1** Normalized streamwise velocity variation ( $u/U_0$  vs  $z/h$ ) around single pier:  
(a) Sand-B (b) Sand-A.

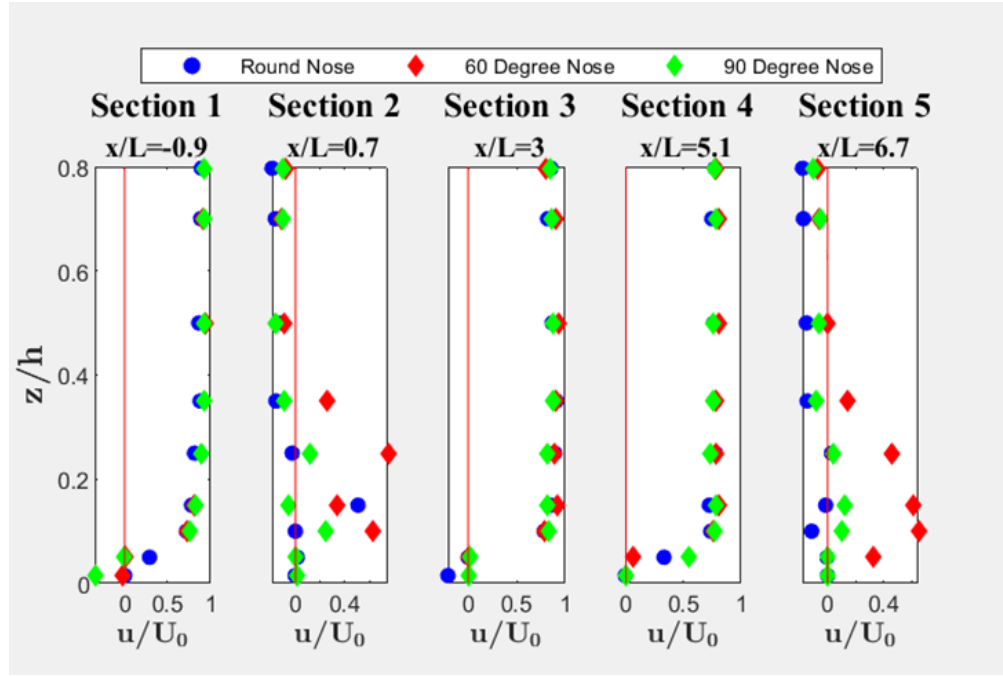
Shrestha (2015) reported that along the centerline of the flume, at the wake of the pier, the value of  $u/U_0$  decreased as the value of  $z/h$  increased. He also noticed that, the value of  $u/U_0$  increased at the wake with increase in the value of  $x/L$  which can be observed at Section-3, where the value of  $u/U_0$  was higher compare to Section-2. Besides, it can be observed that negative streamwise velocity component or flow reversal was found weaker for pier with  $60^\circ$  nose angle. Vijayasree et al. (2019) reported that the weaker stream wise velocity reversal was observed for pier with sharper nose. At Section-3, normalized streamwise velocity profile showed similar behavior r as Section-1. Similar phenomena were also observed for Sand-A bed condition.

#### 4.2.2 Tandem Pier

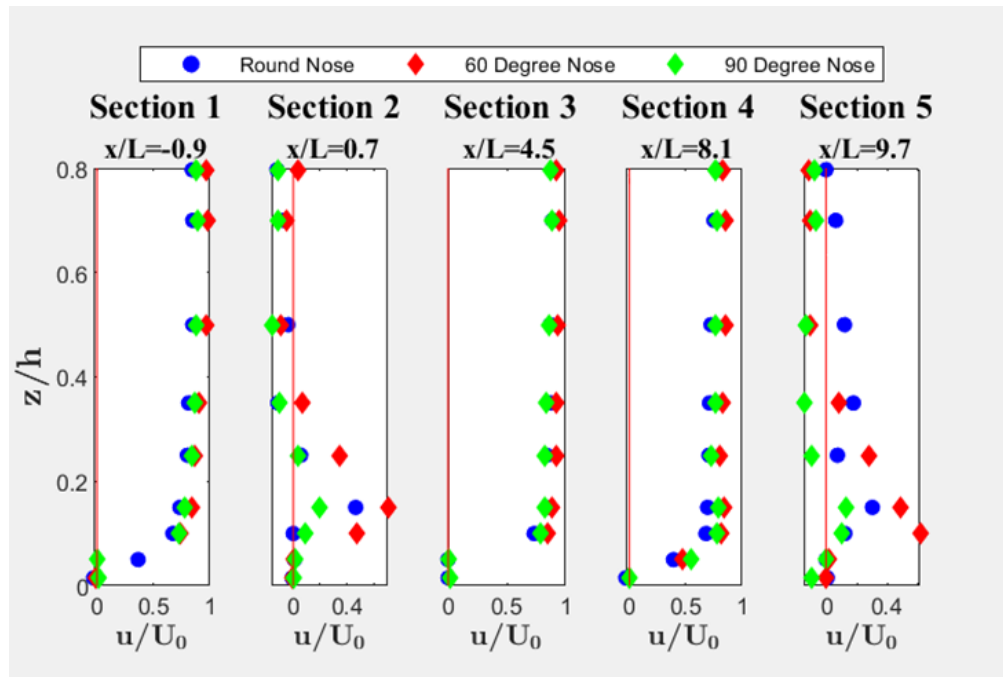
**Figure 4.2** represents the stream wise velocity variation for pier placed in tandem arrangement. From the data, logarithmi velocity profile was observed at Section-1 (upstream of the front pier). At Section-2 and Section-5 (just downstream of the front pier and rear pier, respectively), negative streamwise velocity was observed due to flow reversal. However, at the d/s side of the rear pier a weaker reverse flow was observed in comparison with that of the front pier due to the sheltering effect of the front pier which reduced the approach flow velocity for rear pier. Similar results were reported by Shrestha (2015). The effect of pier shape on this flow reversal was also noticed.



(a)



(b)



(c)

**Figure 4.2** Normalized streamwise velocity variation for piers placed in tandem arrangements at Sand B ( $d_{50}=0.0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

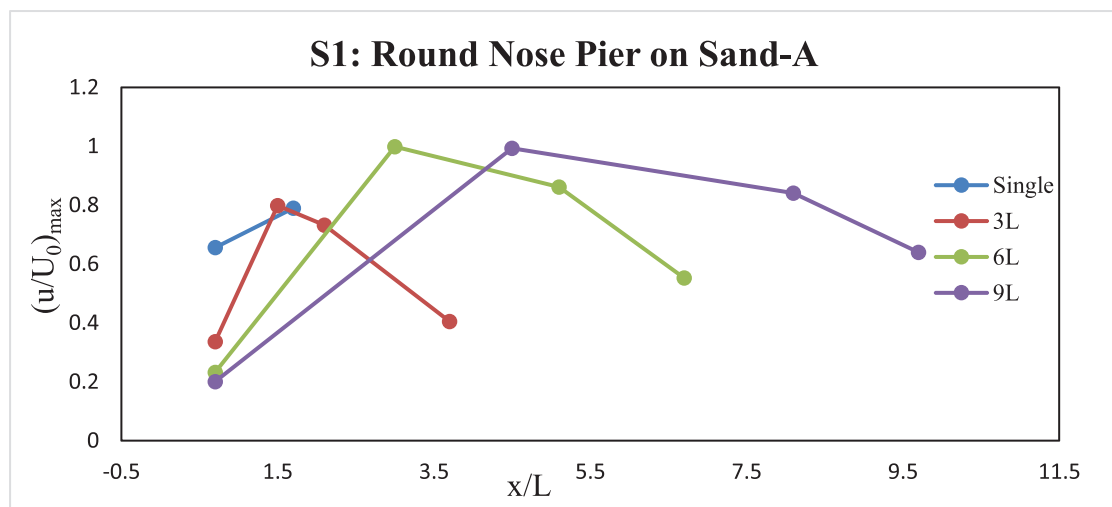
In general, the lowest flow reversal was observed for piers with  $60^\circ$  nose angle and highest flow reversal was observed for piers with  $90^\circ$  nose angle. Besides, the maximum streamwise velocity at Section-2 and Section-5 occur between  $z/h=0.10-0.25$ . At



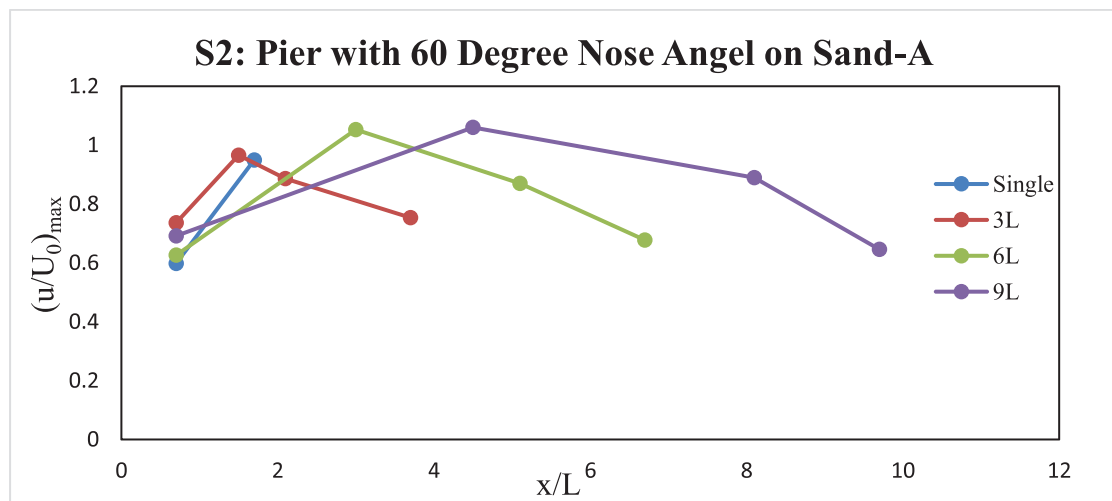
Section-4, logarithmic velocity profile was observed. Besides, the magnitude of the approach velocity towards the rear pier was found smaller compared to the front pier. This occurred due to the sheltering effect of the upstream pier. The streamwise normalized velocity variations for other experiments are presented in **Figure B. 1** of **Appendix-B**.

#### 4.2.3 Maximum Normalized Streamwise Velocity Variation

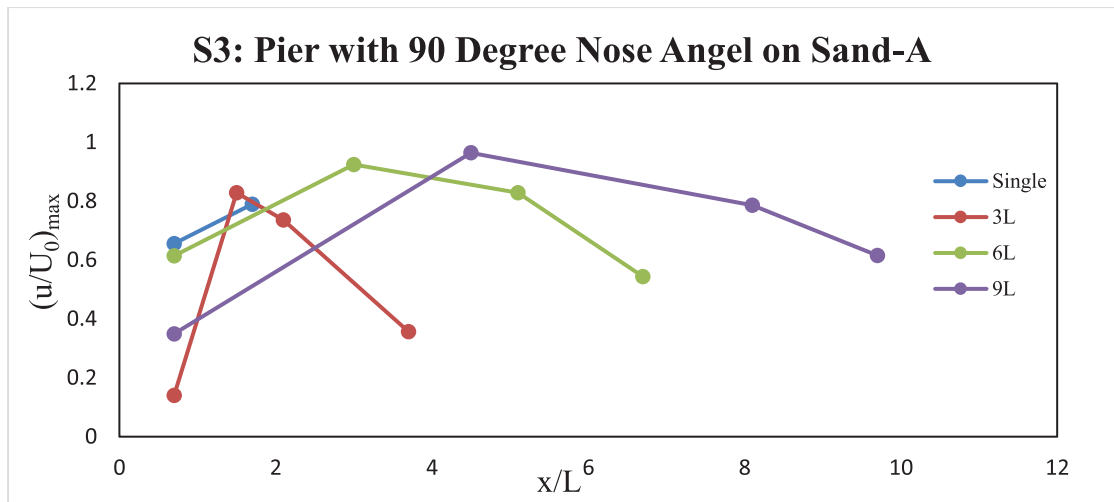
To investigate the maximum normalized streamwise velocity variation along the centerline,  $(u/U_0)_{\max}$  has been plotted against  $x/L$  in **Figure 4.3**.



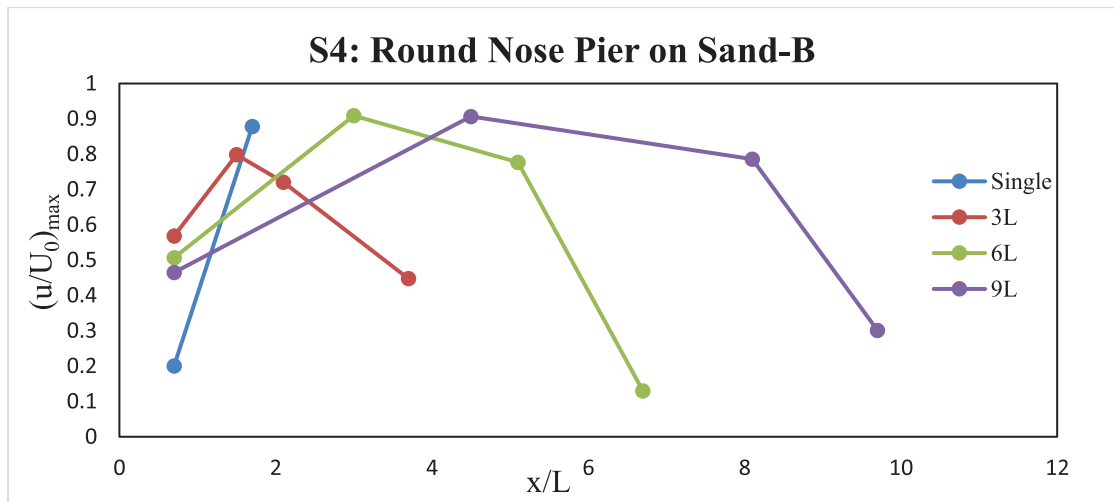
(a)



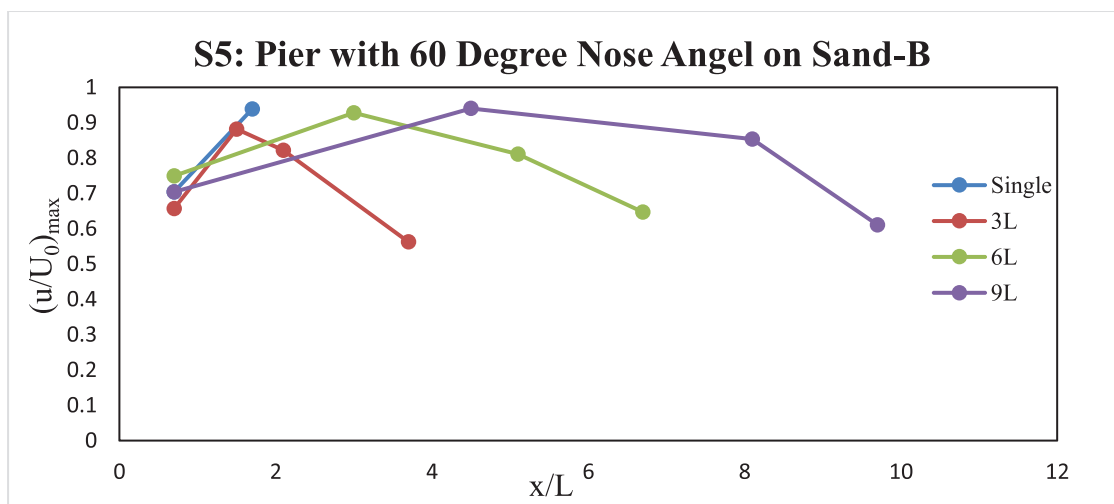
(b)



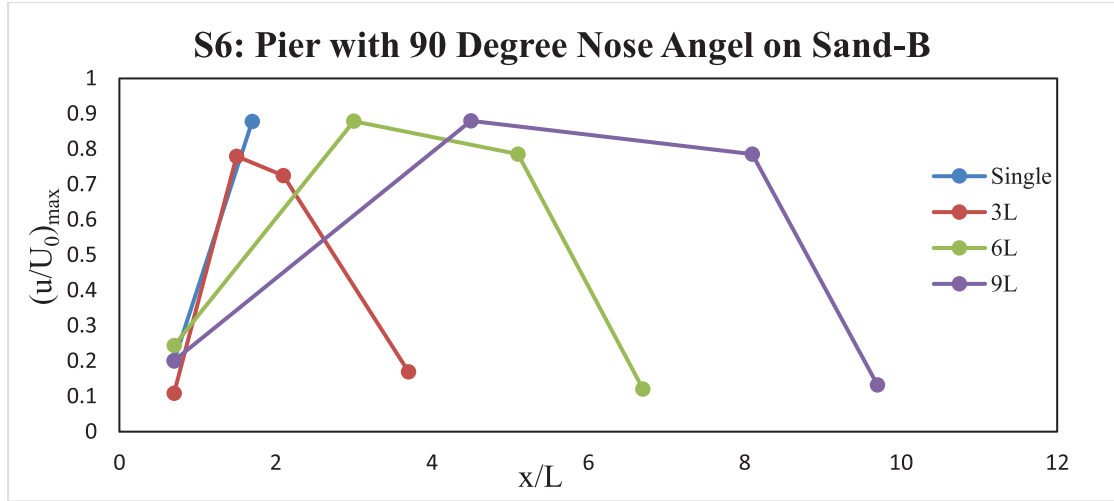
(c)



(d)



(e)



(f)

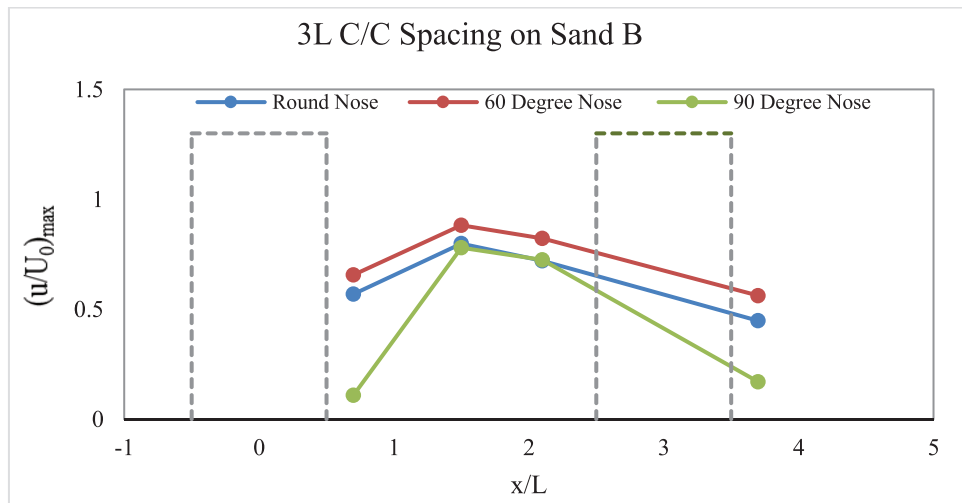
**Figure 4.3** Maximum normalized streamwise velocity variation along the centerline on Sand-A (a, b & c) and Sand-B (d, e & f).

From these figures it can be observed that, in all scenarios, maximum normalized streamwise velocity is higher in the upstream of the front pier than that of the downstream pier. There is a sudden drop in streamwise velocity as the flow passed the pier (Section-2). Normalized stream wise velocity is then increases up to the mid-section (Section-3) in all scenarios then decreases. Nowrin (2020) also reported the similar findings. Besides, at the middle section (Section-3) of the piers placed in tandem arrangements, streamwise velocity is the lowest in the case of piers placed at 3L C/C pier spacing compare to the piers placed at 6L and 9L C/C pier spacing. The approach streamwise velocity to the rear pier is less compared to that of the front pier. This is due to sheltering effect of the front pier. For almost all cases, lowest approach velocity to the rear pier was observed for piers placed at 3L C/C pier spacing. At the downstream of the rear pier, a sudden drop (compare to the upstream) in streamwise velocity was observed. The general effect of the pier spacing on maximum normalized streamwise velocity is shown in **Table 4.1**.

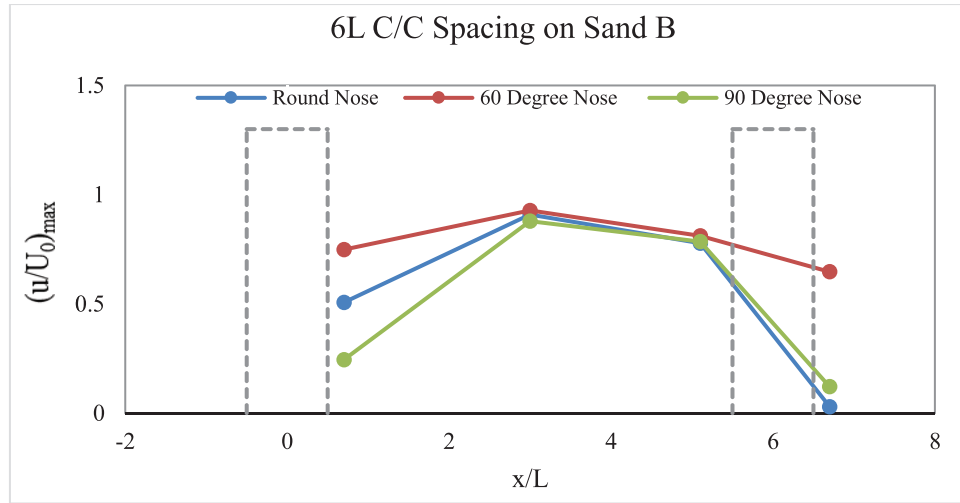
**Table 4.1** Effect of Pier Spacing on Maximum Normalized Streamwise Velocity  $(u/U_0)_{\max}$ .

| Average of the Maximum Normalized Streamwise Velocity |      |      |      |
|-------------------------------------------------------|------|------|------|
| C/C Pier Spacing                                      | 3L   | 6L   | 9L   |
| Section 1                                             | 0.94 | 0.94 | 0.94 |
| Section 2                                             | 0.43 | 0.48 | 0.41 |
| Section 3                                             | 0.85 | 0.94 | 0.96 |
| Section 4                                             | 0.8  | 0.82 | 0.83 |
| Section 5                                             | 0.45 | 0.46 | 0.5  |

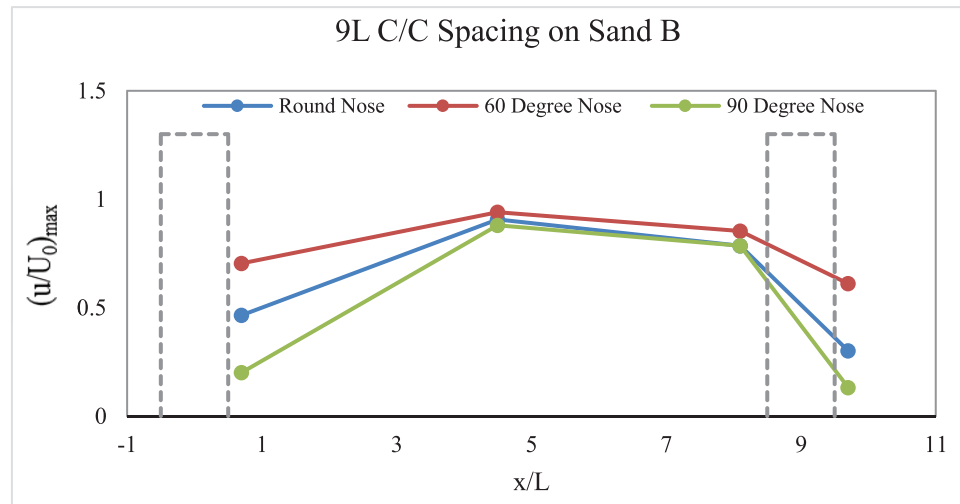
Furthermore, pier nose shape also affected the maximum normalized streamwise velocity (**Figure 4.4** and **Table 4.2**). Effect of pier nose shape on maximum normalized streamwise velocity for other experiments are presented in **Figure C. 1** of **Appendix-C**. At Section-1, averaged maximum normalized streamwise velocity for round nose pier, pier with  $60^\circ$  nose angle and pier with  $90^\circ$  nose angle were found 0.93, 0.93 and 0.94, respectively. In addition, the drop (difference in velocity between u/s and d/s of pier) in maximum normalized streamwise velocity at the front pier was also affected by pier nose shape. Pier with  $90^\circ$  exhibited the highest drop of about 70%. Lowest drop among the three pier's nose shape was obtained for pier with  $60^\circ$  nose angle (27.8%). At Section-3, maximum normalized stream velocity was obtained for both round nose pier and pier with  $60^\circ$  nose angle. Drop in streamwise velocity at rear pier showed similar nature as the front pier. At Section-4 (u/s of rear pier), highest of the maximum normalized stream wise velocity was observed for pier with  $60^\circ$  nose angle.



(a)



(b)



(c)

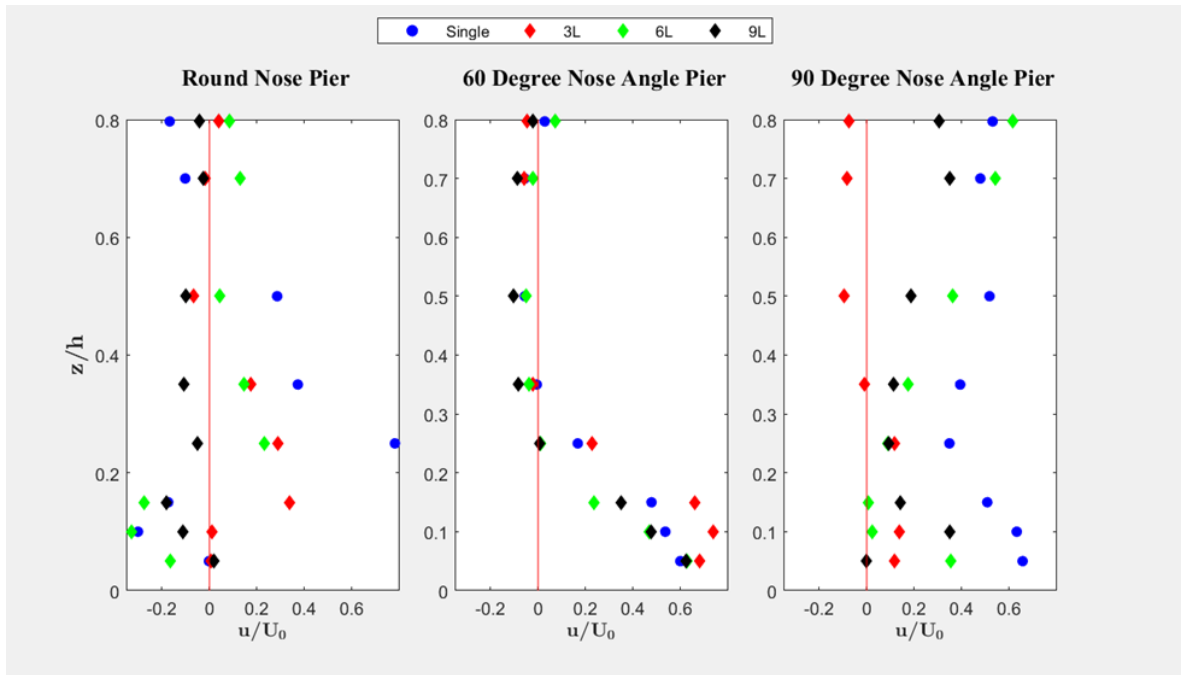
**Figure 4.4** Effect of pier nose shape on maximum streamwise velocity on Sand-B ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

**Table 4.2** Effect of Pier's Nose Shape on Maximum Normalized Streamwise Velocity  $(u/U_0)_{\max}$ .

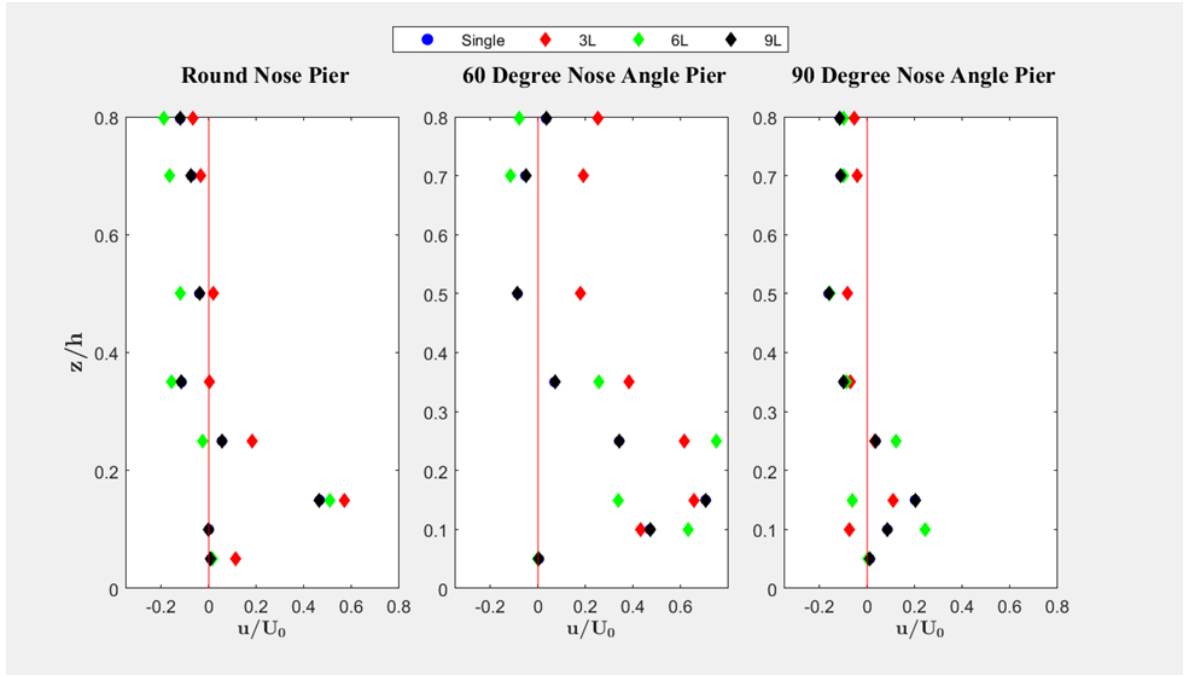
| Average of the Maximum Normalized Streamwise Velocity |       |                 |                 |
|-------------------------------------------------------|-------|-----------------|-----------------|
| Pier's Nose Shape                                     | Round | 60 <sup>0</sup> | 90 <sup>0</sup> |
| Section 1                                             | 0.93  | 0.93            | 0.94            |
| Section 2                                             | 0.36  | 0.7             | 0.28            |
| Section 3                                             | 0.91  | 0.97            | 0.89            |
| Section 4                                             | 0.79  | 0.86            | 0.8             |
| Section 5                                             | 0.4   | 0.65            | 0.33            |

#### 4.2.4 Comparison Between Single and Tandem Pier

**Figure 4.5** represents the comparison of normalized streamwise velocity between single and tandem pier arrangements at Section-2. From which it can be observed that, at Section-2, normalized streamwise velocity was higher when the spacing between the piers were 3L and 6L. At 9L spacing, normalized streamwise velocity at Section-2 showed almost similar values as single pier scenarios.



(a)



(b)

**Figure 4.5** Comparison of normalized streamwise velocity at the downstream of the front pier (Section-2): (a) Sand-A (b) Sand-B.

### 4.3 Normalized Streamwise Turbulent Intensity Variations along the Centerline

Turbulent intensity is calculated by the root mean square of the fluctuating velocity components. To calculate, the streamwise, transverse and vertical components of the turbulent intensity root mean square of the  $u'$ ,  $v'$ , and  $w'$  are used. In this study, only streamwise components of the turbulent intensity analysis are presented.

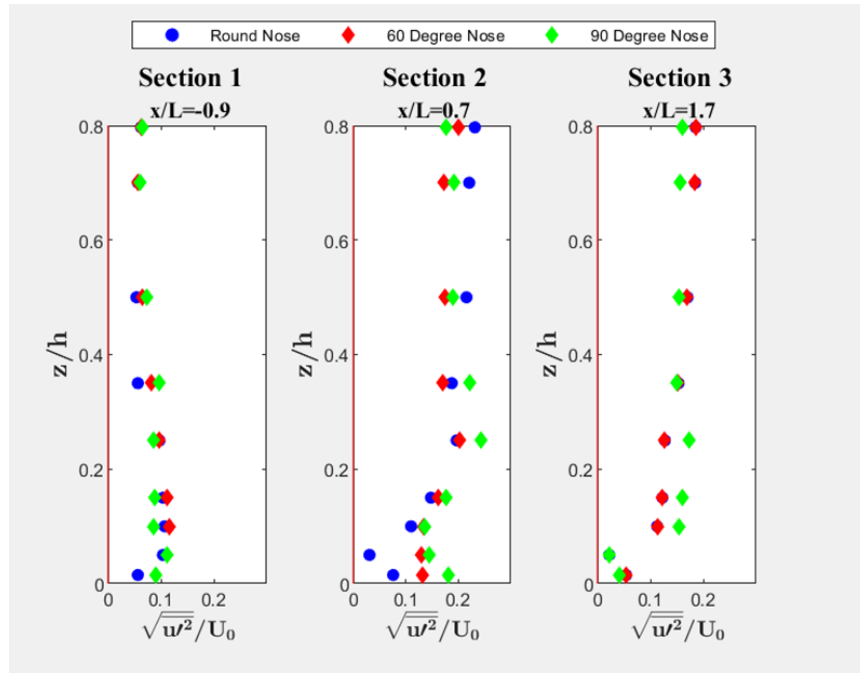
#### 4.3.1 Single Pier

**Figure 4.6** represents the variation of normalized turbulent intensity around single pier. From which it can be observed that, at Section-1 ( $u/s$  of pier) normalized streamwise turbulent intensity was higher near the bed and decreased towards the surface. At Section-2 and Section-3 (wake of the pier) normalized turbulent intensity was observed higher upper levels than at levels close to bed. Among the three sections, turbulence intensity is maximum at Section-2. Similar results were reported by Shrestha (2015).

#### 4.3.2 Tandem Pier

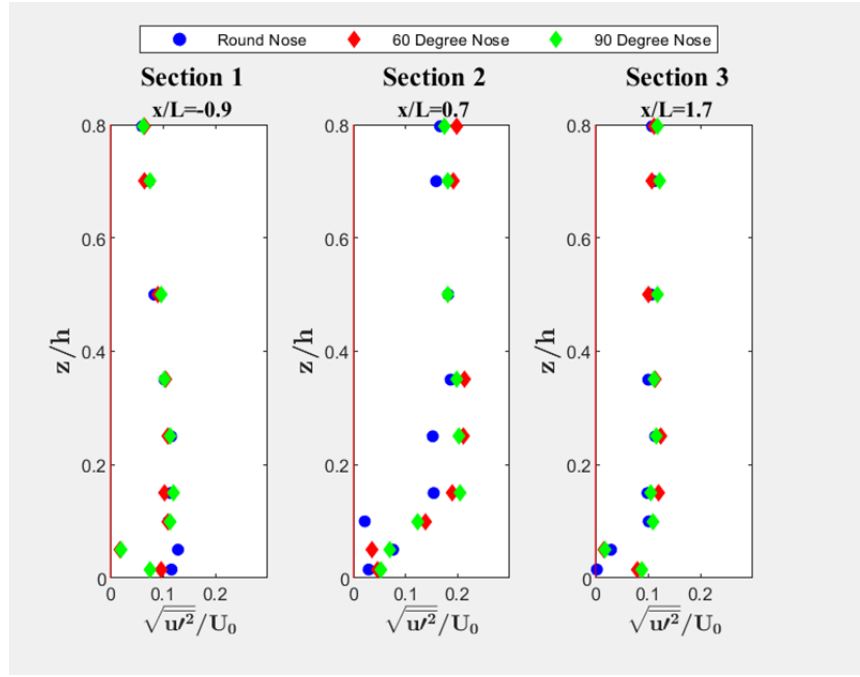
**Figure 4.7** represents the variation of normalized streamwise turbulent intensity around piers placed in tandem arrangements at 3L C/C spacing on Sand-A. In general, turbulence intensity was higher at the downstream of the front pier (Section-1 compare

to the upstream (Section-2), then decreases up to Section-4 (u/s of rear pier) and finally increases at the downstream of the rear pier. At upstream of the front pier, normalized streamwise turbulent intensity was higher near the bed and decreases towards the surface. At the downstream section of the both pier (Section-2 and Section-5), normalized turbulent intensity was higher near the surface then close to the bed. Besides, in almost all cases, turbulent intensity at the downstream of the front pier was higher. The streamwise normalized turbulent intensity variations for other experiments are presented in **Figure D. 1** of **Appendix-D**.



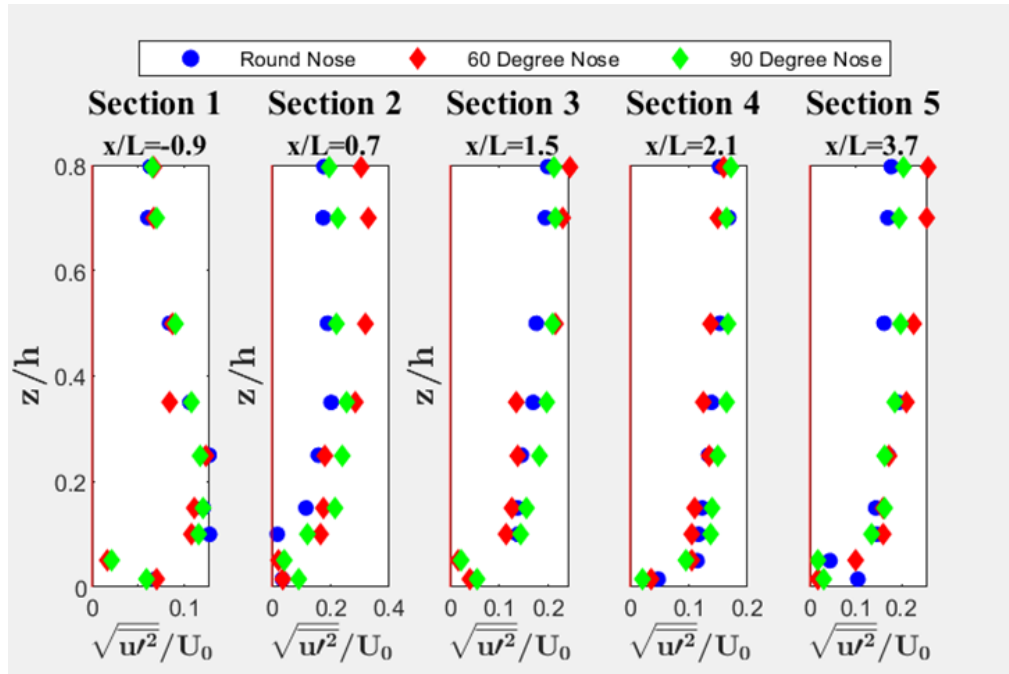
(a)



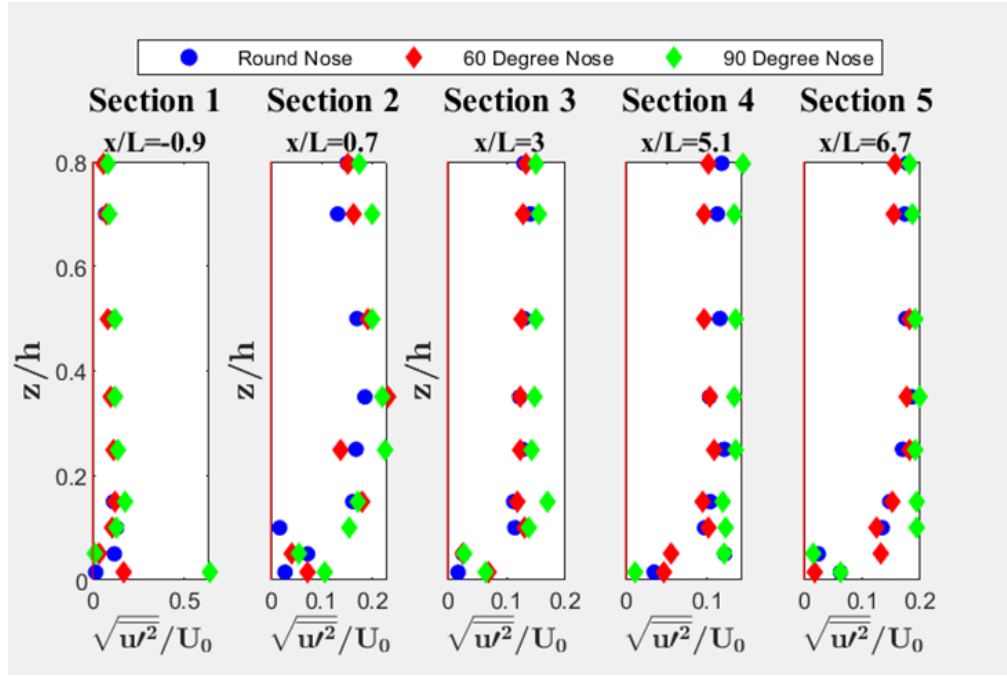


(b)

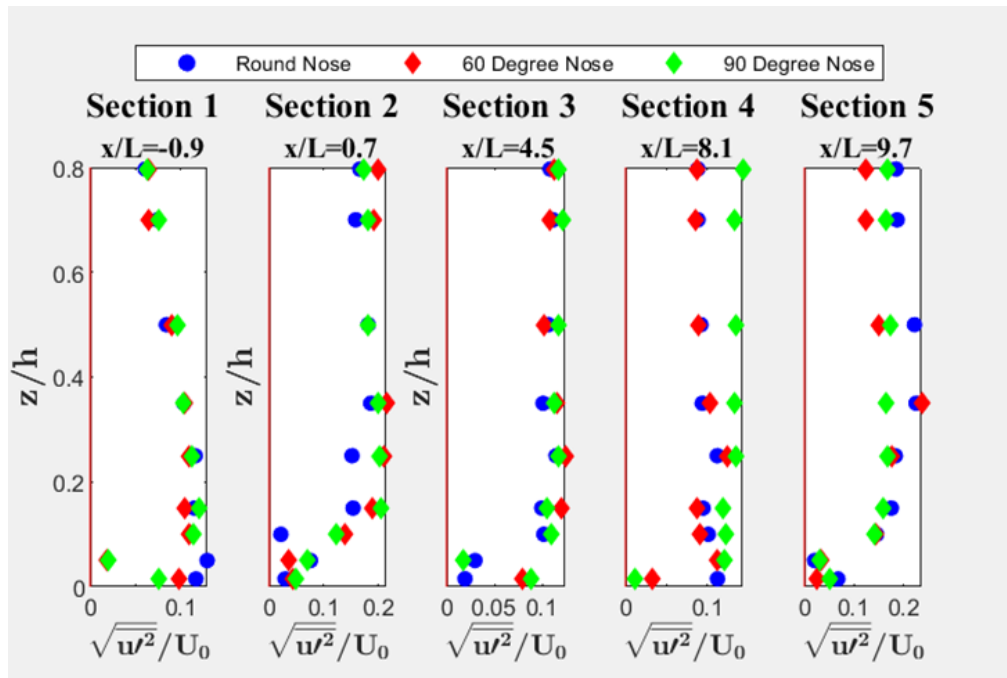
**Figure 4.6** Normalized streamwise turbulent intensity variation ( $\sqrt{u'^2}/U_0$  vs  $z/h$ ) around single pier: (a) Sand-A (b) Sand-B.



(a)



(b)

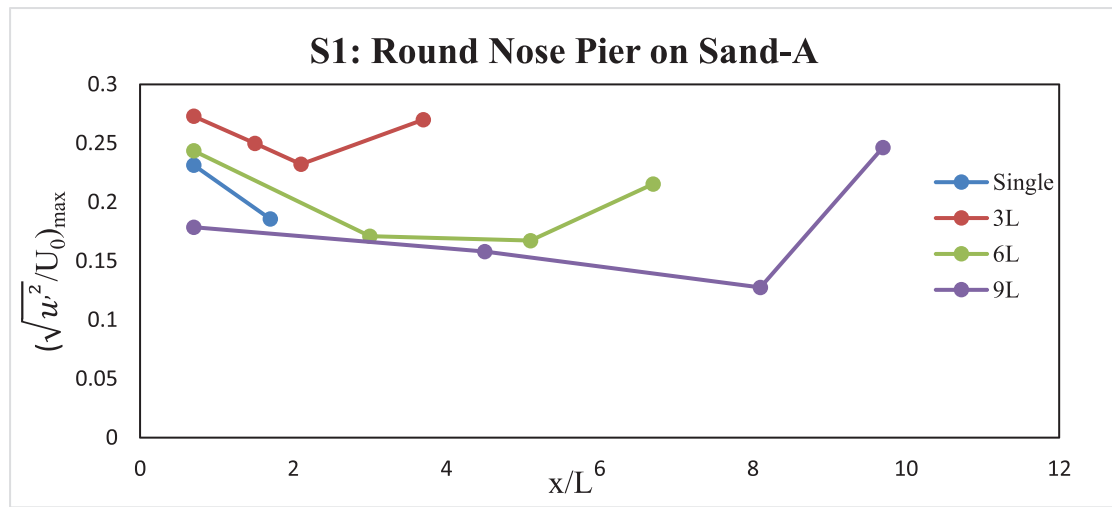


(c)

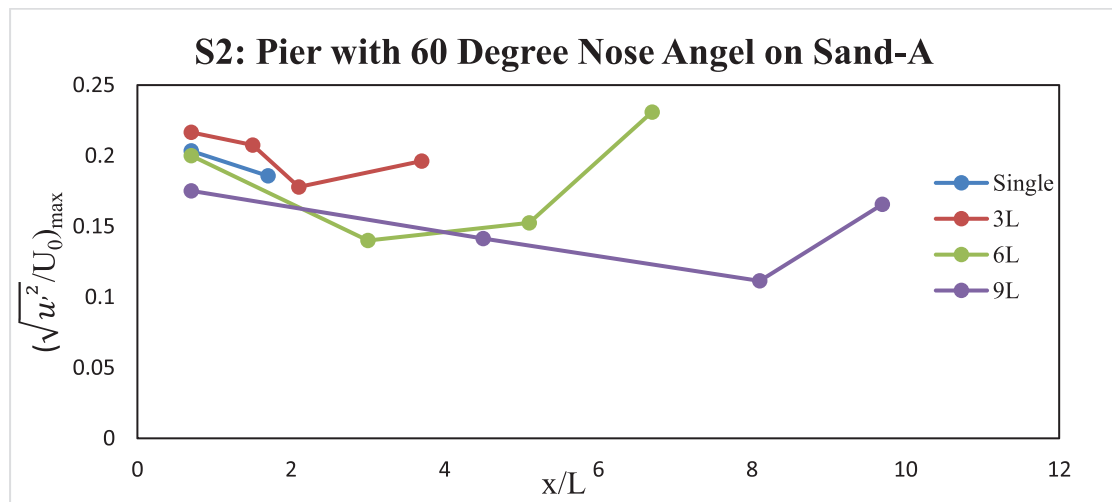
**Figure 4.7** Normalized streamwise turbulent intensity variation ( $\sqrt{u'^2}/U_0$  vs  $z/h$ ) for piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$  mm):  
(a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing

### 4.3.3 Maximum Normalized Streamwise Turbulent Intensity Variation

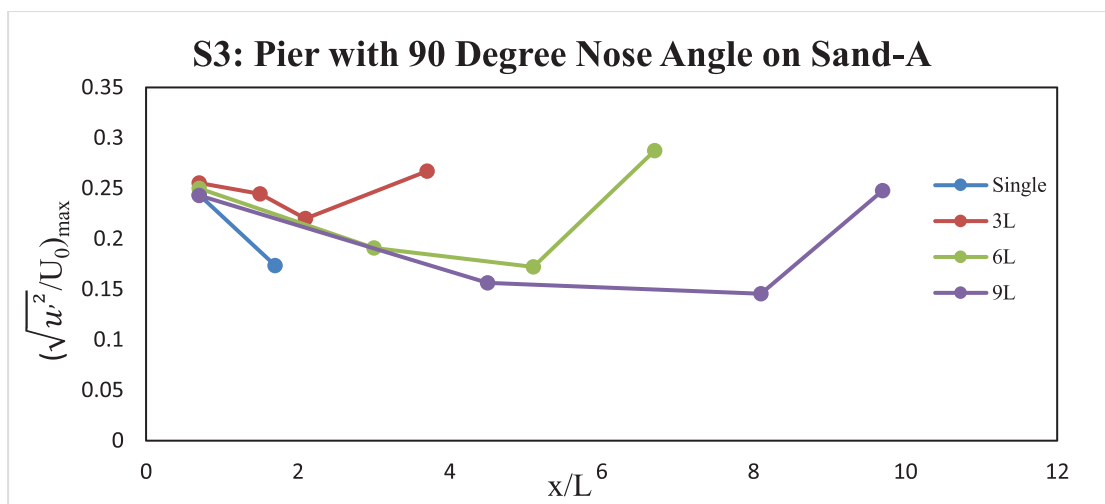
Maximum normalized streamwise turbulent intensity variation for different pier's nose shape and for different pier spacing are shown in **Figure 4.8**. From which it can be observed that, at the upstream of the front pier, maximum normalized streamwise turbulent intensity was almost similar. At Section-2 a sudden jump in turbulent intensity was found, then the turbulent intensity decreased up to Section-4 and increased again at the downstream of the rear pier (Section-5). Maximum normalized turbulent intensity was highest when the piers are placed in tandem arrangements at 3L C/C spacing.



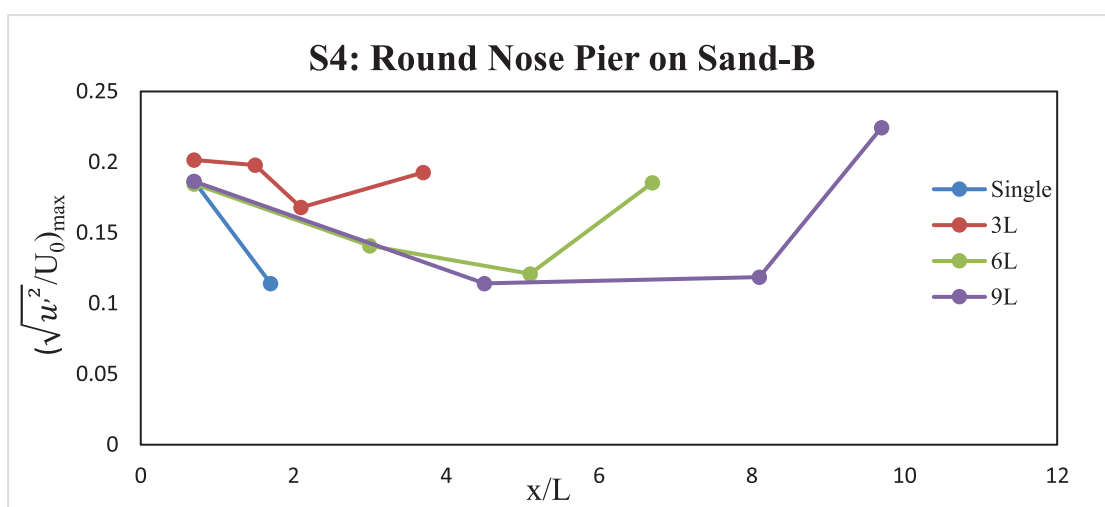
(a)



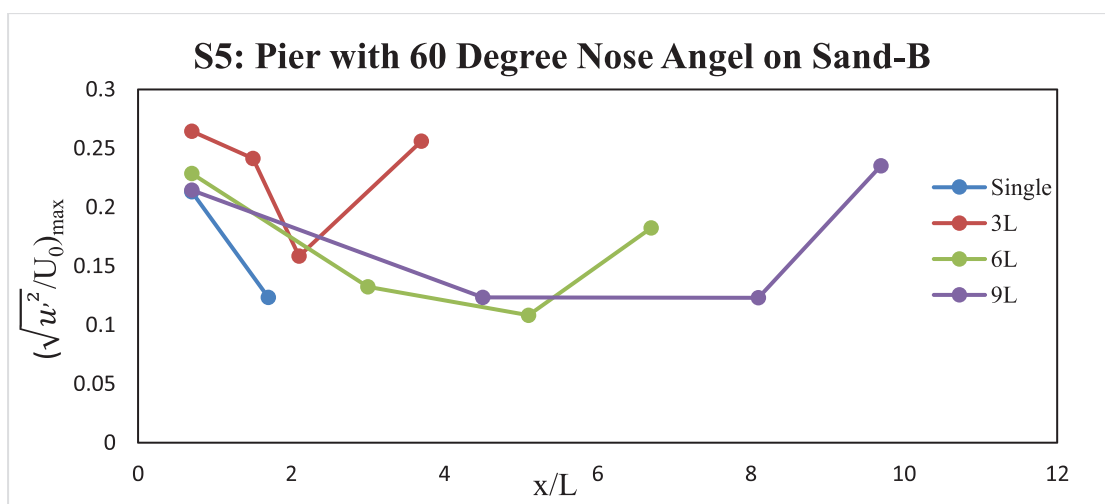
(b)



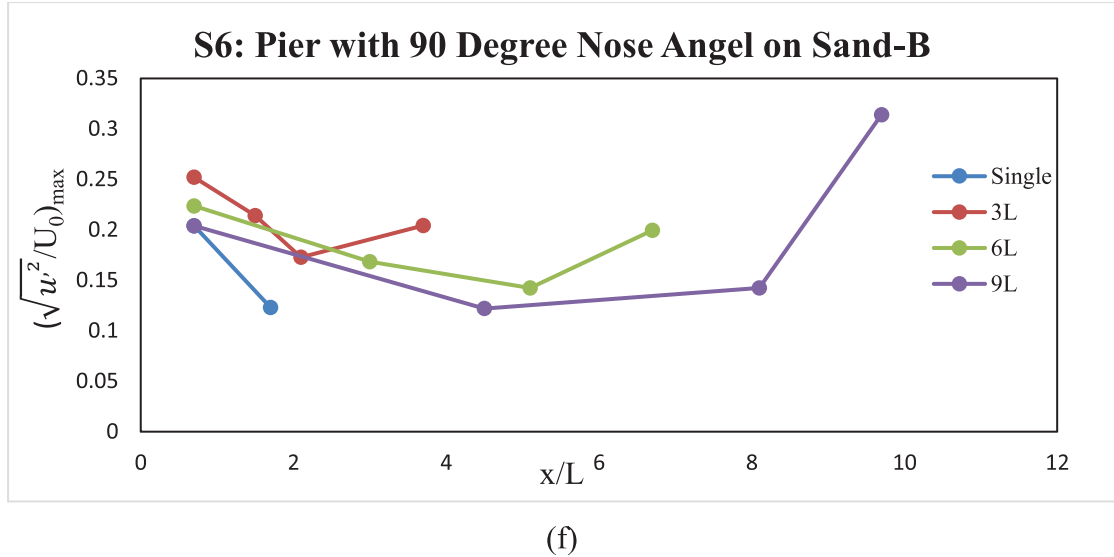
(c)



(d)



(e)



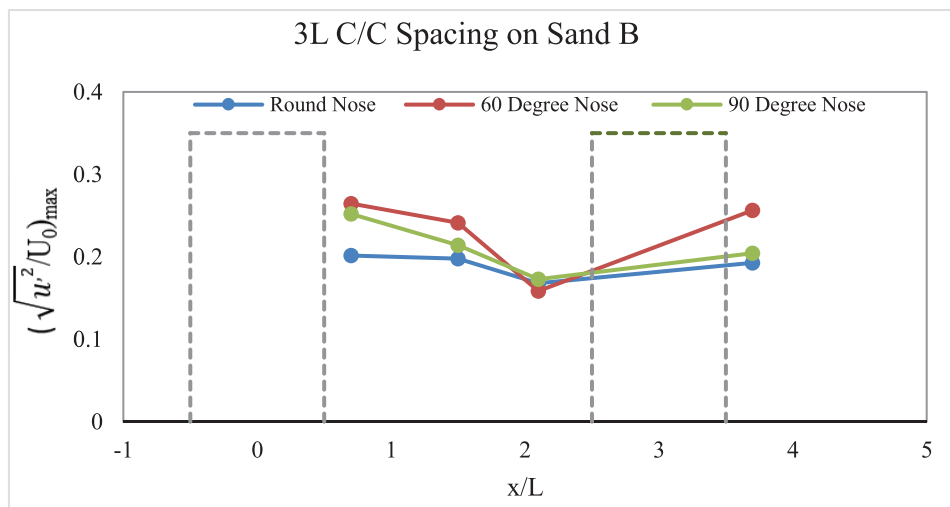
**Figure 4.8** Maximum normalized streamwise turbulent intensity variation along the centerline on Sand-A (a, b & c) and Sand-B (d, e & f).

The effect of pier spacing on maximum normalized streamwise turbulent intensity was shown in **Table 4.3**. From this table it can be observed that, pier spacing had no effect on the average of the maximum turbulent intensity at the upstream of the front pier. In the midstream (zone between two tandem piers) turbulent intensity decreased with distance from the front pier. Nowrin (2020) and Shrestha (2015) reported that when the values of  $S/D = 6$  and  $9$ , normalized turbulent intensity in the midstream region decreased with increase of  $x/D$  ( $D$  = diameter of cylindrical pier).

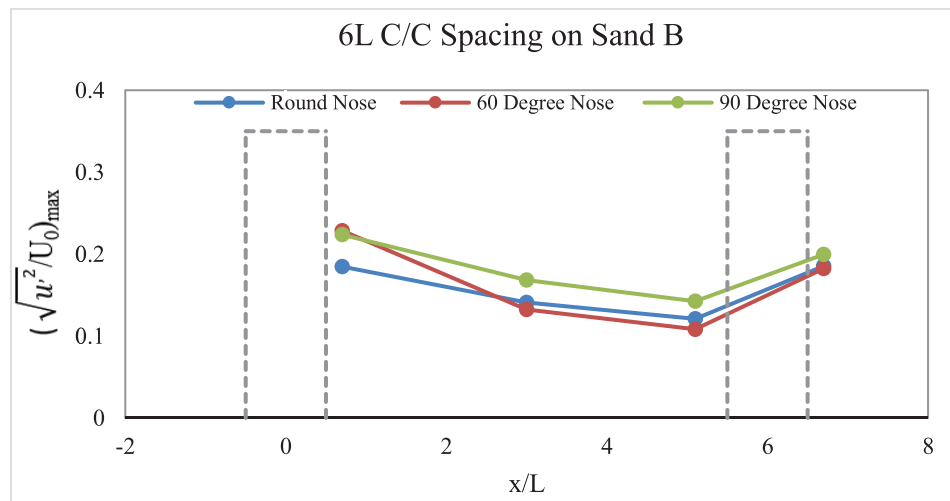
**Table 4.3** Effect of pier spacing on maximum normalized turbulent intensity.

| Average of the Maximum Normalized Streamwise Turbulent Intensity |      |      |      |
|------------------------------------------------------------------|------|------|------|
| C/C Pier Spacing                                                 | 3L   | 6L   | 9L   |
| Section 1                                                        | 0.12 | 0.12 | 0.12 |
| Section 2                                                        | 0.25 | 0.23 | 0.21 |
| Section 3                                                        | 0.23 | 0.16 | 0.14 |
| Section 4                                                        | 0.19 | 0.15 | 0.13 |
| Section 5                                                        | 0.24 | 0.22 | 0.24 |

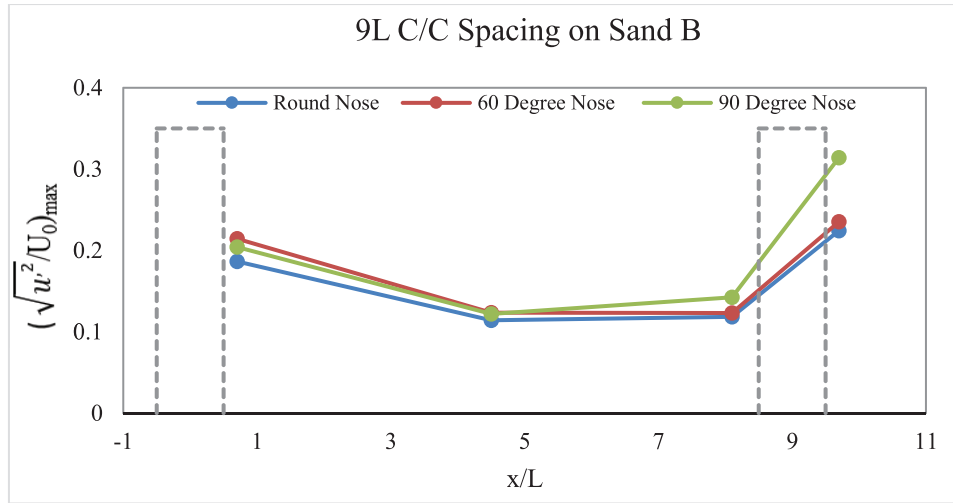
The effect of pier's nose shape on maximum normalized streamwise turbulent intensity is shown in **Figure 4.9** and **Table 4.4**. From which it can be observed that, at the downstream of the front pier in all location, turbulent intensity was the highest for pier with  $90^\circ$  nose angle and lowest for pier round nose pier. At the upstream of the front pier, round nose pier shows highest turbulent intensity though the deviation is very small. At the upstream of the front pier, round nose pier shows highest turbulent intensity though the deviation is very small. The effect of pier nose shape on maximum streamwise turbulent intensity for other experiments are presented in **Figure E. 1** of **Appendix-E**.



(a)



(b)



(c)

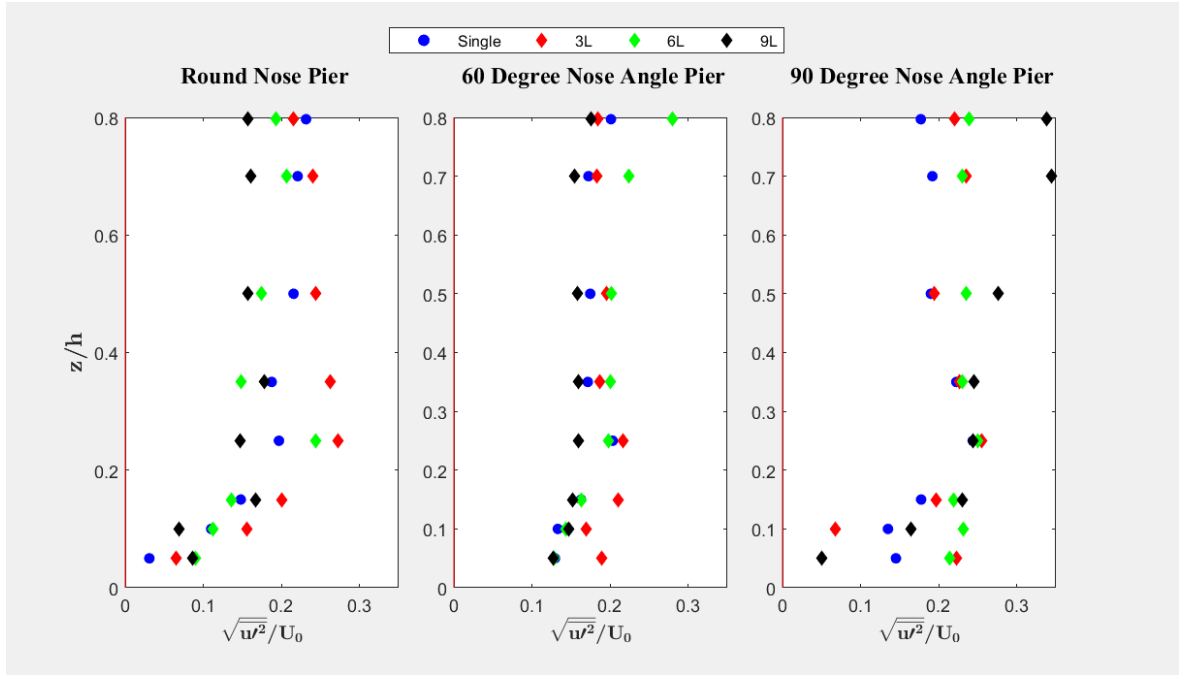
**Figure 4.9** Effect of pier nose shape on maximum turbulent intensity on Sand-B ( $d_{50}=0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing

**Table 4.4** Effect of pier's nose shape on maximum normalized turbulent intensity.

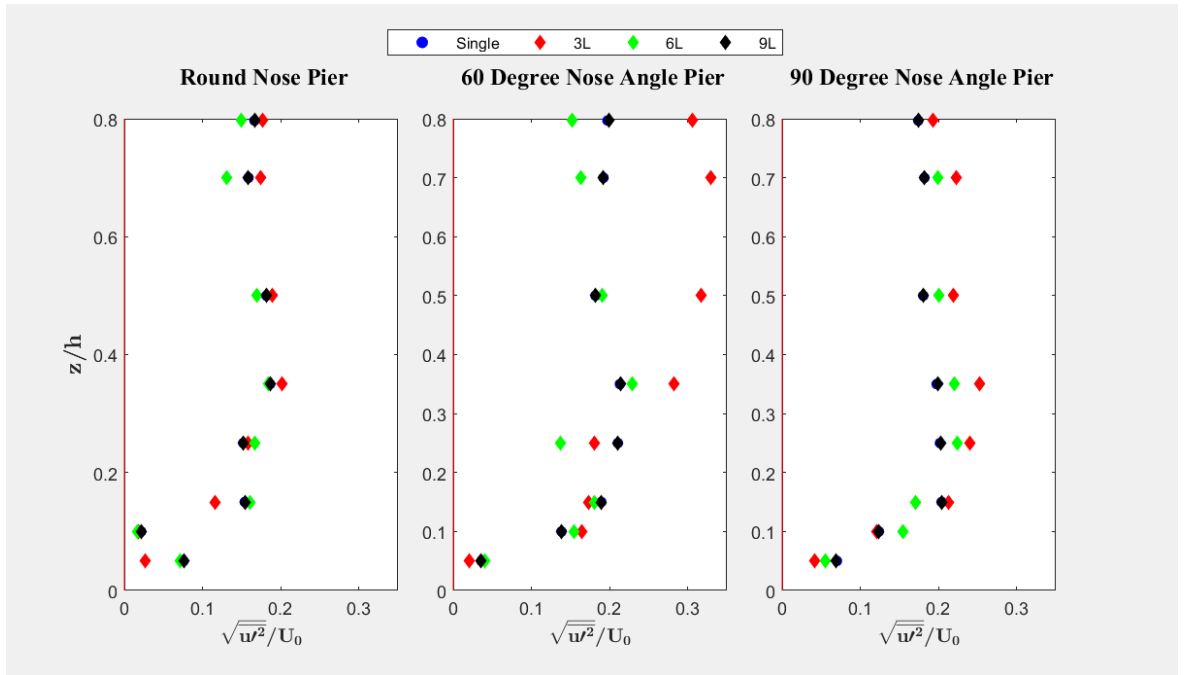
| Average of the Maximum Normalized Streamwise Turbulent Intensity |       |                 |                 |
|------------------------------------------------------------------|-------|-----------------|-----------------|
| Pier's Nose Shape                                                | Round | 60 <sup>0</sup> | 90 <sup>0</sup> |
| Section 1                                                        | 0.122 | 0.116           | 0.117           |
| Section 2                                                        | 0.195 | 0.217           | 0.239           |
| Section 3                                                        | 0.157 | 0.165           | 0.183           |
| Section 4                                                        | 0.142 | 0.139           | 0.166           |
| Section 5                                                        | 0.2   | 0.212           | 0.254           |

#### 4.3.4 Comparison Between Single and Tandem Pier

**Figure 4.10** represents the comparison of normalized streamwise turbulent intensity between single and tandem pier arrangements at Section-2. From which it can be observed that in general turbulent intensity in tandem pier arrangements were higher compare to single pier arrangements at 3L C/C spacing. At 9L C/C spacing, turbulent intensity showed similar values as single pier as the distance between the piers were higher and effect of the d/s pier in the flow field around the u/s pier was reduced.



(a)



(b)

**Figure 4.10** Comparison of normalized streamwise turbulent intensity at the downstream of the front pier (Section-2): (a) Sand-A (b) Sand-B.



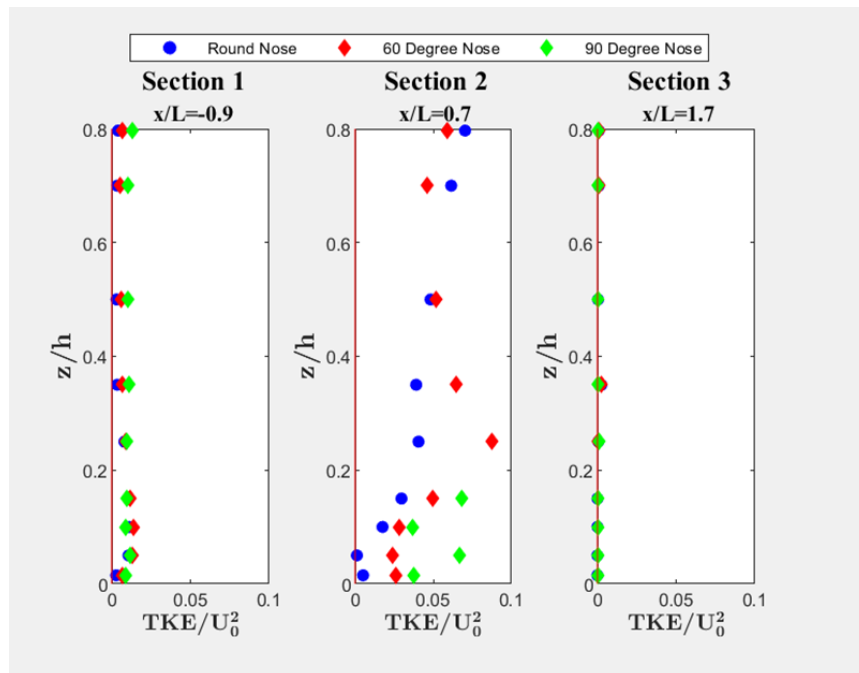
#### 4.4 Normalized Streamwise Turbulent Kinetic Energy (TKE) Variations along the Centerline

To analyze the turbulent kinetic energy profile along the centerline of the pier arrangements, normalized turbulent kinetic energy has been plotted against  $z/h$ . In this study, turbulent kinetic energy (TKE) was normalized by  $U_0^2$ .

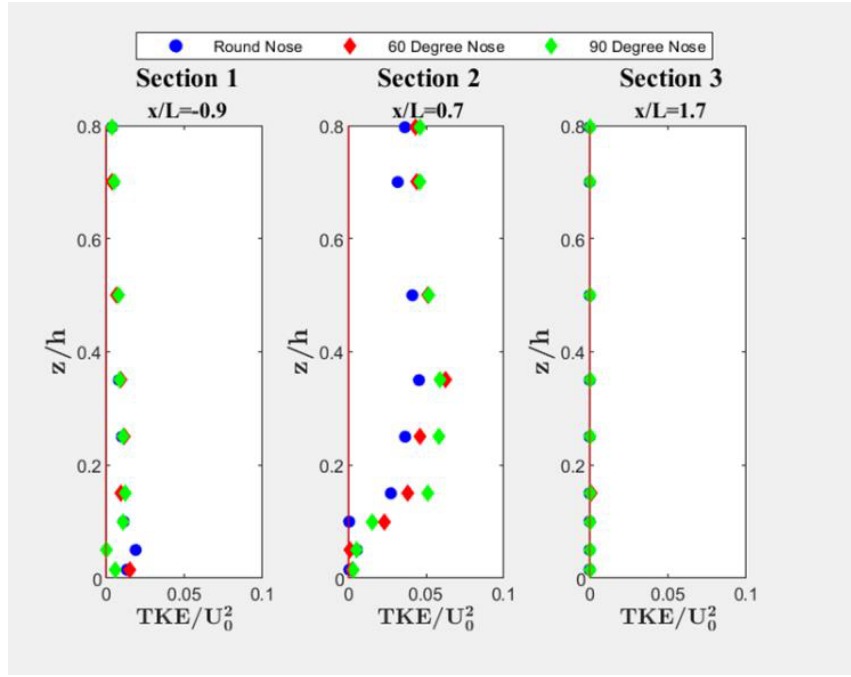
##### 4.4.1 Single Pier

**Figure 4.11** represents the normalized turbulent kinetic energy variation along the centerline around single pier.

For all shapes of pier, at Section-1 (u/s of pier), normalized turbulent kinetic energy was higher near the bed and decreased towards the surface. At Section-2 (just d/s of pier), normalized turbulent kinetic energy was smaller near the bed, and with increase of distance from the bed, normalized turbulent kinetic energy increased for round nose pier, pier with  $60^\circ$  nose angle and pier with  $90^\circ$  nose angle and reached a maximum value then decreased. At Section-3, normalized turbulent kinetic energy was smaller near the bed and near the surface and had very low value compared to other two sections. In most scenarios, maximum normalized turbulent kinetic energy was observed at  $z/h=0.35$ . Among the three sections, normalized turbulent kinetic energy is maximum at Section-2 (just d/s of the pier).



(a)



(b)

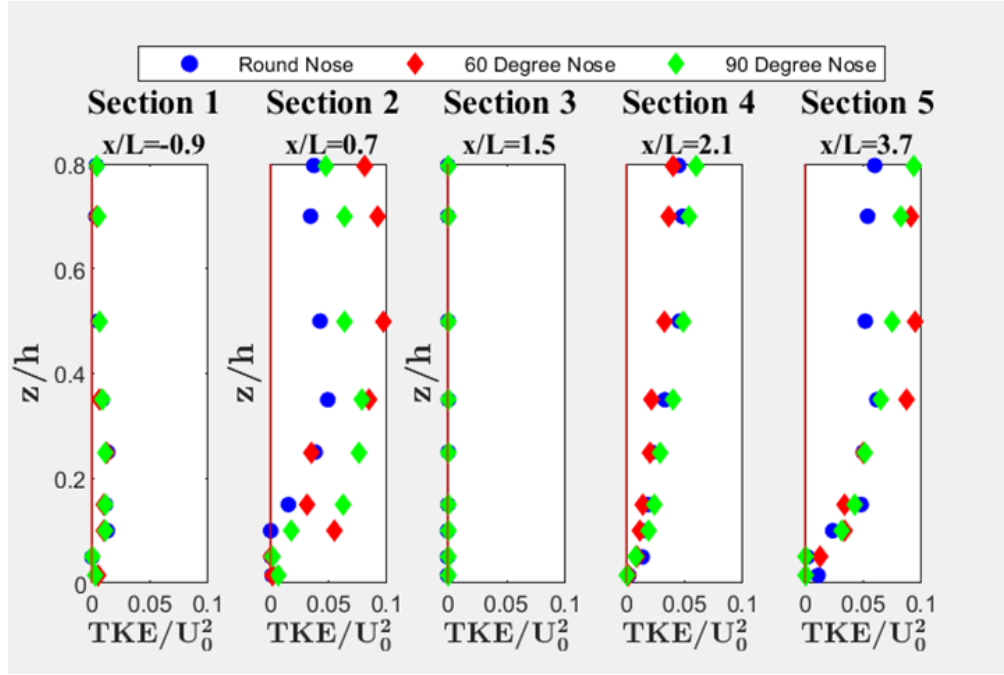
**Figure 4.11** Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$  vs  $z/h$ ) around single pier: (a) Sand-A (b) Sand-B.

#### 4.4.2 Tandem Pier

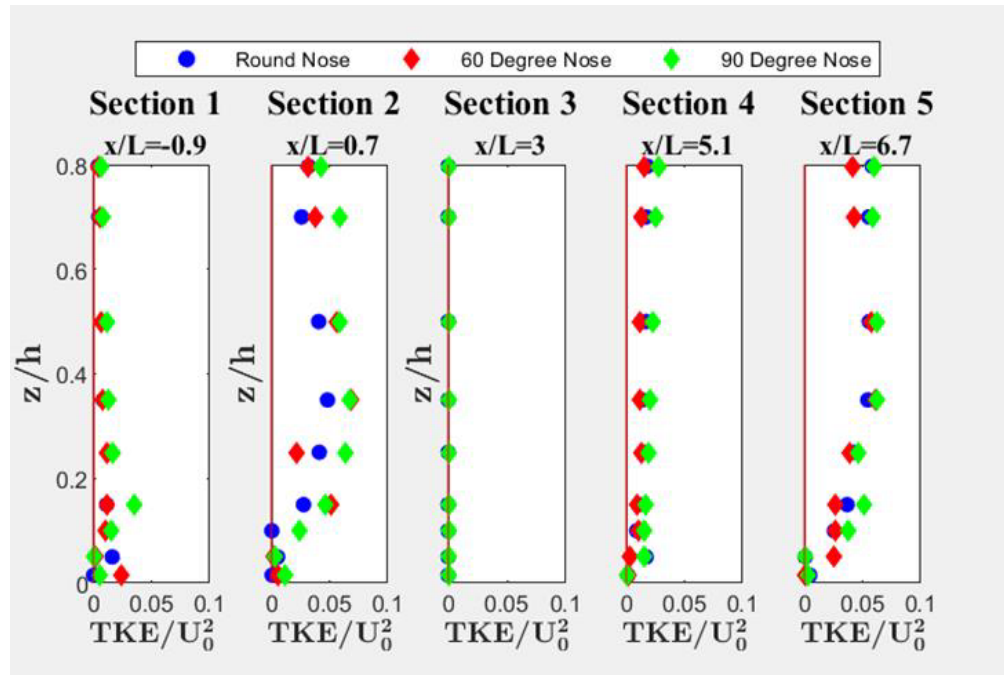
The variation of normalized turbulent kinetic energy around piers placed spacing in tandem arrangement on Sand-B is shown in **Figure 4.12**. from which it can be observed that, turbulent kinetic energy at the upstream of the front piers showed similar behavior as single pier arrangement. At Section-1 (u/s of the front pier), normalized turbulent kinetic energy was higher near the bed. With increasing distance from the bed, it decreased and near the surface it increased a bit. At Section-2 (d/s of front pier), turbulent kinetic energy was lower near the bed, with increasing distance from the bed, turbulent kinetic energy increased and reached a maximum value at  $z/h=0.25$  to  $z/h=0.35$ , and then started to decreased. Vertical profile of the turbulent kinetic energy at the d/s of the front pier was different from the single pier scenarios as turbulent kinetic energy at the d/s of the single pier was maximum near the surface.

At Section-3, turbulent kinetic energy value was very low compared to other sections and increased towards the surface from bed. The major difference between Section-2 and Section-3 in vertical profile of turbulent kinetic energy was that the turbulent kinetic energy at Section-3 was maximum at surface whereas maximum turbulent kinetic energy was observed between  $z/h=0.25$  to  $z/h=0.35$ .

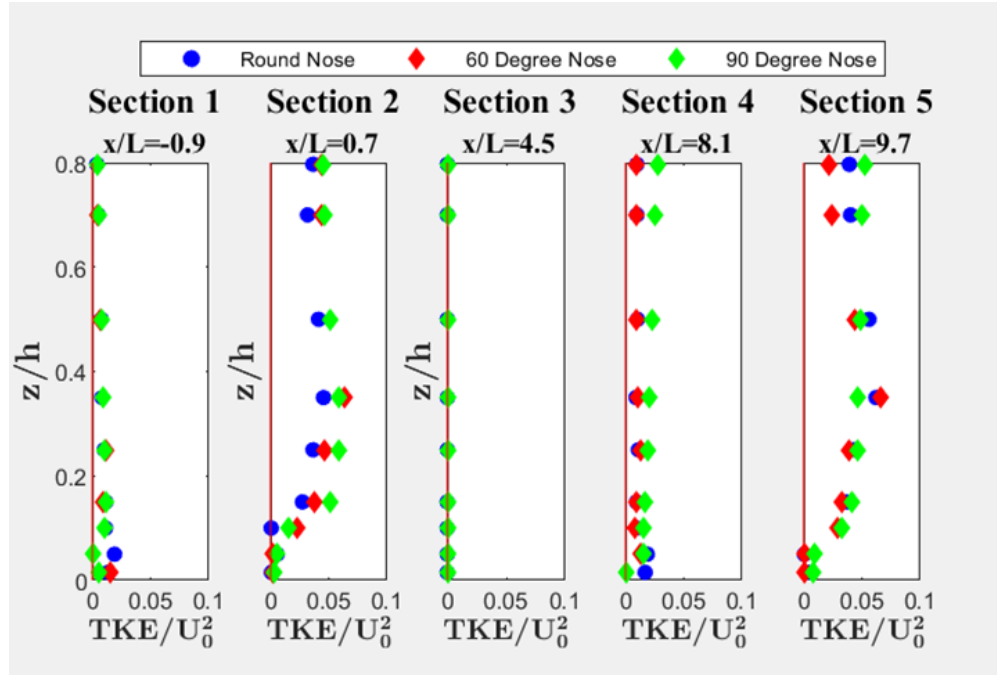
At Section-4, turbulent kinetic energy increased from Section-3 and maximum turbulent kinetic energy was observed near the surface. At Section-5, vertical profile of the turbulent kinetic energy shows similar patterns as single pier as the turbulent kinetic energy increased towards the surface from bed. Similar pattern was also reported by Ataie-Ashtiani and Aslani-Kordkand (2013) and Shrestha (2015).



(a)



(b)



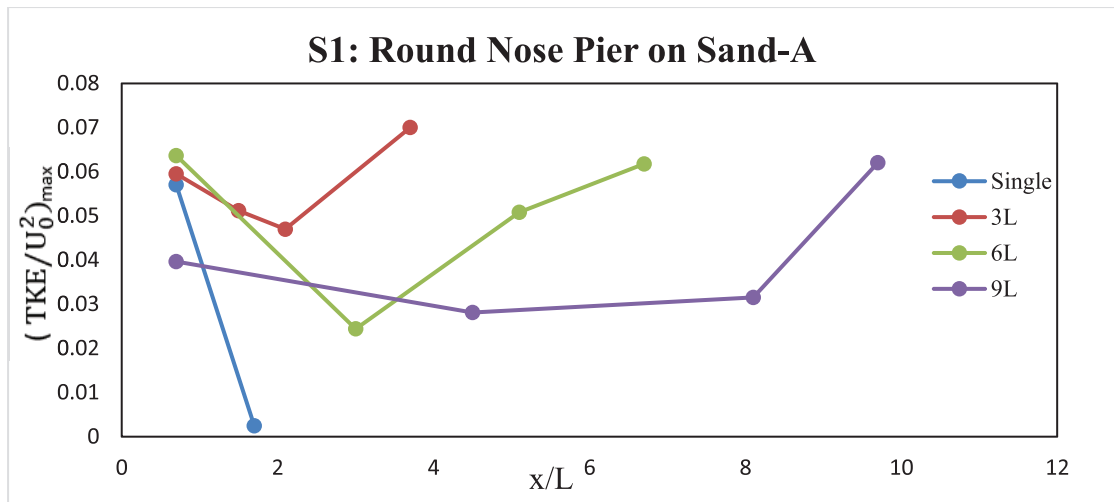
(c)

**Figure 4.12** Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$  vs  $z/h$ ) for piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

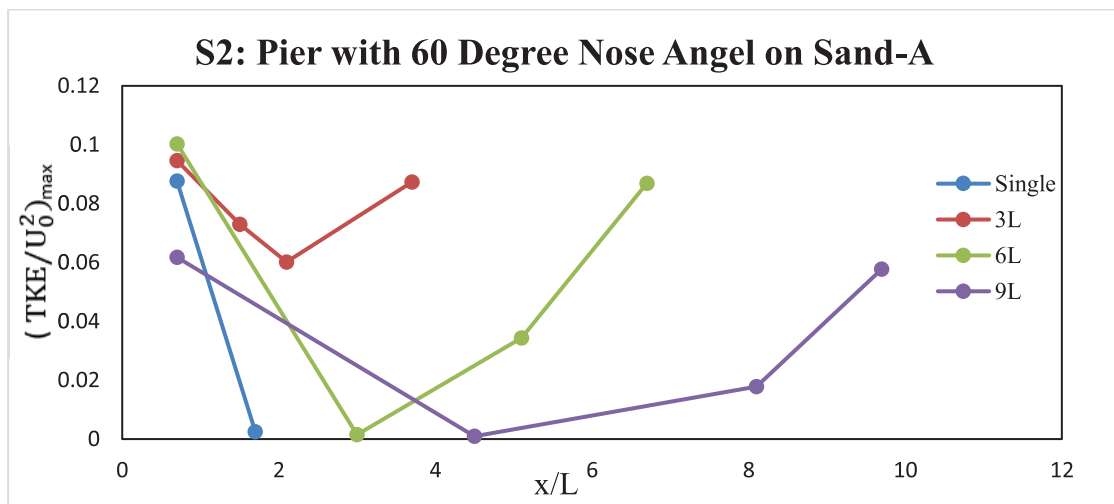
The normalized turbulent kinetic energy variations for other experiments are presented in **Figure F. 1** of **Appendix-F**.

#### 4.4.3 Maximum Normalized Turbulent Kinetic Energy Variation

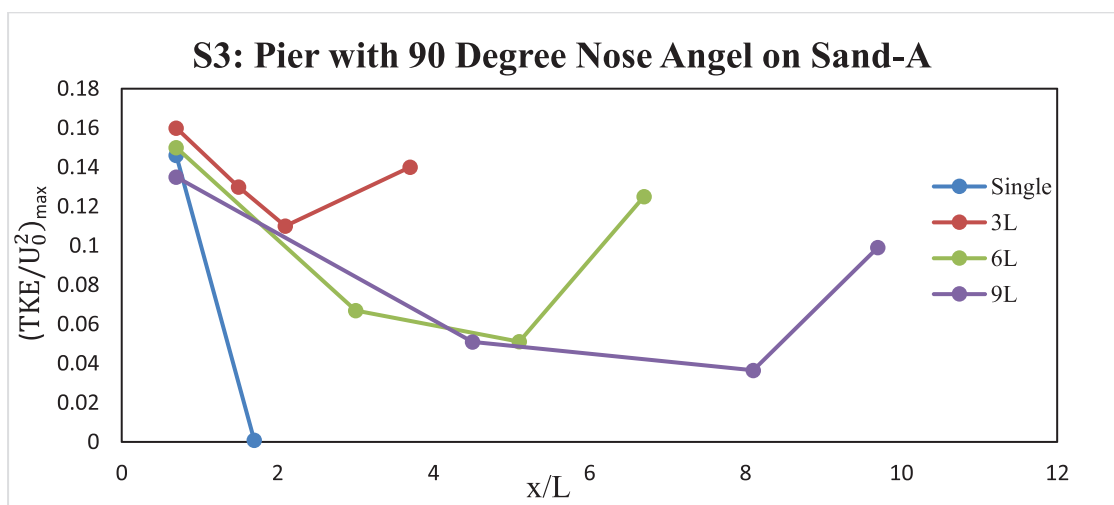
**Figure 4.13** represents the maximum normalized turbulent kinetic energy variation along the centerline. From which, it can be observed that in almost all the scenarios, turbulent kinetic energy at Section-1 (u/s of the front pier) were almost similar. Which indicated that, pier's nose shape or pier spacing didn't have much effect on turbulent kinetic energy at the u/s of the front pier. When the flow passes the pier, there was a sudden increase in maximum turbulent kinetic energy (at Section-2). For piers placed at 3L C/C pier spacing, turbulent kinetic energy decreased at Section-3 and increased at Section-4. At Section-5 (d/s of the rear pier), turbulent kinetic energy was higher than that of Section-4. For piers placed at 6L and 9L C/C pier spacing, maximum normalized turbulent kinetic energy decreased up to Section-4 and then increased at Section-5 as the flow passed the rear pier.



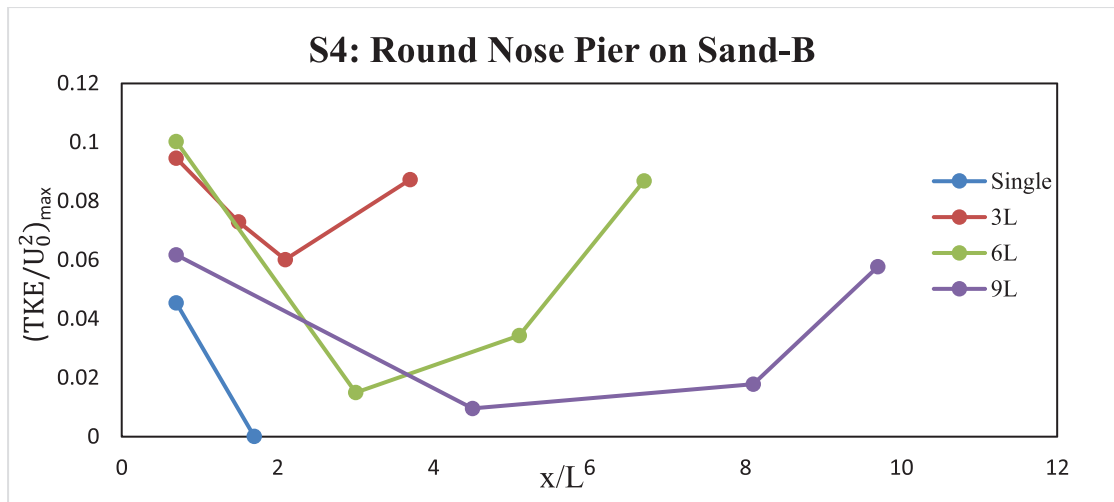
(a)



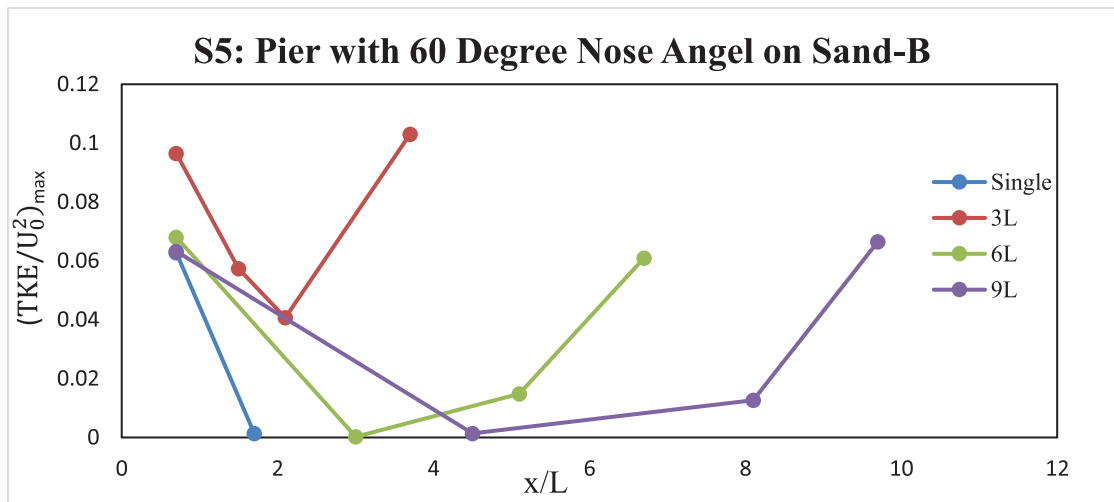
(b)



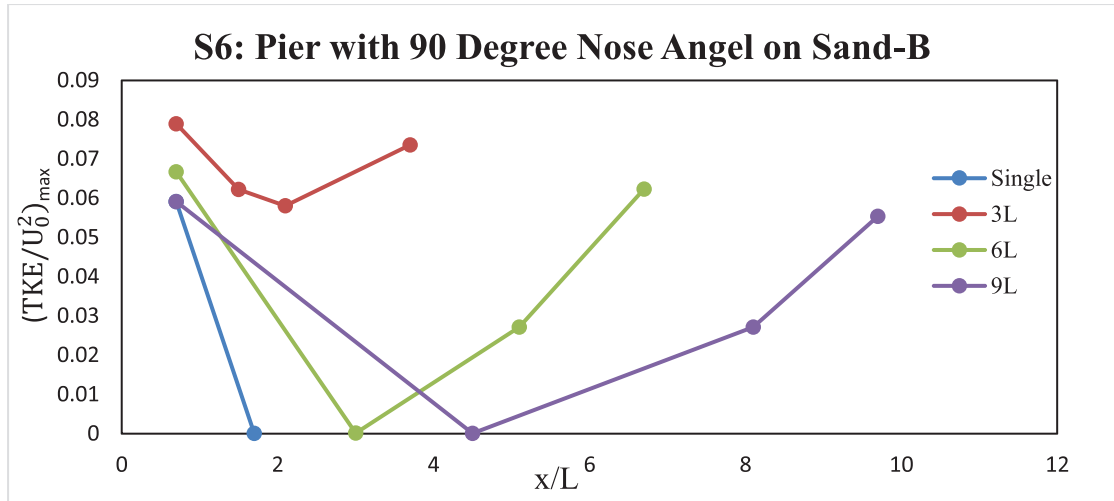
(c)



(d)



(e)



(f)

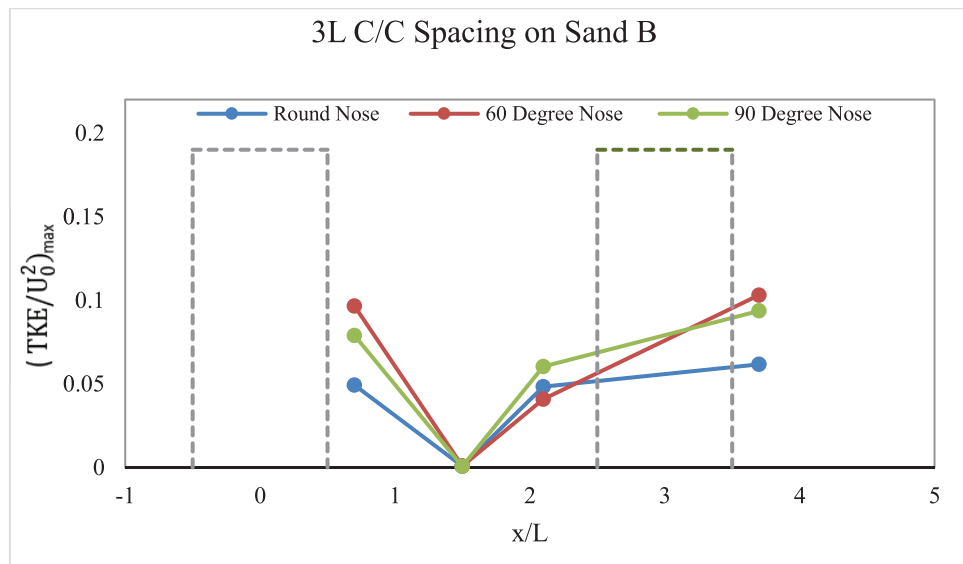
**Figure 4.13** Maximum normalized turbulent kinetic energy variation along the centerline on Sand-A (a, b & c) and Sand-B (d, e & f).

The effect of pier spacing on maximum normalized turbulent kinetic energy is shown in **Table 4.5**. From which it can be observed that, turbulent kinetic energy at Section-1 (u/s of front pier) was almost independent of pier spacing. Pier spacing had large effect on turbulent kinetic energy at Section-2 (d/s of front pier). In the midstream region (Section-2,3,4 & 5), maximum normalized turbulent kinetic energy decreased when the C/C spacing between two piers were increased, and the maximum turbulent kinetic energy was observed for piers placed at 3L C/C pier spacing. Shrestha (2015) also reported similar findings.

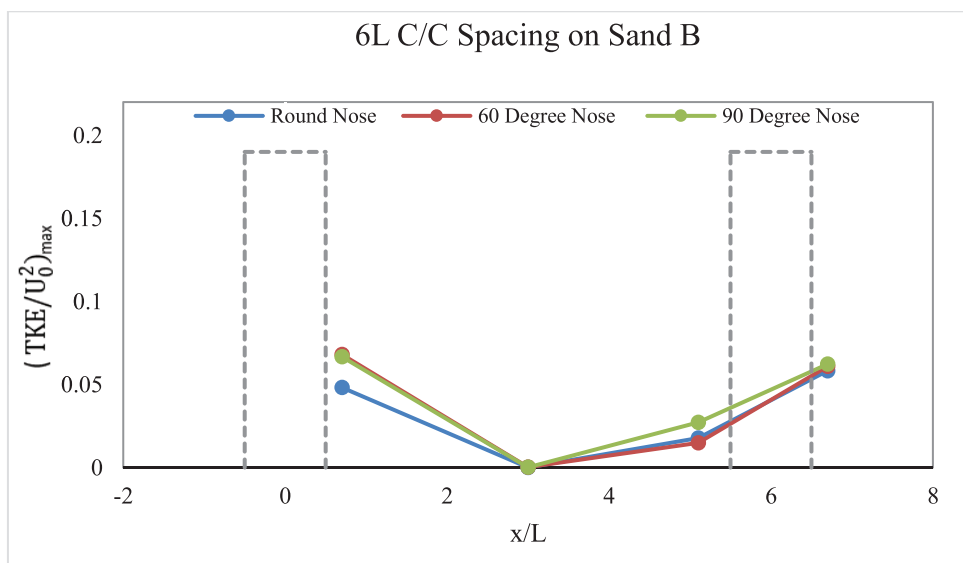
**Table 4.5** Effect of pier spacing on maximum normalized turbulent kinetic energy.

| Average of the Maximum Normalized Turbulent Kinetic Energy |       |       |       |
|------------------------------------------------------------|-------|-------|-------|
| C/C Pier Spacing                                           | 3L    | 6L    | 9L    |
| Section 1                                                  | 0.014 | 0.015 | 0.015 |
| Section 2                                                  | 0.096 | 0.084 | 0.076 |
| Section 3                                                  | 0.027 | 0.021 | 0.017 |
| Section 4                                                  | 0.07  | 0.03  | 0.022 |
| Section 5                                                  | 0.105 | 0.086 | 0.068 |

The effect of pier's nose shape on maximum normalized turbulent kinetic energy is shown in **Figure 4.14** and **Table 4.6**. From which it can be observed that pier's nose shape had almost no effect on maximum turbulent kinetic energy at Section-1 (u/s of front pier). At Section-2 (d/s of front pier), lowest and highest of the maximum turbulent kinetic energy was observed for round nose pier and pier with 90° nose angle, respectively. At Section-3 and Section-4, higher maximum normalized turbulent kinetic energy was observed for pier with 90° nose angle and round nose pier. At Section-5 (d/s of rear pier), similar effect of the pier's nose shape on d/s of front pier was found. The effect of pier nose shape for other experiments are shown in **Figure G. 1** of **Appendix-G**.

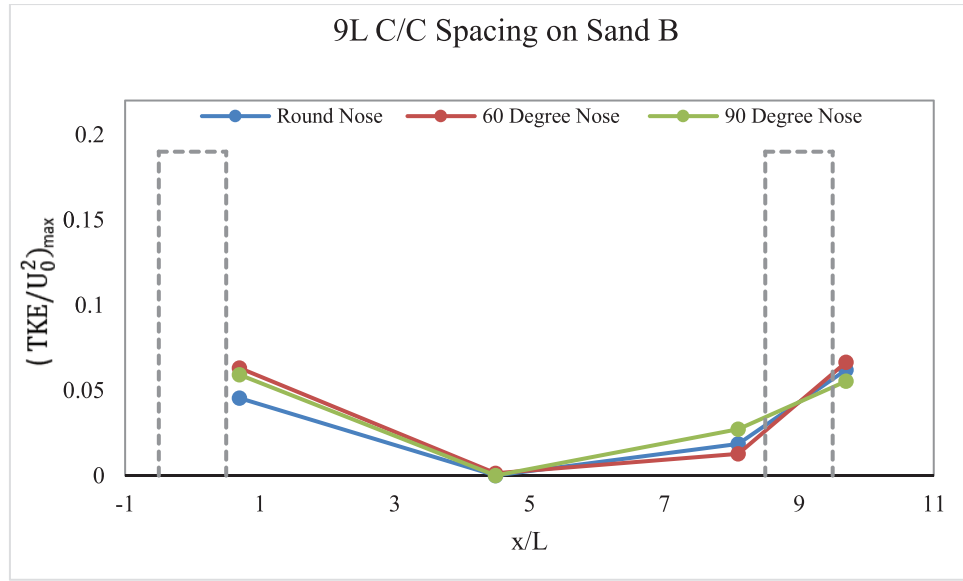


(a)



(b)





(c)

**Figure 4.14** Effect of pier nose shape on maximum turbulent kinetic energy on Sand-B ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing

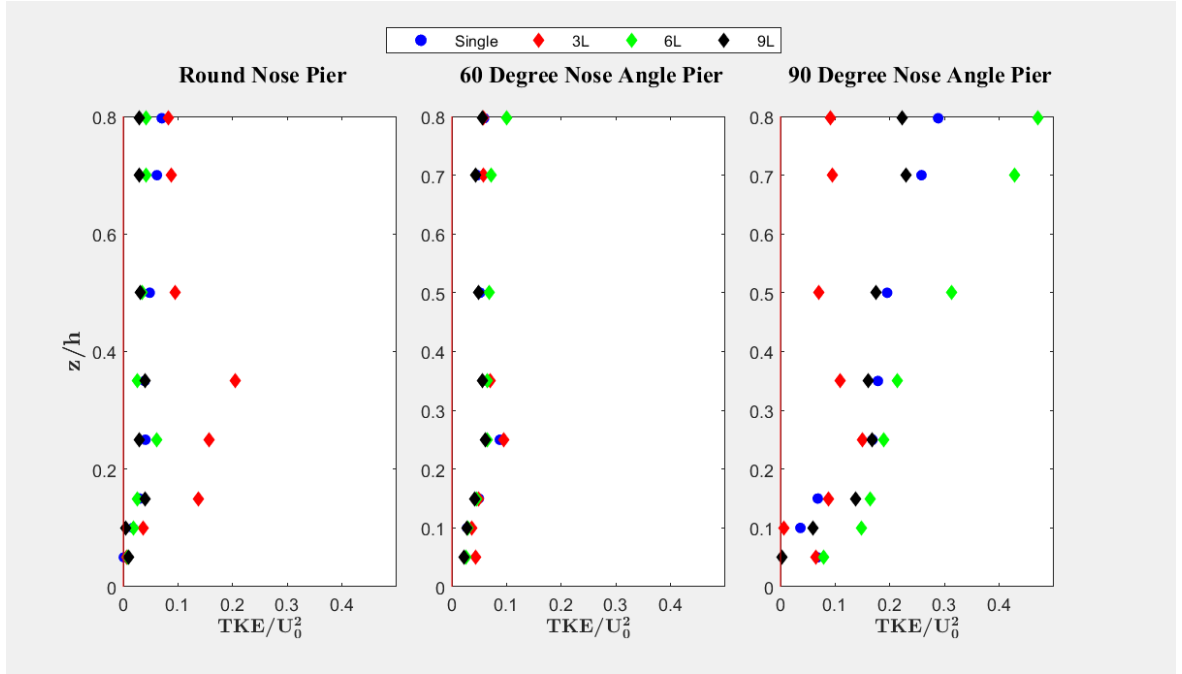
**Table 4.6** Effect of pier's nose shape on maximum normalized turbulent kinetic energy.

| Average of the Maximum Normalized Turbulent Kinetic Energy |       |       |       |
|------------------------------------------------------------|-------|-------|-------|
| Pier's Nose Shape                                          | Round | 60°   | 90°   |
| Section 1                                                  | 0.015 | 0.014 | 0.014 |
| Section 2                                                  | 0.055 | 0.081 | 0.12  |
| Section 3                                                  | 0.019 | 0.008 | 0.039 |
| Section 4                                                  | 0.035 | 0.031 | 0.057 |
| Section 5                                                  | 0.066 | 0.075 | 0.118 |

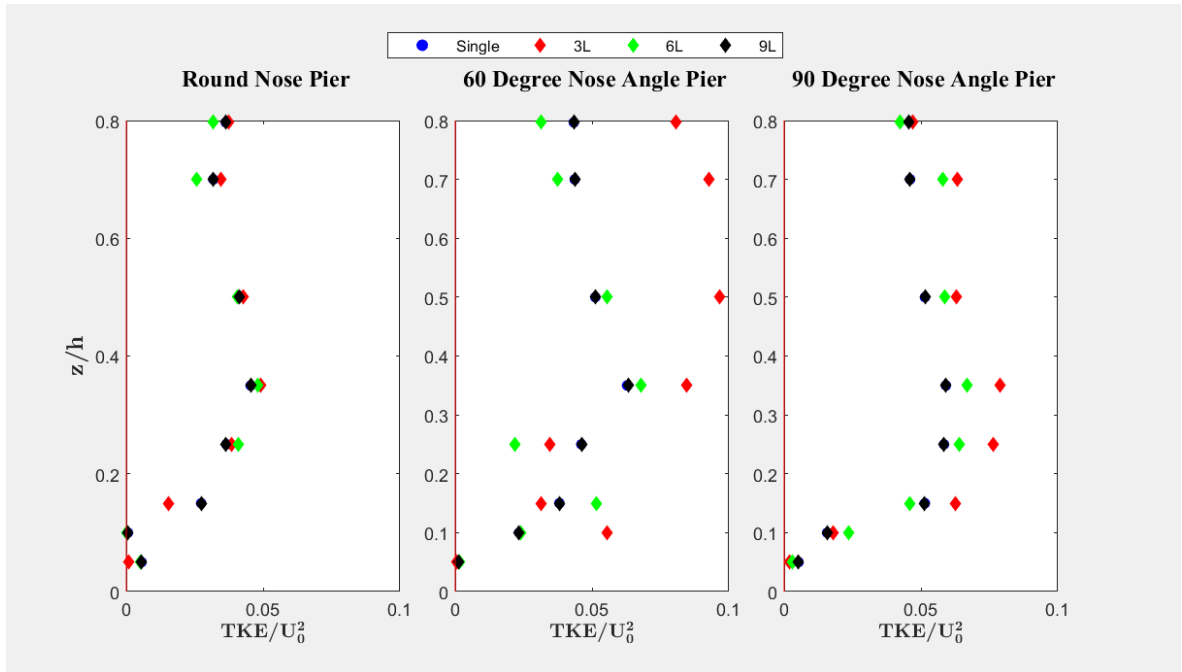
#### 4.4.4 Comparison Between Single and Tandem Pier

**Figure 4.15** represents the comparison of normalized turbulent kinetic energy between single and tandem pier arrangements. From which it can be observed that, in general turbulent kinetic energy was higher when the piers were placed at 3L and 6L C/C

spacing compare to single pier. When the C/C spacing between the piers were 9L, normalized turbulent kinetic energy showed almost similar values to single pier.



(a)



(b)

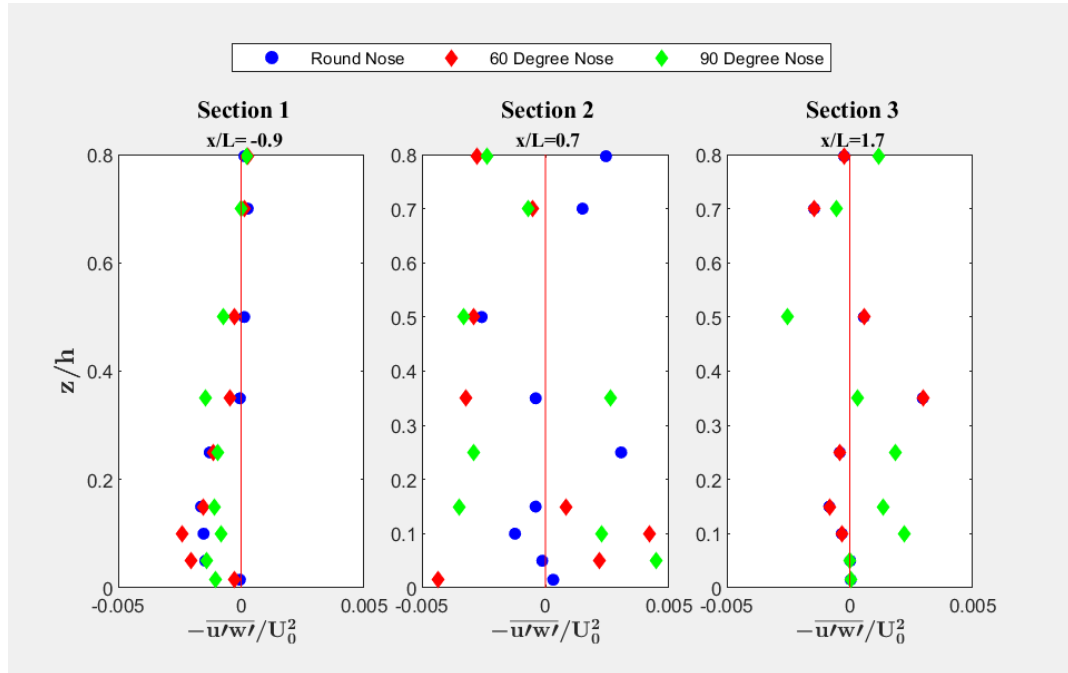
**Figure 4.15** Comparison of normalized turbulent kinetic energy at the downstream of the front pier (Section-2): (a) Sand-A (b) Sand-B.

#### 4.5 Normalized Streamwise Reynolds Shear Stress Variations along the Centerline

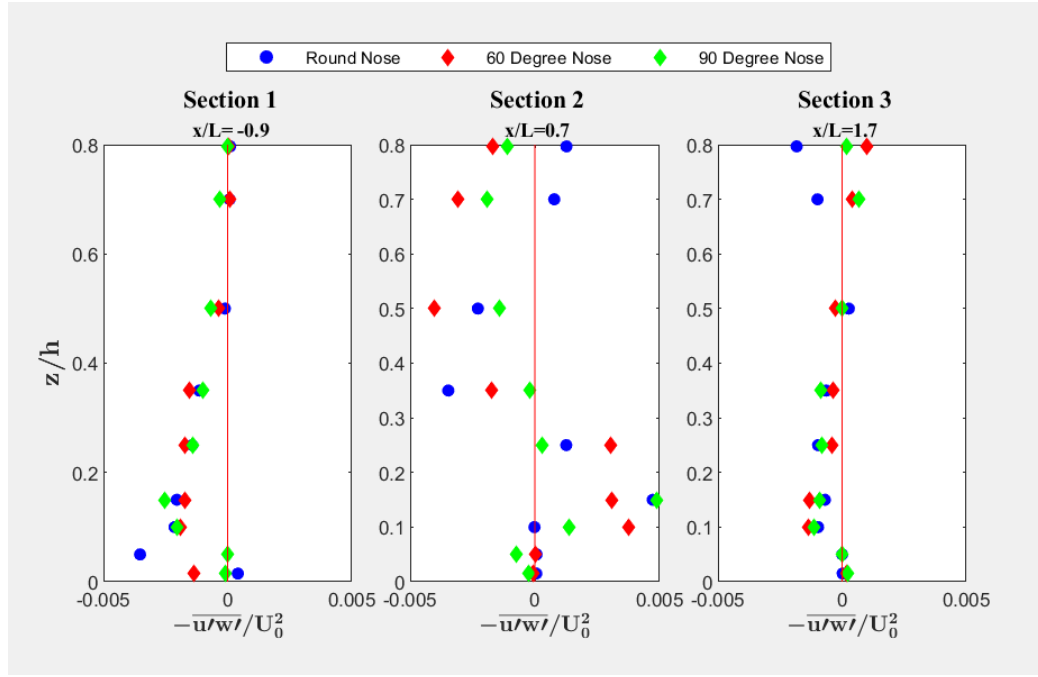
Using only the streamwise and vertical components of velocity variation, Reynolds shear stress was calculated along the centerline in this study, and they are denoted by  $-\rho\overline{u'w'}$ . Normalization of Reynolds shear stress was done by  $\rho U_0^2$  and plotted against  $z/h$  to evaluate the vertical profile.

##### 4.5.1 Single Pier

**Figure 4.16** represents the normalized Reynolds Shear Stress (RSS) variation along the centerline around single pier. From which it can be observed that at Section-1 (u/s of pier), RSS had higher magnitude near the bed and was close to zero near the surface. Near the bed the value of RSS was negative. At Section-2 (just d/s of the pier), RSS showed oscillatory nature (positive and negative values) which indicates flow separation and vortex shedding. Chavan (2018) observed that at the downstream of the pier, RSS fluctuates heavily due to the continuous development of vortex region. At Section-3 (further d/s of pier), the magnitude of Reynolds shear stress was decreased compared to Section-2 and the oscillatory nature of shear stress was also observed in that section. Besides the maximum positive value of RSS was observed at the downstream section of the pier.



(a)



(b)

**Figure 4.16** Normalized Reynolds shear stress variation ( $-\overline{u'w'}/U_0^2$  vs  $z/h$ ) around single pier on: (a) Sand-A (b) Sand-B

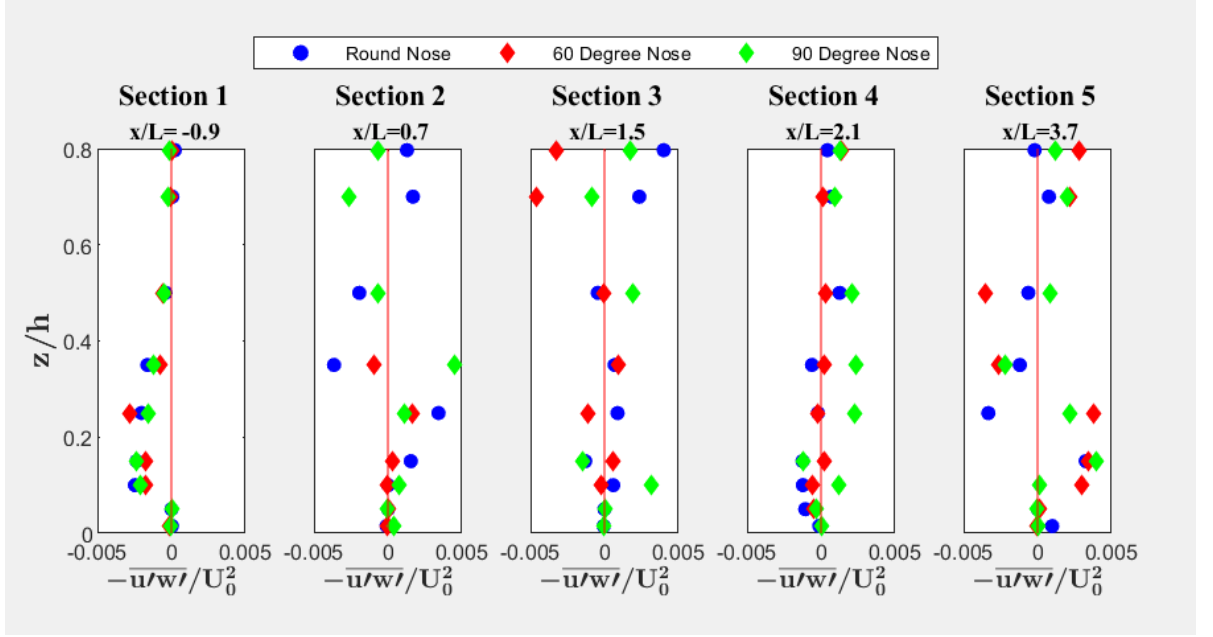
Among the three sections, the maximum magnitude of the shear stress was observed at Section-2 (just d/s of the pier) for all nose shapes of pier. Shrestha (2015) reported that the maximum positive value of RSS was observed at the wake of the pier.

#### 4.5.2 Tandem Pier

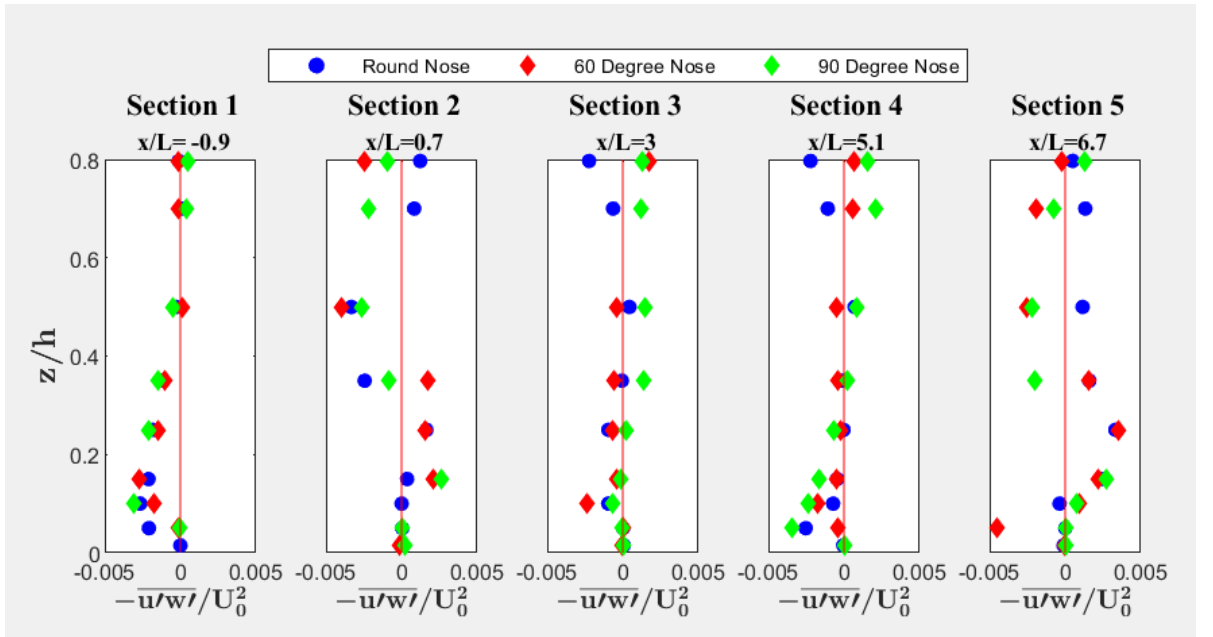
Variation of normalized Reynolds shear stress along the centerline of the channel at different locations, when the piers are placed in tandem on Sand-B shown in **Figure 4.17**.

At Section-1 (u/s of front pier), negative values of shear stress were observed near the bed. With increasing distance from the bed, the magnitude of the shear stress decreased and reached nearly zero values at surface. This negative value near the bed occurs due to flow reversal. At Section-2 (d/s of front pier), magnitude of the shear stress increased and an oscillatory nature was observed. This oscillatory nature was observed due to flow separation and vortex shedding. At Section-3, Reynolds shear stress was almost zero near the bed and reached a maximum magnitude at  $z/h=0.1$  to  $z/h=0.15$ . Near the surface the value was almost zero. At Section-4 (u/s of the rear pier), negative values of Reynolds shear stress were observed near the bed due to flow reversal. Vertical

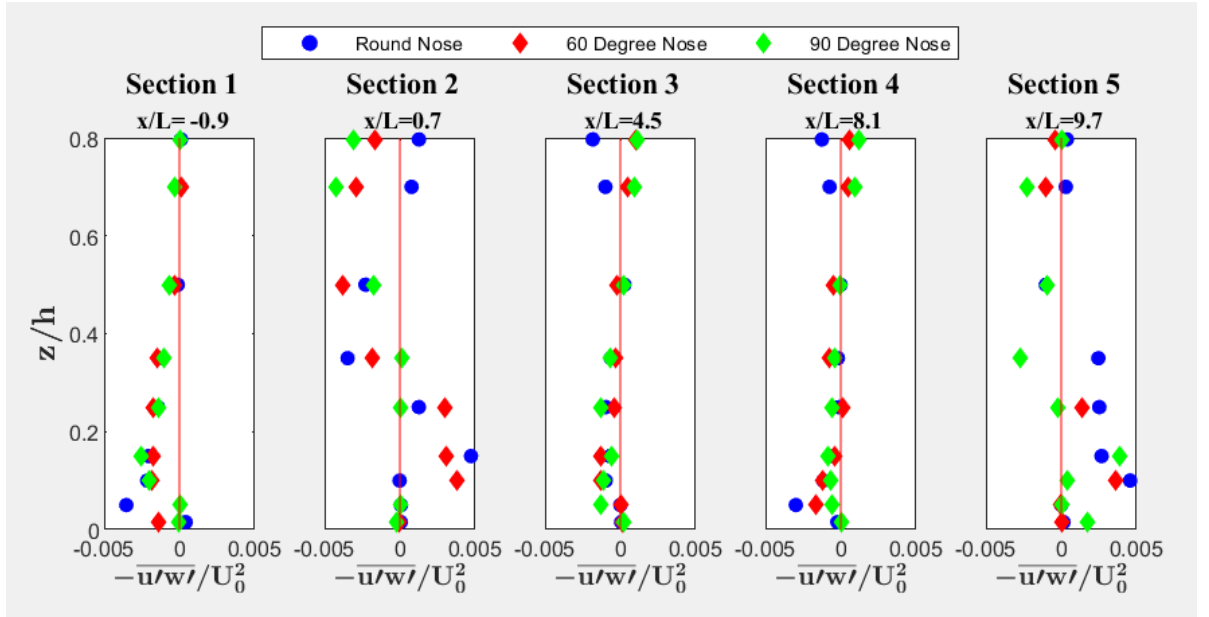
profiles of Reynolds shear stress at u/s of front and rear pier showed some dissimilarity, though values were negative near the bed in both cases but for rear pier Reynolds shear stress attained positive value after a certain distance from the bed (approximately  $z/h=0.2$ ). At the u/s of the front pier the value was negative throughout the depth and at surface it was close to zero. At Section-5 (d/s of rear pier), oscillatory behavior of the Reynolds shear stress was observed. The Reynolds Shear Stress (RSS) variations for other experiments are presented in **Figure H. 1** of **Appendix-H**.



(a)



(b)

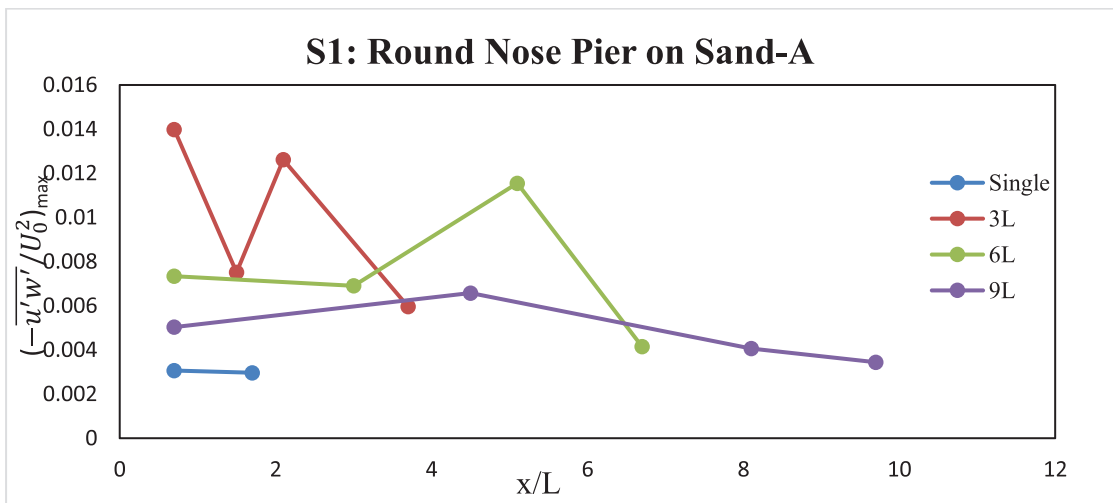


(c)

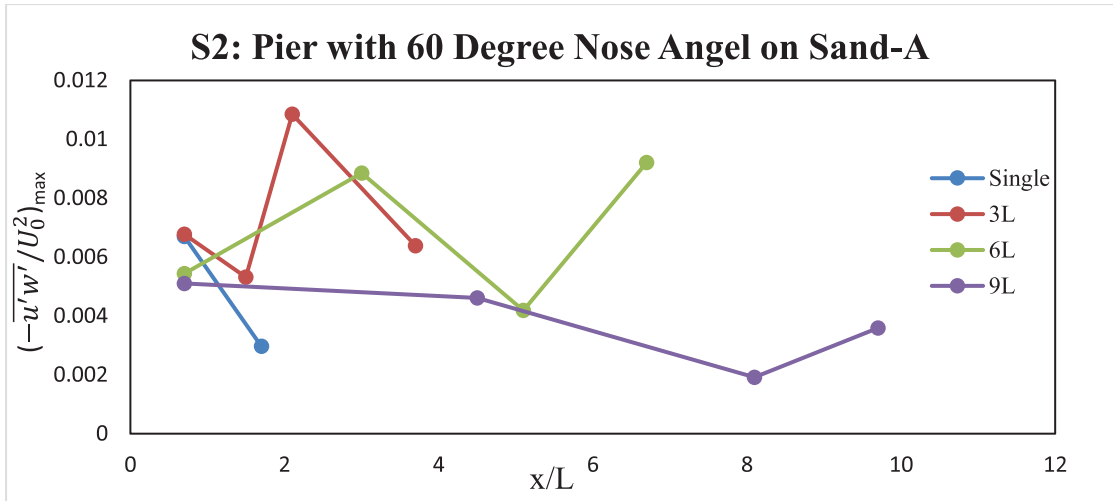
**Figure 4.17** Normalized streamwise turbulent kinetic energy variation ( $TKE/U_0^2$  vs  $z/h$ ) for piers placed in tandem arrangements at 3L C/C spacing on Sand-B ( $d_{50}=0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

#### 4.5.3 Maximum Normalized Reynolds Shear Stress Variation

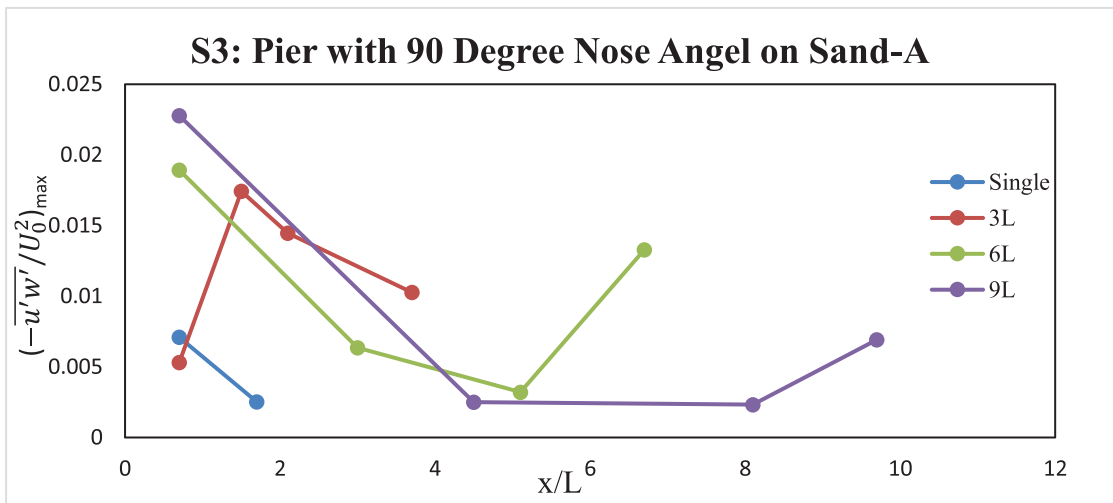
**Figure 4.18** represents the maximum normalized Reynolds shear stress at different location along the centerline. At Section-1, maximum normalized Reynolds shear stress didn't vary much for different piers nose shape or different pier spacing. At Section-2 (d/s of the front pier), a sudden increase in maximum normalized Reynolds shear stress had been observed for all shapes of pier at all spacings.



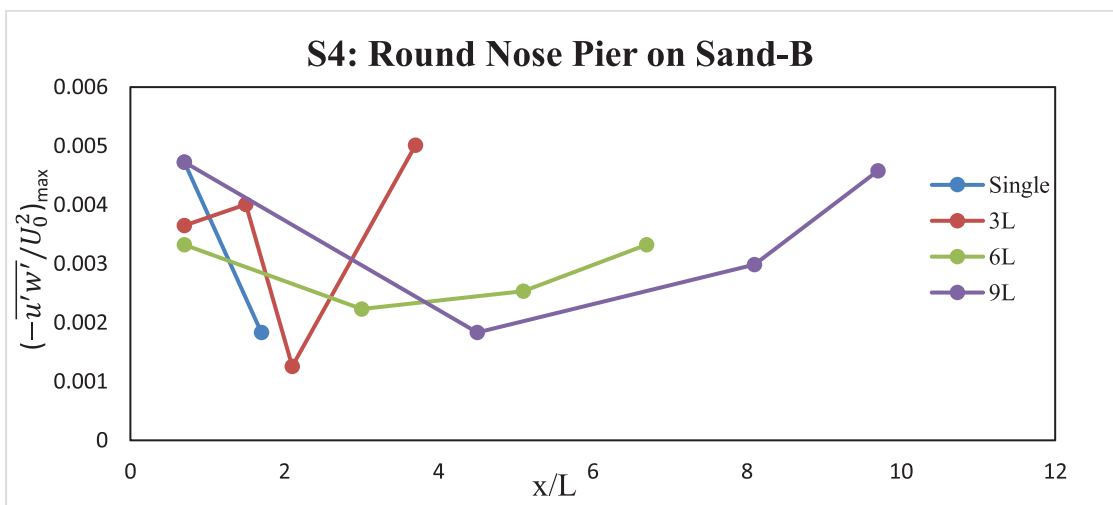
(a)



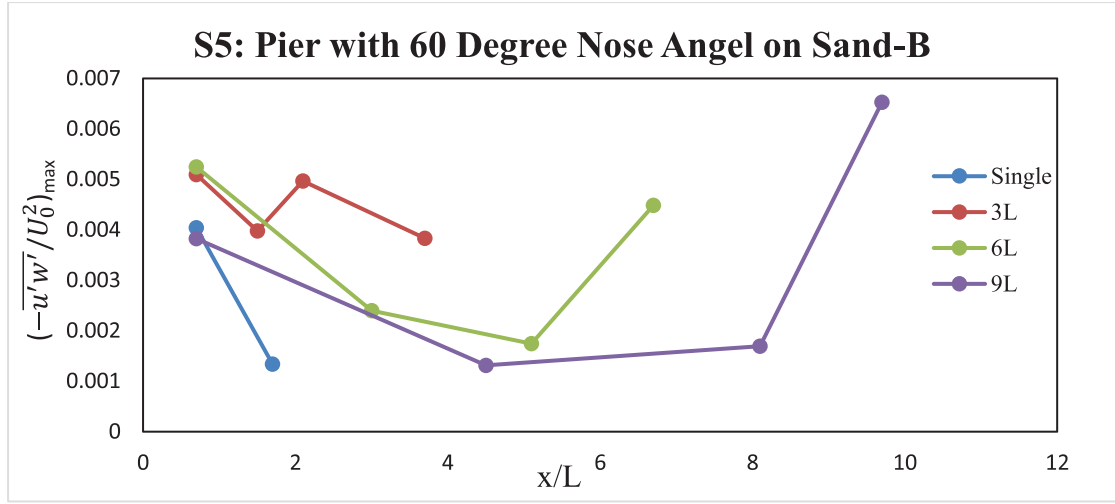
(b)



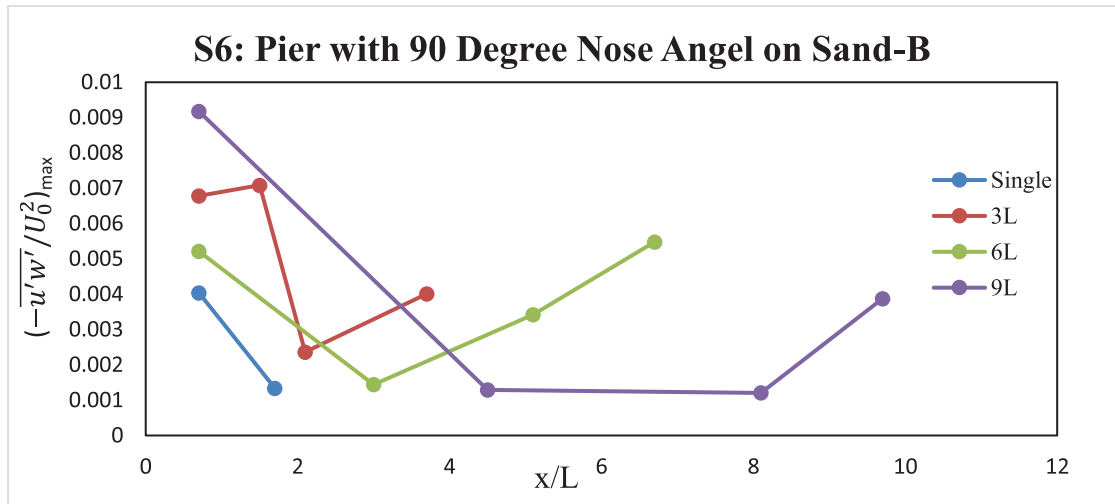
(c)



(d)



(e)



(f)

**Figure 4.18** Maximum normalized Reynolds shear stress variation along the centerline on Sand-A (a, b & c) and Sand-B (d, e & f).

At Section-3, a sudden decrease in Reynolds shear stress was observed which again increased at Section-4 in almost all the scenarios. At Section-5, maximum normalized Reynolds shear stress was higher compare to Section-4 in almost all scenarios except for piers placed 3L C/C spacing on fine sand.

The effect of pier spacing on maximum normalized Reynolds shear stress is also shown in **Table 4.7**. At Section-1, maximum value of the average of the maximum normalized Reynolds shear stress was observed when the piers were placed at 6L C/C pier spacing whereas minimum value was observed for 9L C/C pier spacing. Shear stress then suddenly increased at Section-2 and maximum value observed for 9L C/C pier spacing.

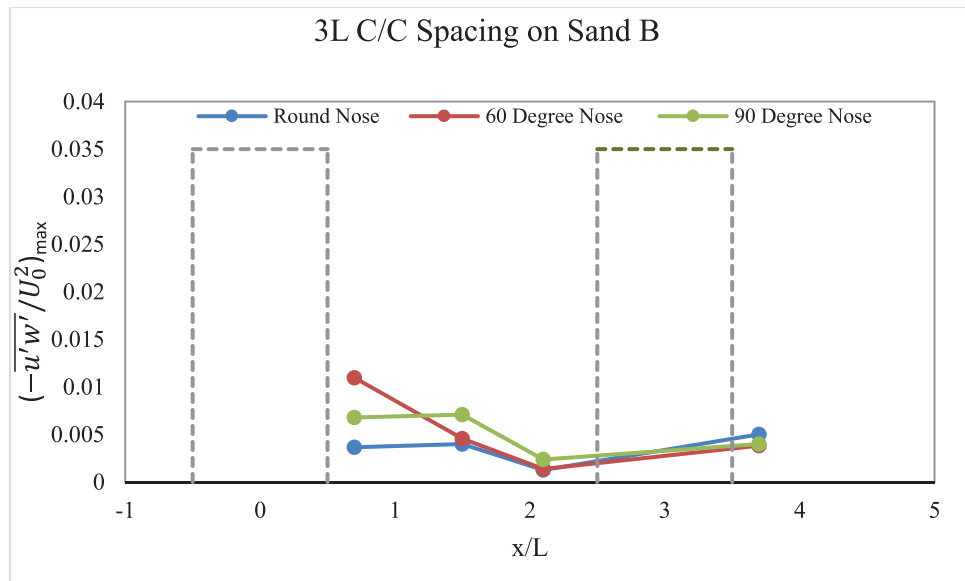


At Section-3 and Section-4 and Section-5, average of the maximum normalized Reynolds shear stress was maximum for piers placed at 3L C/C spacing and minimum for piers placed at 9L C/C spacing.

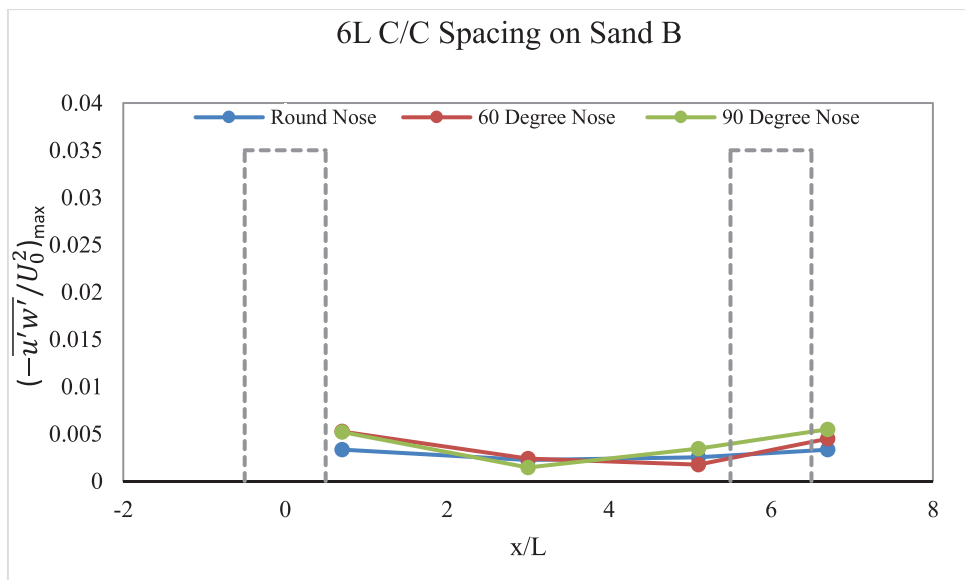
**Table 4.7** Effect of pier spacing on maximum normalized Reynolds shear stress.

| <b>Average of the Maximum Normalized Reynolds Shear Stress</b> |           |           |           |
|----------------------------------------------------------------|-----------|-----------|-----------|
| <b>C/C Pier Spacing</b>                                        | <b>3L</b> | <b>6L</b> | <b>9L</b> |
| Section 1                                                      | 0.0026    | 0.0033    | 0.0024    |
| Section 2                                                      | 0.008     | 0.0076    | 0.0089    |
| Section 3                                                      | 0.0077    | 0.0047    | 0.0031    |
| Section 4                                                      | 0.0089    | 0.0045    | 0.0024    |
| Section 5                                                      | 0.0091    | 0.0067    | 0.0052    |

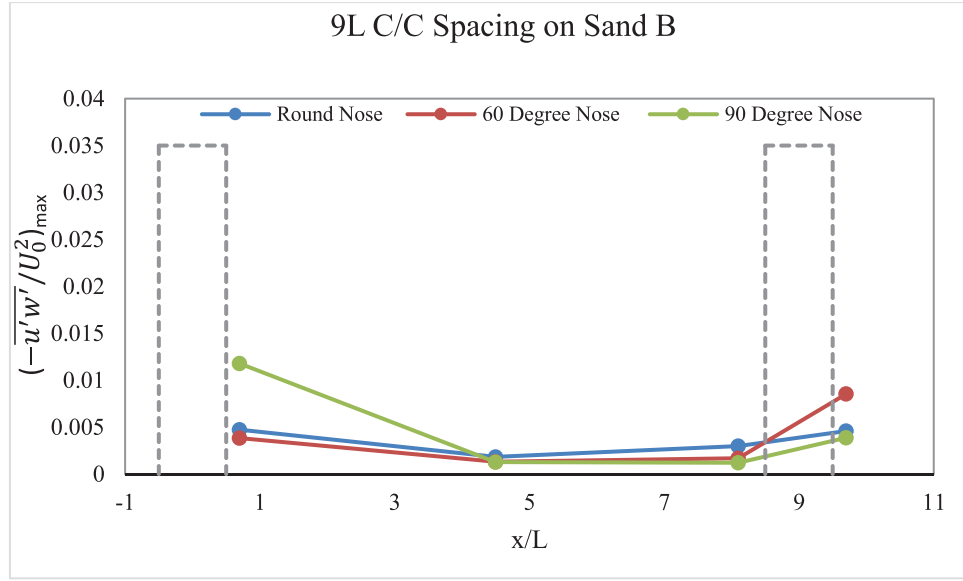
The effect of pier's nose shape on maximum normalized Reynolds shear stress is shown in **Figure 4.19** and **Table 4.8**. From which it can be observed that, at the u/s of the front pier (Section-1), the average value of the maximum normalized Reynolds shear stress wasn't affected by pier's nose shape. At all other locations, maximum Reynolds shear stresses were observed for round nose pier and minimum Reynolds shear stresses were observed for pier with 90<sup>0</sup> nose angle. The effect of pier nose shape on maximum normalized Reynolds Shear Stress for other experiments are shown in **Figure I. 1** of **Appendix-I**.



(a)



(b)



(c)

**Figure 4.19** Effect of pier nose shape on maximum Reynolds Shear Stress on Sand-B ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing

**Table 4.8** Effect of pier's nose shape on maximum normalized Reynolds shear stress.

| Average of the Maximum Normalized Reynolds Shear Stress |        |                 |                 |
|---------------------------------------------------------|--------|-----------------|-----------------|
| Pier's Nose Shape                                       | Round  | 60 <sup>0</sup> | 90 <sup>0</sup> |
| Section 1                                               | 0.0028 | 0.0028          | 0.0028          |
| Section 2                                               | 0.0064 | 0.0063          | 0.005           |
| Section 3                                               | 0.0049 | 0.0046          | 0.0027          |
| Section 4                                               | 0.0076 | 0.0037          | 0.0022          |
| Section 5                                               | 0.0076 | 0.0061          | 0.0032          |

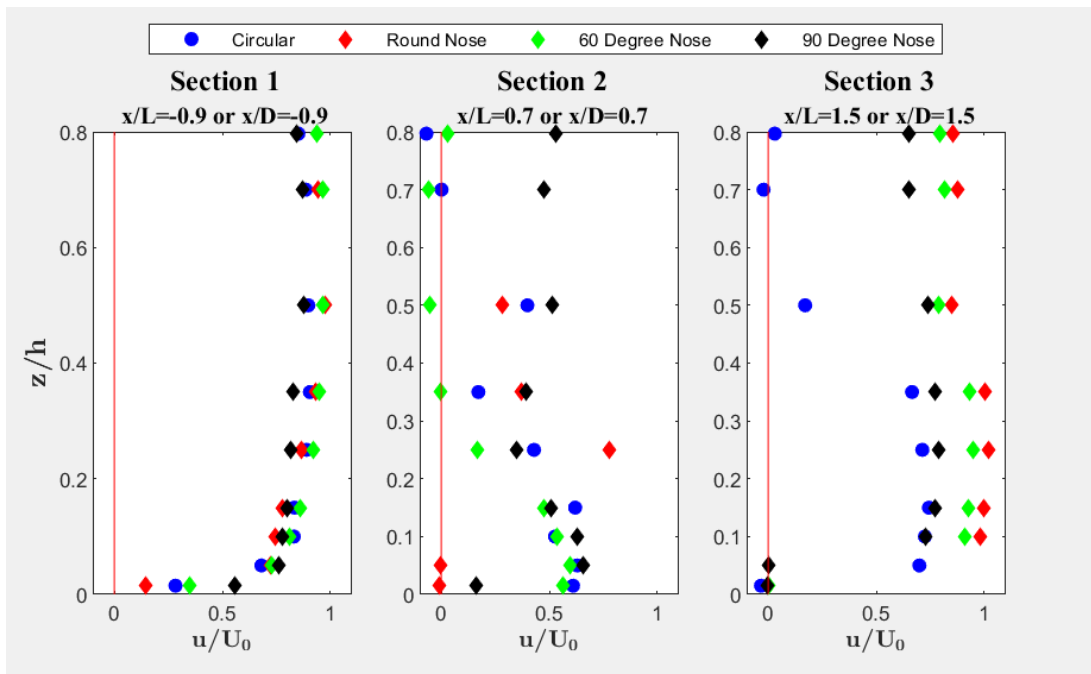
#### 4.6 Comparison of Turbulent Characteristics between Circular and Non-circular pier.

Basir (2022) conducted laboratory experiment to investigate the local scour and turbulence characteristics around circular pier in single and tandem arrangements. A comparison of turbulent parameters (dimensional turbulent intensity and dimensional turbulent kinetic energy) between circular and non-circular pier has been made. **Figure 4.20** represents the comparison of streamwise velocity variation between circular and

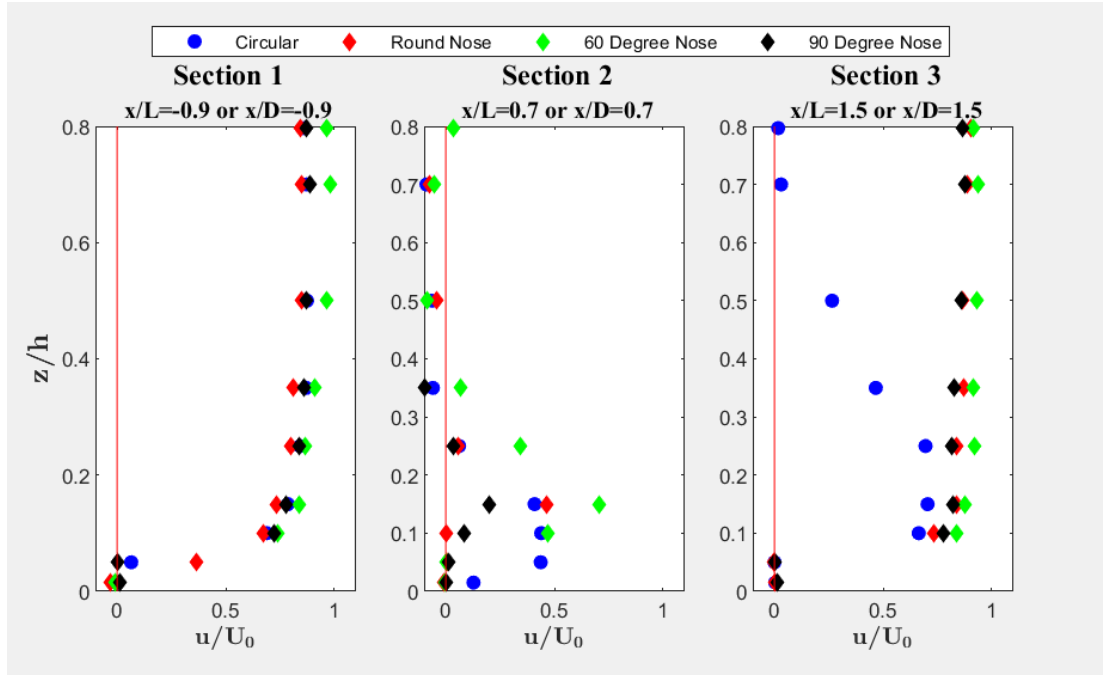
non-circular pier. From which it can be observed that, circular pier experienced higher flow reversal compare to non-circular pier

**Figure 4.21** represents the comparison between circular and non-circular single piers placed in both Sand-A and Sand-B. From which it can be observed that at the u/s of the pier (Section-1), normalized streamwise turbulent intensity was almost similar for all shapes of pier. Near the bed circular pier showed slightly higher turbulent intensity. At the d/s of the pier, highest turbulent intensity was observed for circular pier due to higher magnitude of flow circulation. Extent of higher turbulent intensity region was found higher for circular pier.

**Figure 4.22** represents the comparison of normalized turbulent kinetic energy between circular and non-circular pier. From which it can be observed that, at u/s of pier (Section-1), turbulent kinetic energy showed almost similar values for all shapes of pier. At the d/s of the pier, circular pier showed highest turbulent kinetic energy. Besides the extent of the higher turbulent kinetic region was found higher for circular pier. At Section-3, magnitude of the turbulent kinetic energy was reduced for all shapes of pier, but the lowest reduction was observed for circular pier.

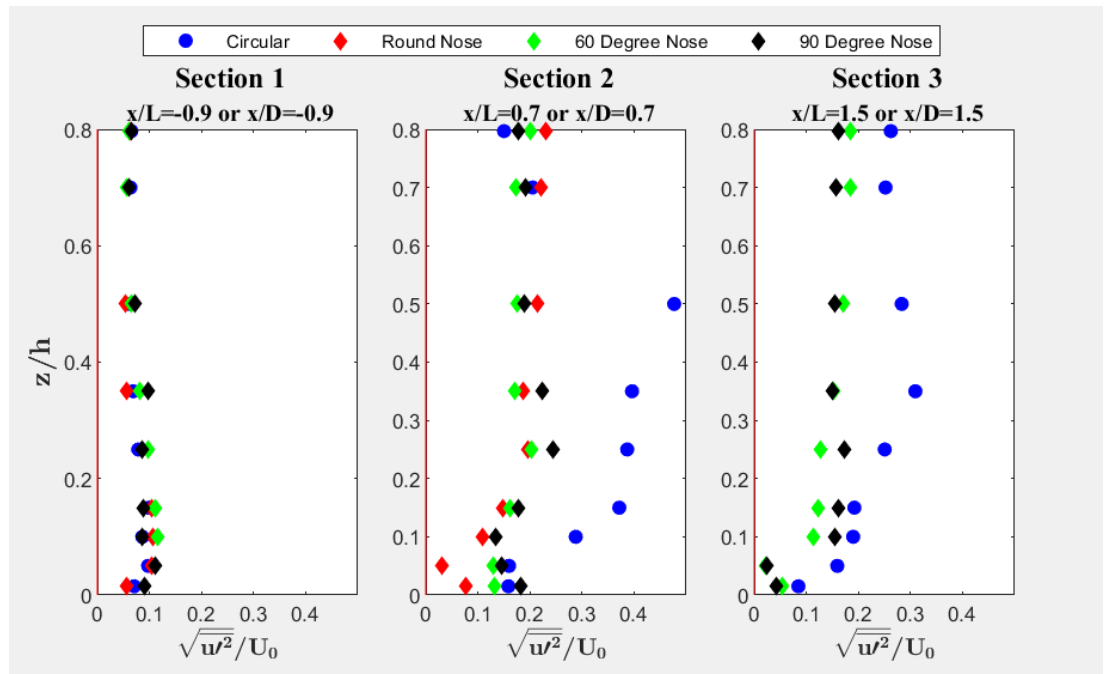


(a)

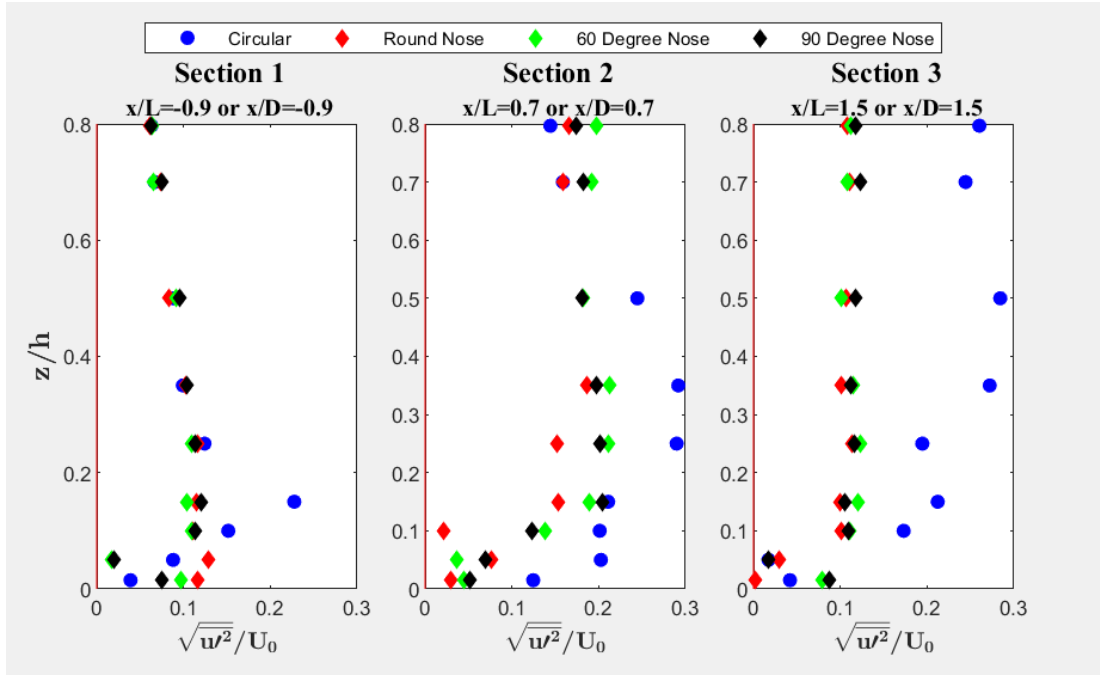


(b)

**Figure 4.20** Comparison of normalized streamwise velocity between circular and non-circular pier: (a) Sand-A (b) Sand-B

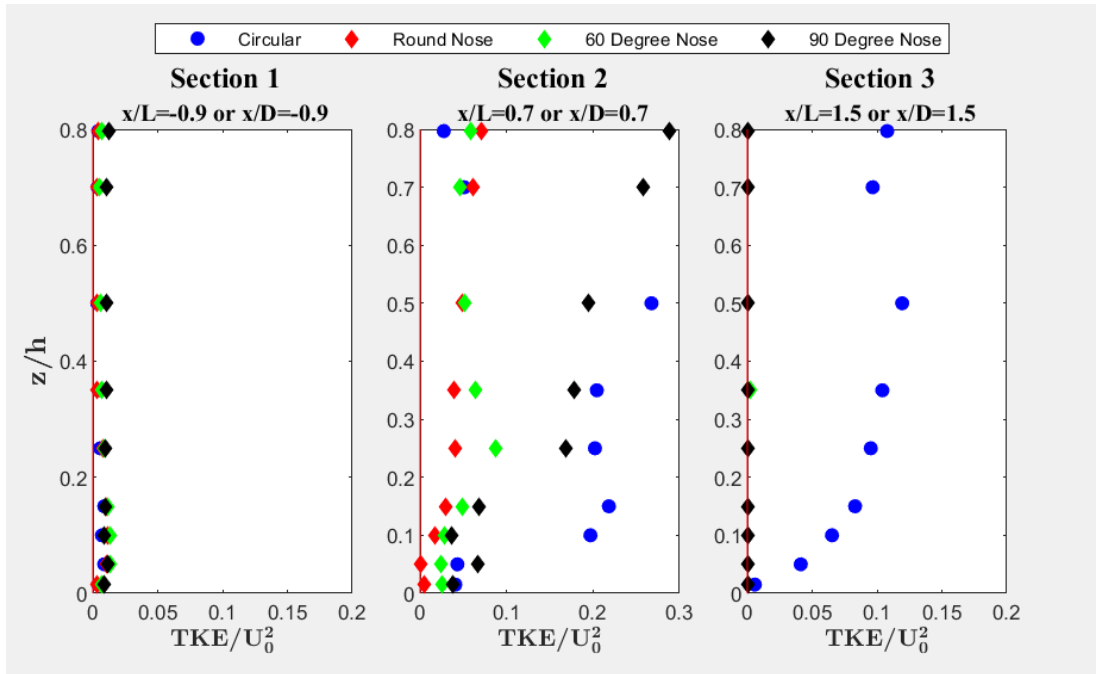


(a)

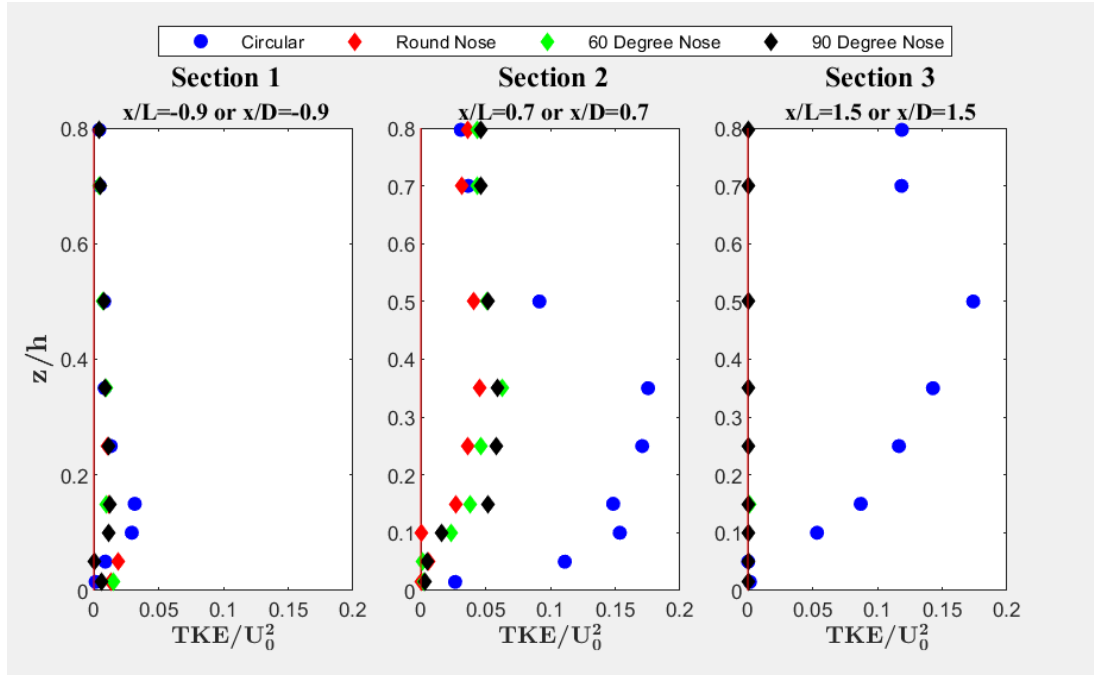


(b)

**Figure 4.21** Comparison of normalized turbulent intensity between circular and non-circular pier: (a) Sand-A (b) Sand-B



(a)



(b)

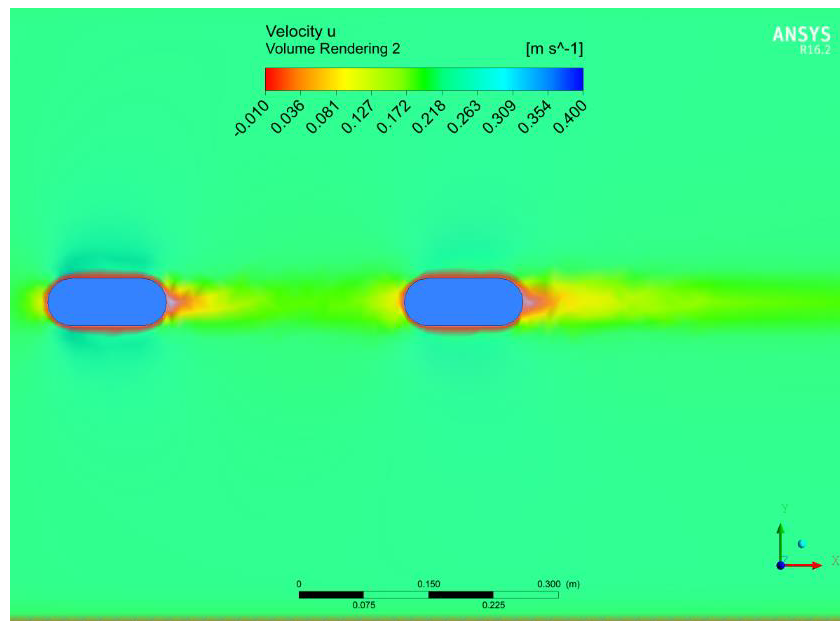
**Figure 4.22** Comparison of normalized turbulent kinetic energy between circular and non-circular pier: (a) Sand-A (b) Sand-B.

#### 4.7 Comparison between Computational Fluid Dynamics (CFD) Model and Observed Data.

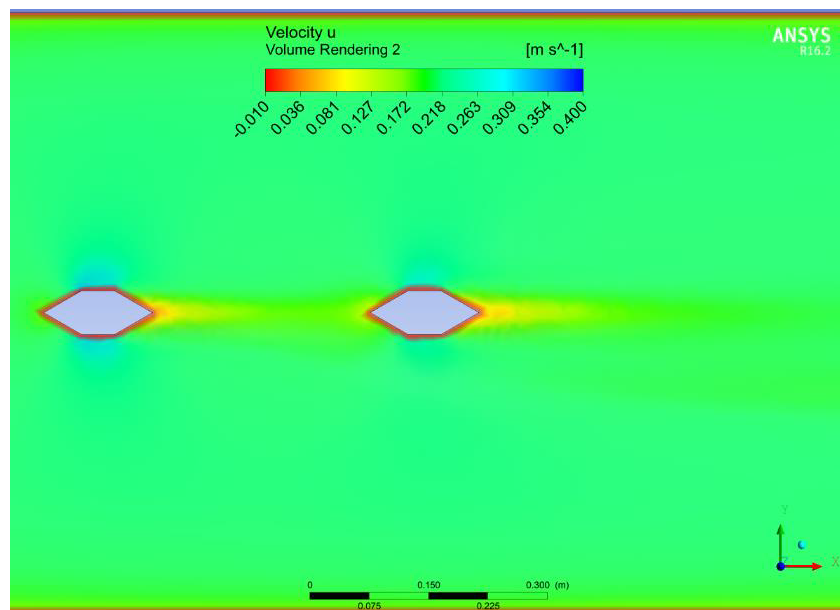
In this study, Computational fluid dynamics (CFD) simulation had been conducted for round nose, pier with 60<sup>0</sup> nose angle and pier with 90<sup>0</sup> nose angle placed at 3L C/C spacing on fixed bed condition using ANSYS (R16.2).

**Figure 4.23** represents streamwise velocity variation for two piers in tandem arrangement placed at 3L C/C spacing. From which it can be observed that velocity at the u/s of each pier was higher than the d/s of the pier due to flow reversal. In the wake of the pier streamwise velocity was negative or had very low value. Besides, in the midstream region, streamwise velocity increased with increased distance from the front pier and then decreased behind the rear pier. Earlier discussion revealed that similar findings were also observed for laboratory experiments.

Besides, CFD simulation indicated that the approach flow velocity for the rear pier (just u/s section of the rear pier) was lowest for 90<sup>0</sup> nose angle pier and highest for 60<sup>0</sup> nose angle pier. From the experiments average normalized streamwise velocity at Section-4 was obtained as 0.648, 0.735, and 0.606 for round nose, 60<sup>0</sup> nose angle and 90<sup>0</sup> nose angle pier respectively.

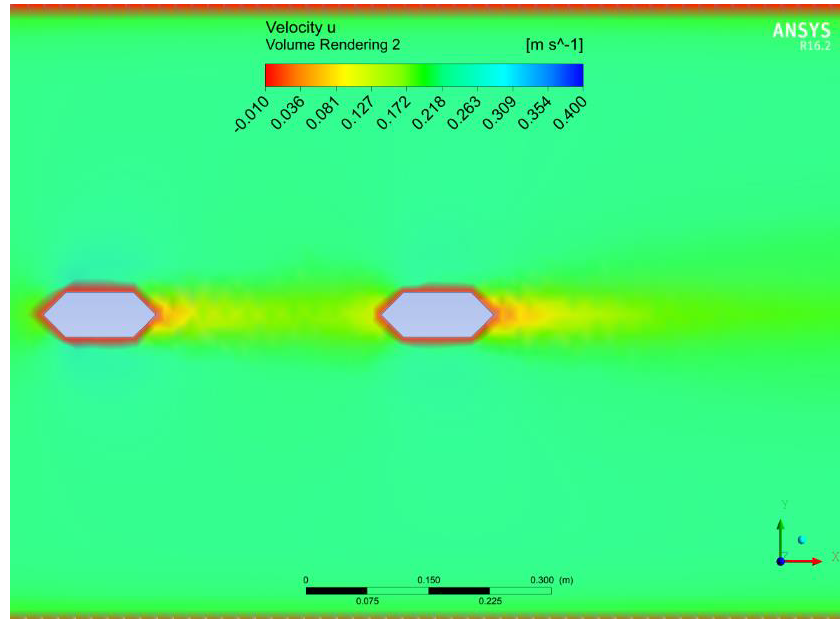


(a)



(b)

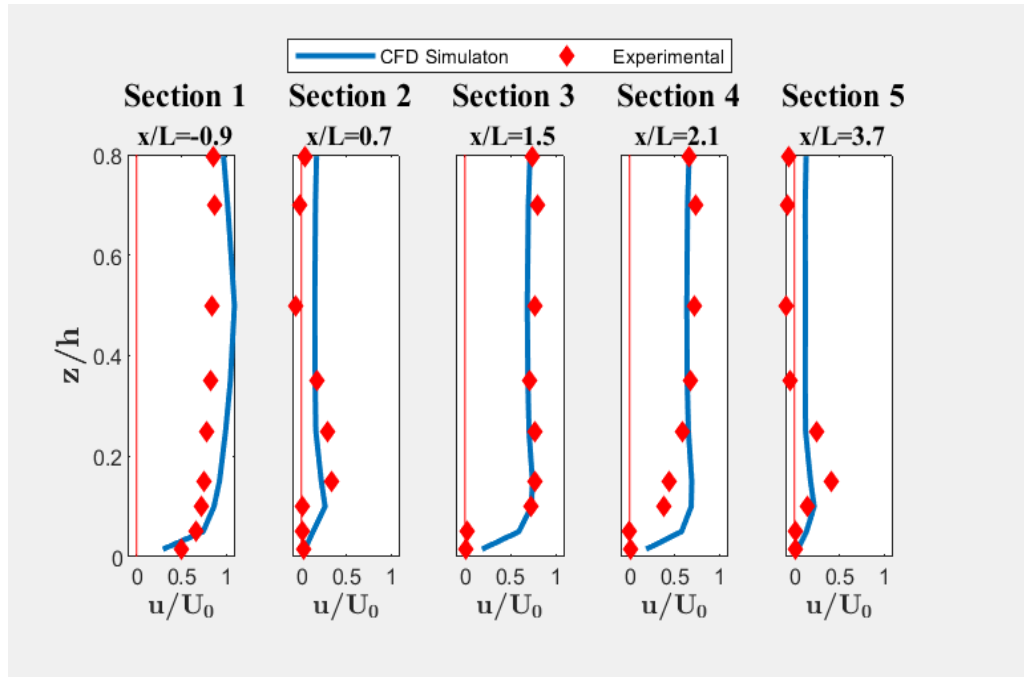




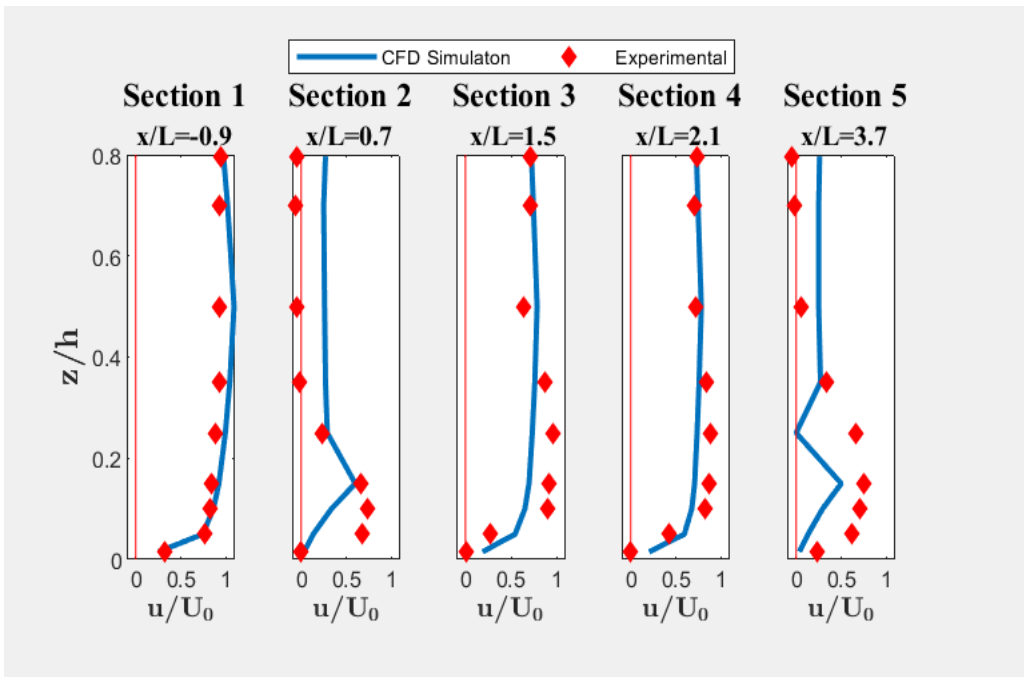
(c)

**Figure 4.23** Streamwise velocity variation around piers placed at 3L C/C spacing: (a) Round Nose (b) Pier with 60° nose angle and (c) Pier with 90° nose angle.

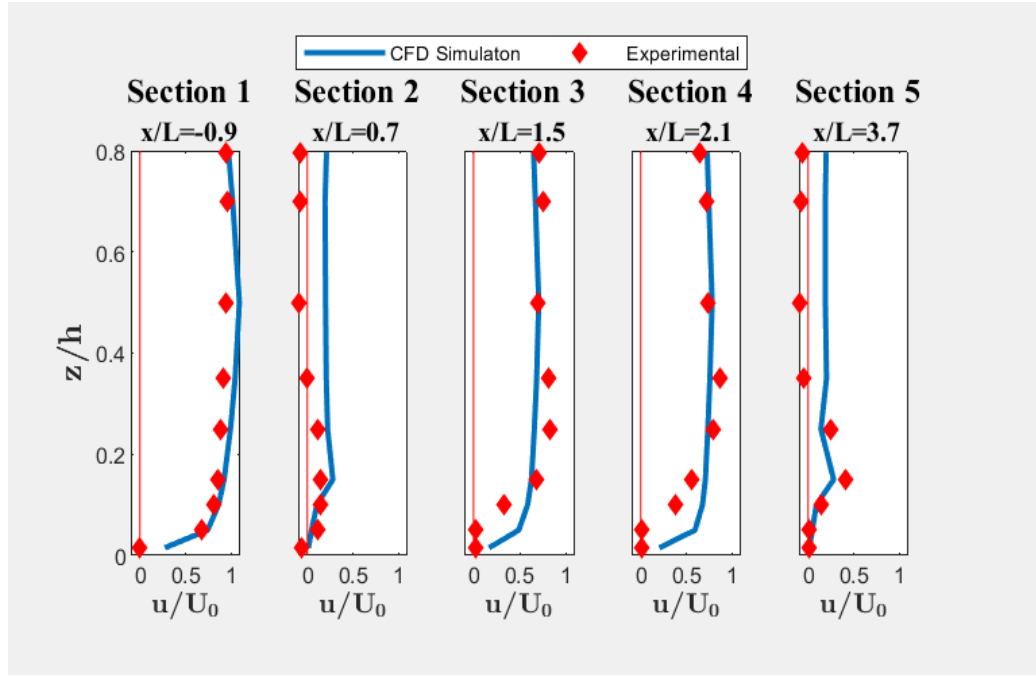
**Figure 4.24** represents the comparison of normalized streamwise velocity between CFD simulation and experimental observation for round nose pier, pier with 60° nose angle and 90° nose angle. It can be observed that, CFD simulation and experimental observation showed similar pattern but there were some differences in magnitude. In general, CFD simulation showed higher velocity towards the surface compare to the experimental observation. This higher velocity was more prominent at the downstream of the pier compared to the upstream. At mid depth ( $z/h=0.5$ ), at Section-1, Section-2 and Section-5, CFD simulation showed 23.22%, 145.78% and 180.7322% higher velocity compare to experimental observation for round nose pier. For pier with 60° nose angle, at Section-1, Section-2, Section-3, Section-4 and Section-5, CFD simulation showed 15.1%, 118.94%, 18.57%, 8.76% and 76.40% higher velocity respectively compare to experimental observation. So, it was evident that, at the d/s of both front and rear pier CFD simulation overestimated normalized streamwise velocity by higher magnitude compare to other sections.



(a)



(b)



(c)

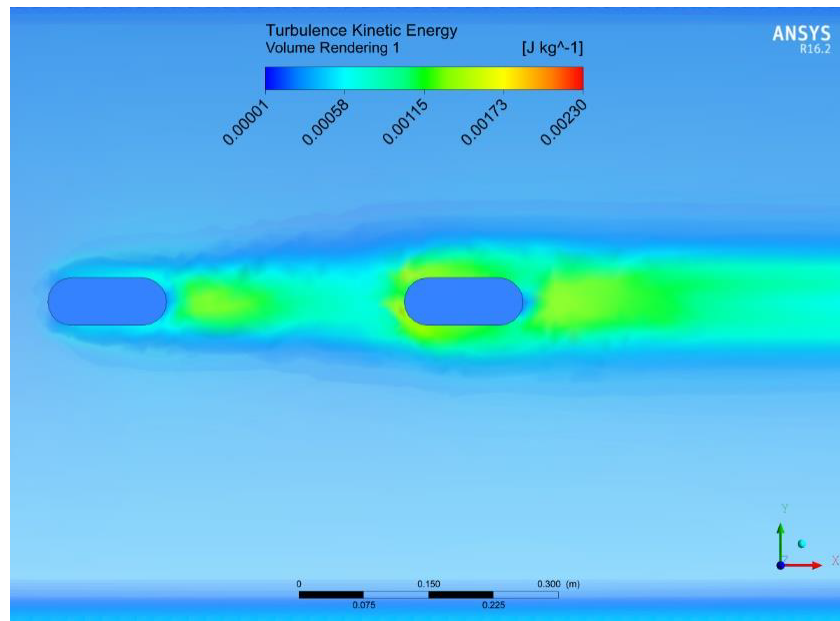
**Figure 4.24** Comparison of normalized streamwise velocity variation between CFD simulation and experiments: (a) Round Nose (b) Pier with  $60^\circ$  Nose Angle (c) Pier with  $90^\circ$  Nose Angle.

**Figure 4.25** represents the turbulent kinetic energy variation around two piers placed in tandem arrangements at  $3L$  C/C spacing. Turbulent kinetic energy at the d/s of both pier was higher compare to the u/s of the pier and in the midstream region along the centerline, turbulent kinetic energy decreased with increase distance from the front pier. Similar findings were obtained in the laboratory experiment as discussed earlier.

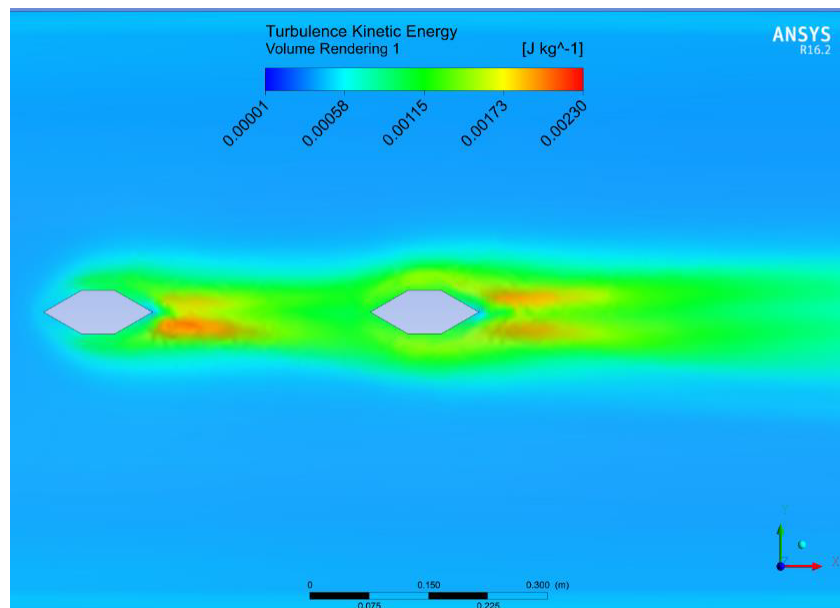
Besides it can be observed that pier with  $60^\circ$  nose angle showed different pattern compare to the other two shape. Turbulent kinetic energy was higher along the centerline for round nose pier. Higher values of turbulent kinetic energy started to move to the sides for pier with  $90^\circ$  nose angle, with a further sharp nose of pier ( $60^\circ$  nose angle) much higher turbulent kinetic energy value was observed at both side of the centerline of the flume. This indicated the increased flow separation for pier with sharper nose and increased sideward scour rather than frontal scour was observed for pier with sharper nose.

For round nose, pier with  $60^\circ$  nose angle and pier with  $90^\circ$  nose angle placed at  $3L$  C/C spacing the values of average turbulent kinetic energy at Section-2 (d/s of the front pier) from the experiment were found as 0.033, 0.069, and 0.058 respectively. From CFD

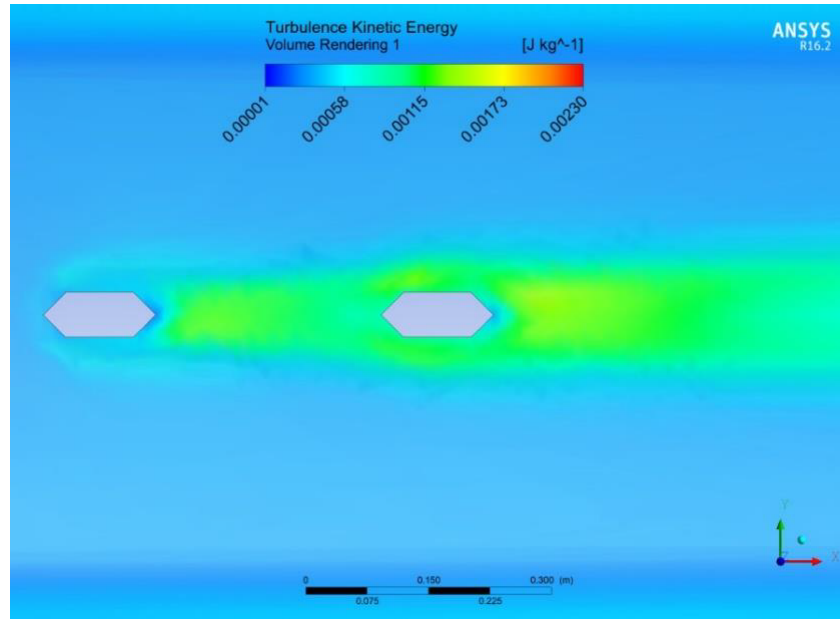
simulation highest turbulent kinetic energy at the d/s of the front pier was found for 60<sup>0</sup> nose angle pier. Besides, turbulent kinetic energy at the d/s of the front pier was observed to be lower than the rear pier in CFD simulation which was also confirmed by the value of turbulent kinetic energy at the d/s of rear pier found in the experiment as 0.048, 0.071, and 0.061 for round nose, pier with 60<sup>0</sup> nose angle and pier with 90<sup>0</sup> nose angle respectively.



(a)



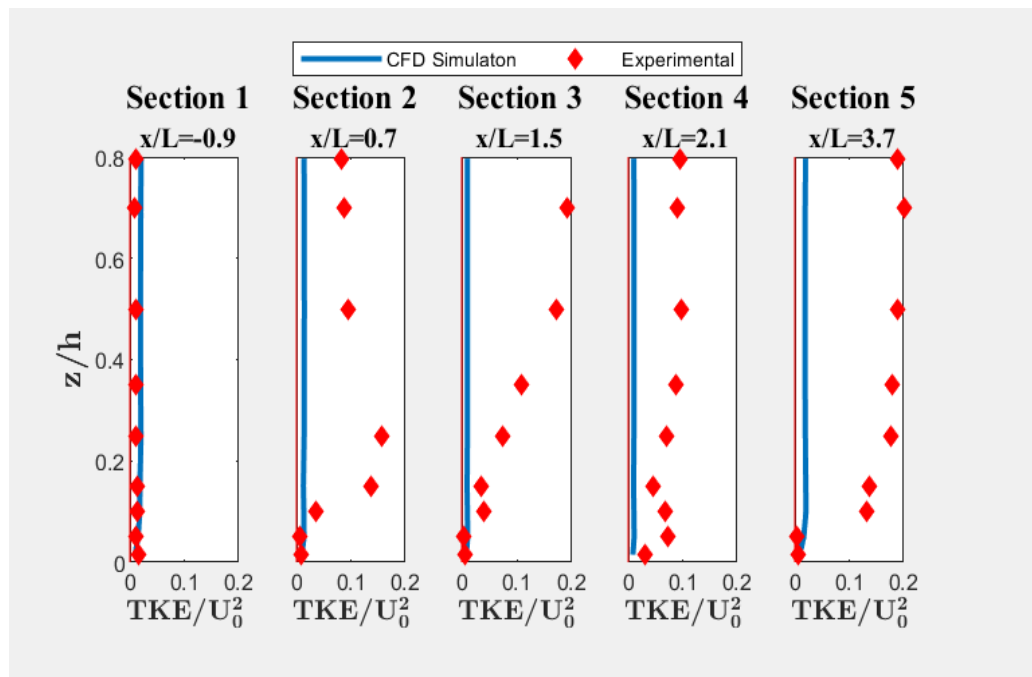
(b)



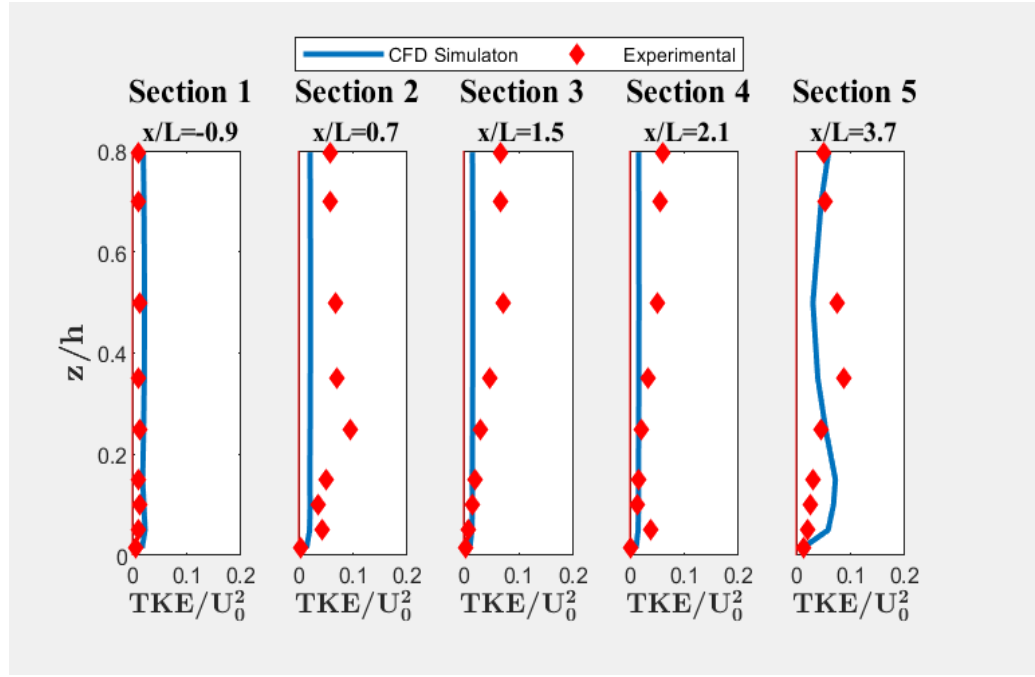
(c)

**Figure 4.25** Turbulent kinetic energy variation around piers placed at 3L C/C spacing: (a) Round Nose (b) Pier with 60° nose angle and (c) Pier with 90° nose angle.

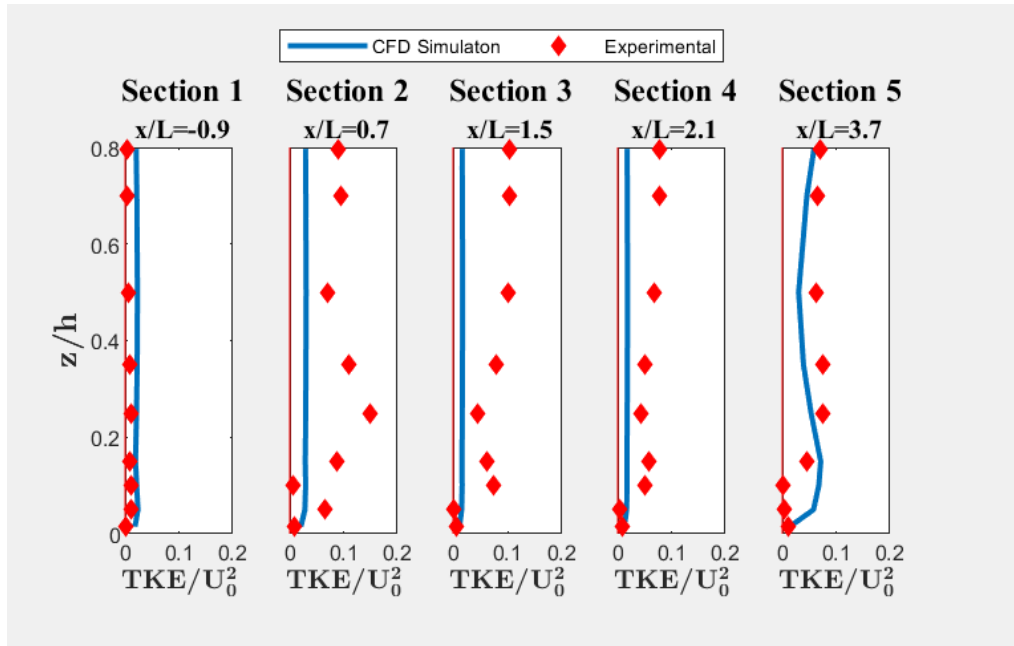
In **Figure 4.26** a comparison of normalized turbulent kinetic energy between CFD simulation and experimental observations are shown for round nose pier, pier with 60° nose angle and pier with 90° nose angle. From which it can be observed that, CFD simulation showed higher magnitude of turbulent kinetic energy compare to the experimental observations at Section-1.



(a)



(b)



(c)

**Figure 4.26** Comparison of normalized turbulent kinetic energy variation between CFD simulation and experiments: (a) Round Nose (b) Pier with 60° Nose Angle (c) Pier with 90° Nose Angle.

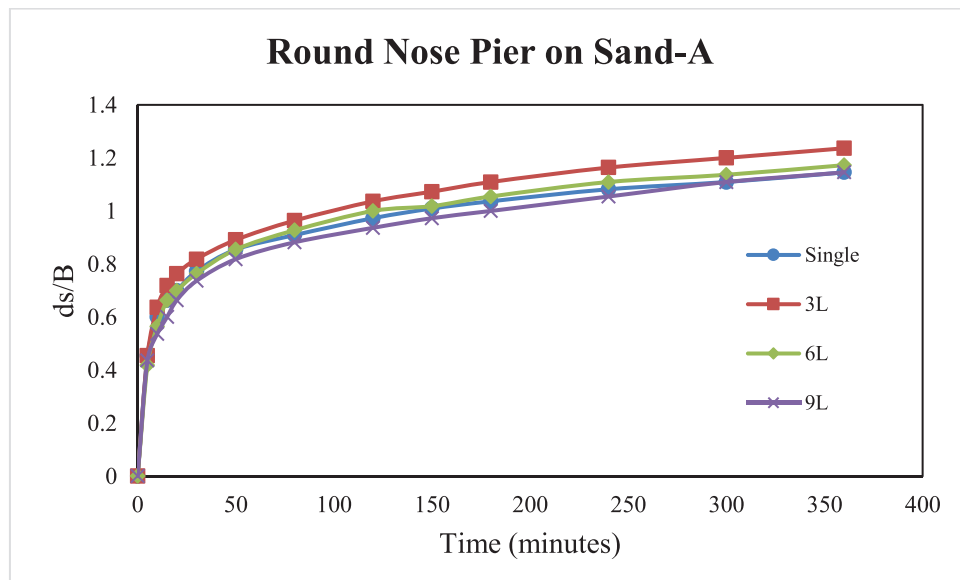
Turbulent kinetic energy at the d/s of pier was found higher compare to the u/s of the pier, both in CFD simulation and experimental observation. At Section-2, Section-3, Section-4 and Section-5, experimental observation showed 85%, 93.93%, 89.16% and

90% higher turbulent kinetic energy compare to CFD simulation for round nose pier at mid depth ( $z/h=0.5$ ).

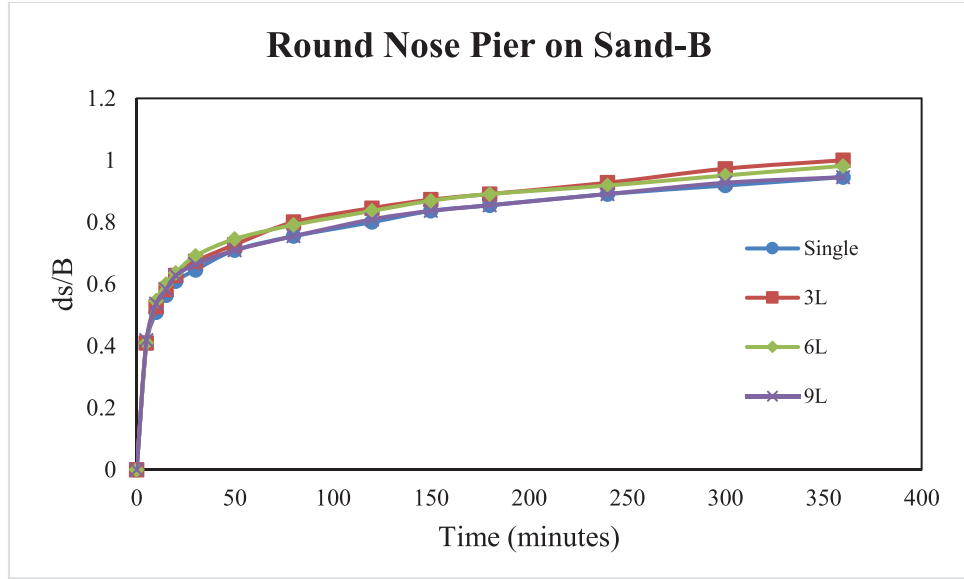
For pier with  $60^\circ$  nose angle, experimental observation showed 68.35%, 77.32%, 67.1658% and 58.73% higher turbulent kinetic energy at Section-2, Section-3, Section-4 and Section-5 respectively compare to the CFD simulation at mid depth ( $z/h=0.5$ ).

#### 4.8 Temporal Development of Scour Depth

In this study, temporal development of scour depth around front pier was measured in each experiment. **Figure 4.27** represents the temporal development of scour depth around front pier for round nose piers placed at varying spacing both on Sand-A and Sand-B. Temporal evolution of other experiments are presented in **Figure J. 1** and **Figure J. 2** of **Appendix-J**. From this figure it can be observed that, temporal development of scour depth around front pier weren't affected much by spacing between pier (when two piers are placed in tandem arrangement). So the pattern of the temporal development of scour depth around front piers are almost identical in all spacing. The rate of scour was higher at the beginning, and around 75%-80% of the 6-h scour depth was achieved within the first hour.



(a)



(b)

**Figure 4.27** Temporal Development of Scour Depth around Front Piers Placed at Different Spacing (a) Round Nose Pier on Sand-A ( $d_{50}=0.23$  mm) (b) Round Nose Pier on Sand-B ( $d_{50}=0.89$  mm).

#### 4.9 Spatial Variation of Scour Depth around Piers

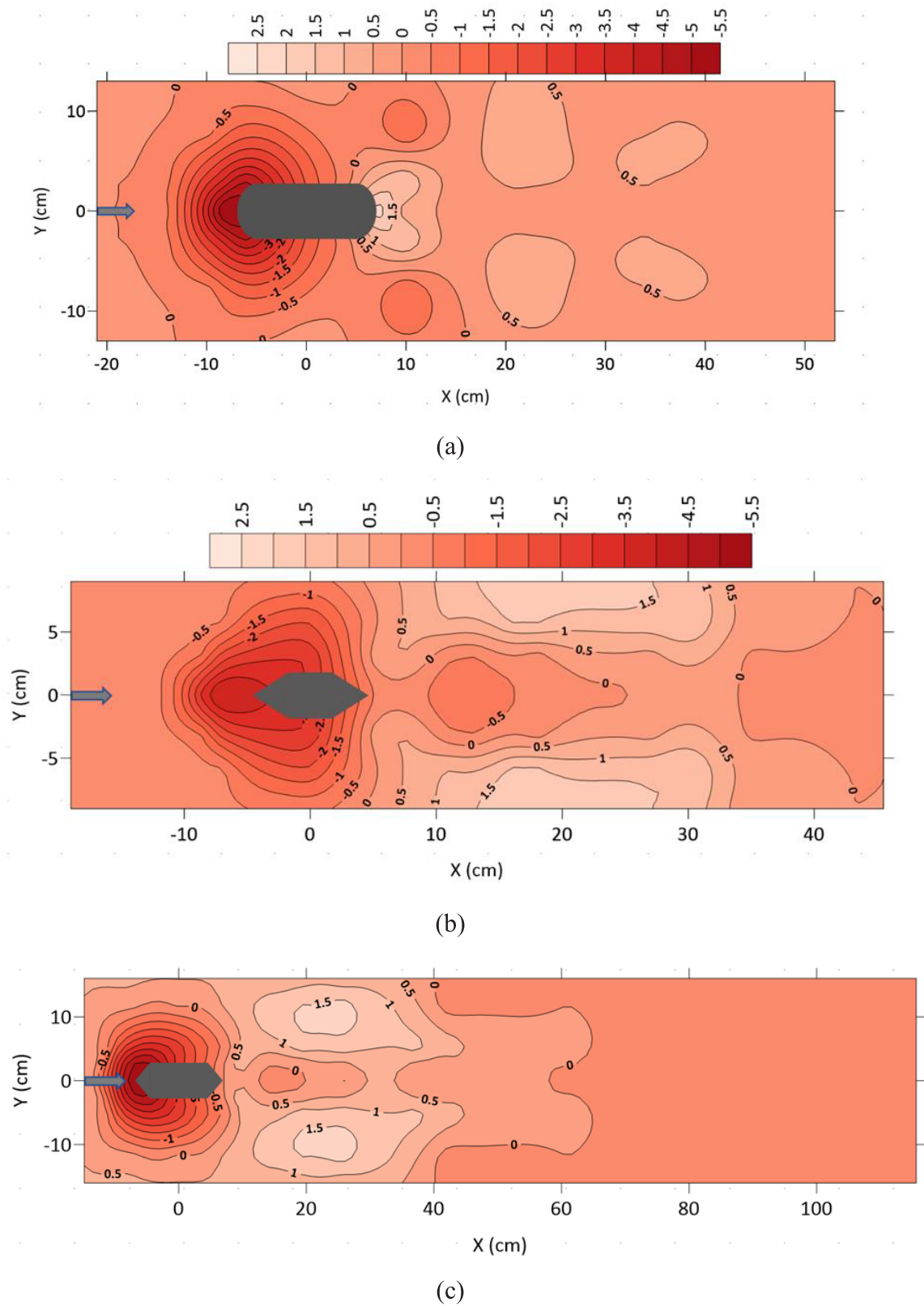
As discussed in Chapter 3, at the end of each experimental run, final bed elevation was measured using vertically mounted point gauge. These elevation data were plotted using Golden Software Surfer.

**Figure 4.29** represents the contours of surface elevation around single piers placed on Sand-B. From which it can be observed that, scour hole around round nose pier and pier with  $90^\circ$  nose angle was almost circular whereas for pier with  $60^\circ$  nose angle, it was slightly conical shape. Due to higher flow separation for sharper edge pier ( $60^\circ$  angle) the scour hole got wider further downstream of the front edge of the pier and form a conical shape hole.

Besides, deposition of sediment at the downstream toe of the pier was observed for round nose pier, whereas for  $60^\circ$  and  $90^\circ$  nose angle pier, a depressed canal like feature was observed. From CFD simulation, it was observed that for  $60^\circ$  nose angle pier, higher turbulent kinetic energy occurred at both side of the centerline of the flume, which kept the scoured sediment in suspension and the incoming flow moved the sediment towards the downstream. Deposition of sediment occurred outside of this zone forming a canal shape feature. For round nose pier higher turbulent kinetic energy was observed at just  $d/s$  of the pier along centerline of the flume. But the velocity in this



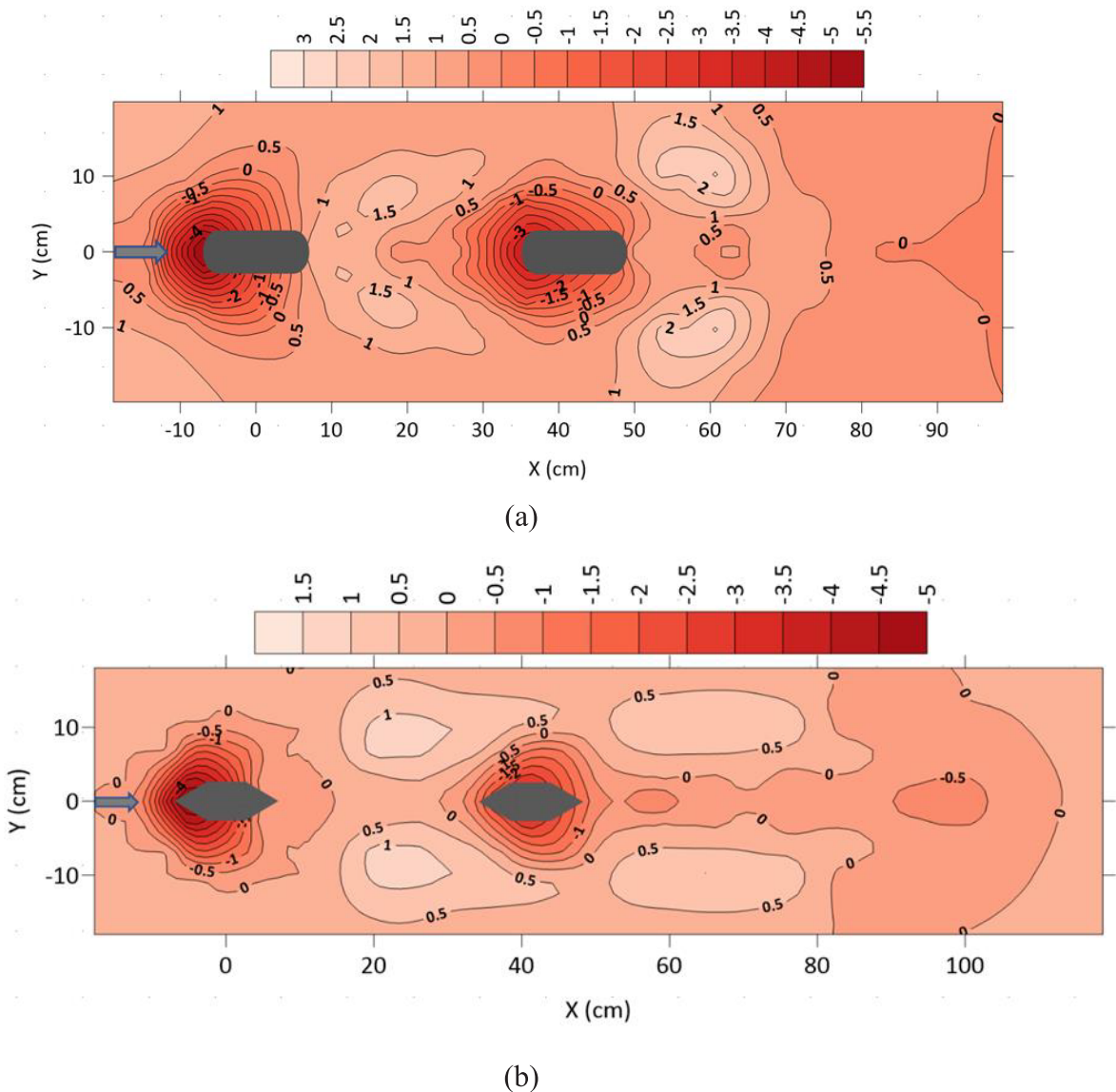
zone was very low, so the sediment deposition at the downstream toe of the pier was observed.

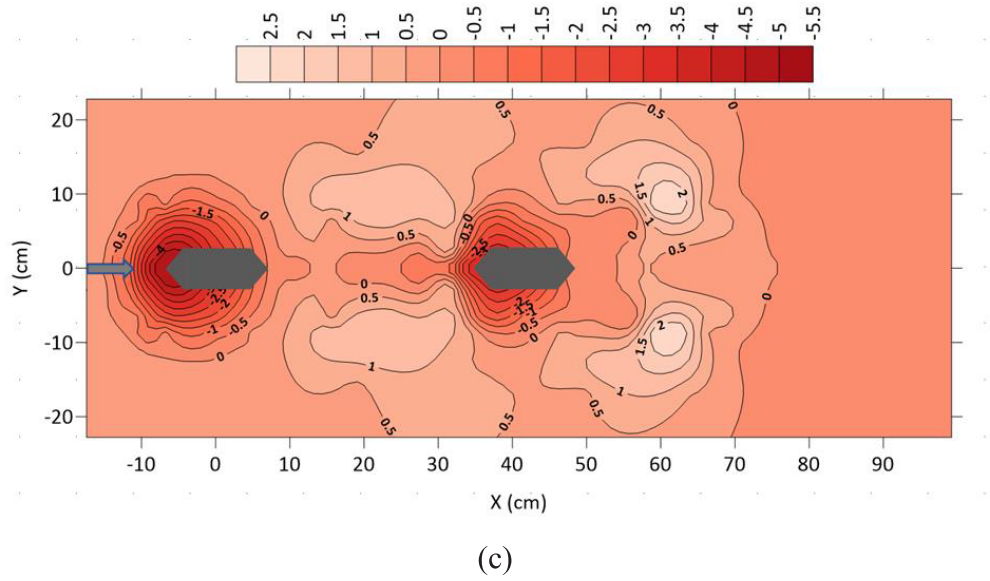


**Figure 4.28** Contours of bed surface elevation around single pier in Sand-B: (a) Round Nose (b) 60° Nose Angle & (c) 90° Nose Angle.

**Figure 4.29** represents the contours of surface elevation around piers in tandem arrangements placed at 3L C/C pier spacing on Sand-B. The shape of the scour hole around the piers were almost similar to the single pier scenarios. Maximum scour depth around round nose piers were observed at the upstream face of the pier, whereas for piers with  $60^\circ$  and  $90^\circ$  nose angle, maximum scour depth occurred at side-ward frontal edge of the pier. Vijayasree et al. (2019) also reported the similar findings.

Besides it can also be observed that the extent of scour hole around the front pier was larger compared to that of the rear pier. CFD simulation showed the presence of higher turbulent kinetic energy throughout the mid-stream region for pier with  $90^\circ$  angle placed at 3L C/C spacing compare to the other two shapes, for that reason a slightly depressed region along the centerline of the flume extending from the front to the rear pier was observed for  $90^\circ$  nose angle pier.





**Figure 4.29** Contours of bed surface elevation around tandem piers in Sand-B ( $S/L=3$ ): (a) Round Nose (b)  $60^\circ$  Nose Angle & (c)  $90^\circ$  Nose Angle.

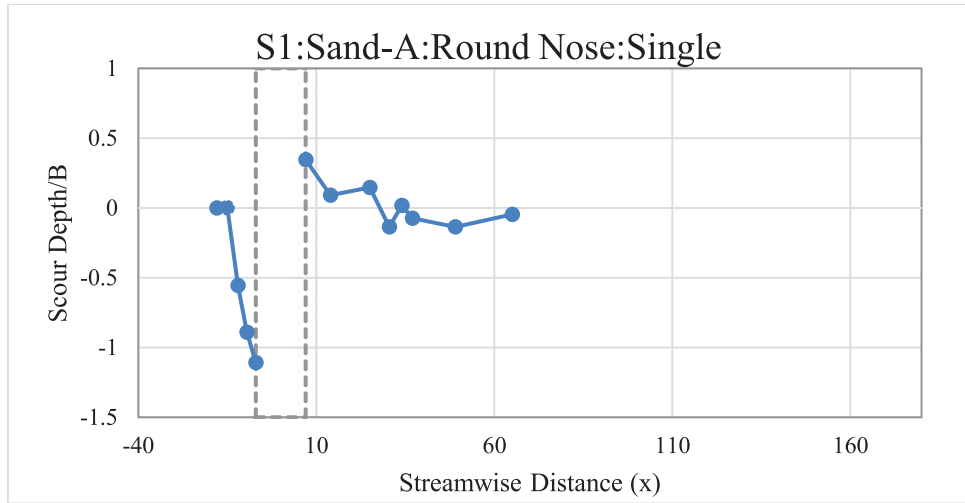
With increasing C/C spacing, extent of scour hole around the rear pier increased. Spatial variation of scour depth for other experiments are presented in **Figure K. 1** to **Figure K. 6** of **Appendix-K**.

#### 4.10 Development of Scour along the Centerline of the Flume

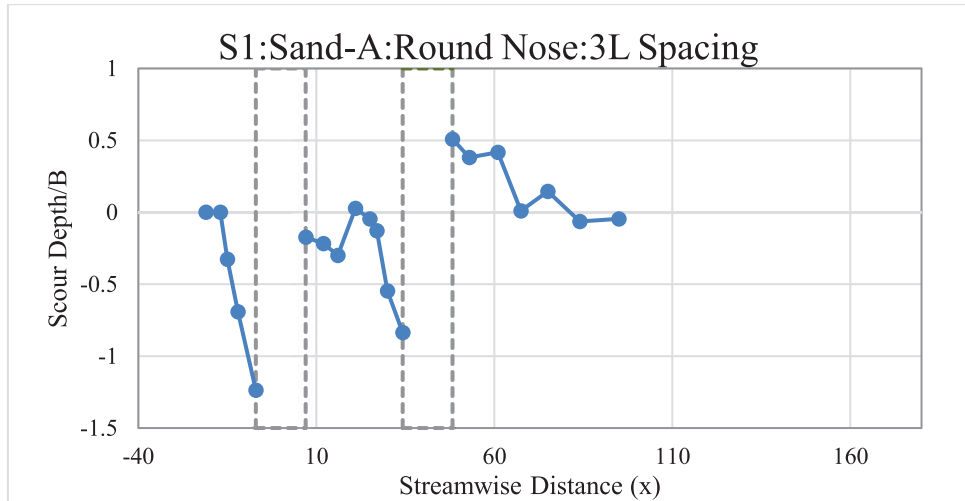
**Figure 4.30** represents the development of scour long the centerline of the flume for round nose piers placed at varying spacing on Sand-A). For other experimental sets, the bed elevation in the longitudinal direction along the centerline of the flume is presented in **Figure L. 1** to **Figure L. 5** of **Appendix-L**.

From **Figure 4.30** it can be observed that, the depth of scour at the upstream side of the pier was much higher compared to that of the downstream side of the pier. The extent of scour hole along the centerline of the flume was different around front and rear pier. The extent was higher near the front pier as the eroded sediment were deposited near the scour hole of the rear pier.

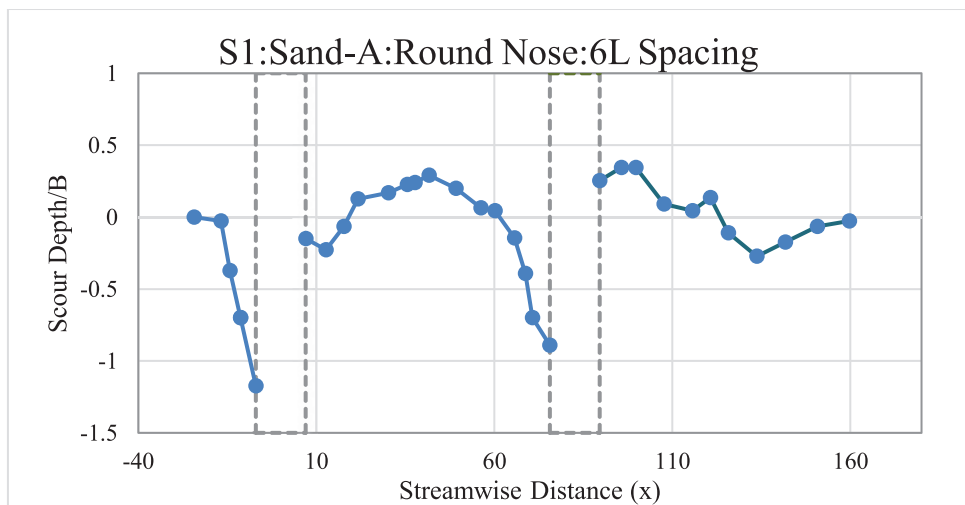
Besides when the piers were placed at 6L and 9L C/C pier spacing, in the midstream region (zone between front and rear pier), the bed elevation was higher compared to that of the non-scoured condition due to the accumulation of the scoured bed material coming from the front pier region. In almost all the cases, highest elevation in the mid-stream region were observed for piers placed at 6L spacing.



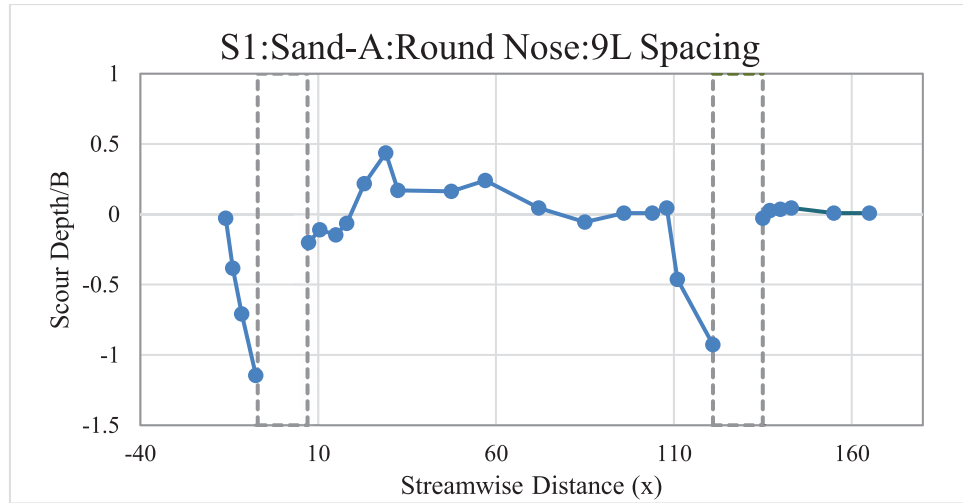
(a)



(b)



(c)



(d)

**Figure 4.30** Development of scour along the centerline of the flume for round nose pier placed on Sand-A. (a) Single (b)  $S/L=3$  (c)  $S/L=6$  & (d)  $S/L=9$ .

**Table 4.9** represents the summary of scour extent both in longitudinal and transverse direction. From which it can be observed that, for round nose pier longitudinal and transverse extent of scour hole was dominant, whereas for pier with  $60^\circ$  nose angle, extent of scour hole in transverse direction was prominent.

Vijayasree et al. (2019) reported that, for sharp nose pier, frontal scour was less compare to the sides. Higher frontal scour was observed for round nose pier as the scour was mostly by horse-shoe vortex. For sharp nose pier ( $60^\circ$  nose angle and  $90^\circ$  nose angle), scour was mainly due to the flow separation. Besides, it was also observed that with the increase of  $C/C$  pier spacing, the extent of scour hole increased for rear pier. At  $9L$   $C/C$  spacing, extent of scour hole around the front pier was almost equal to the single pier arrangements.

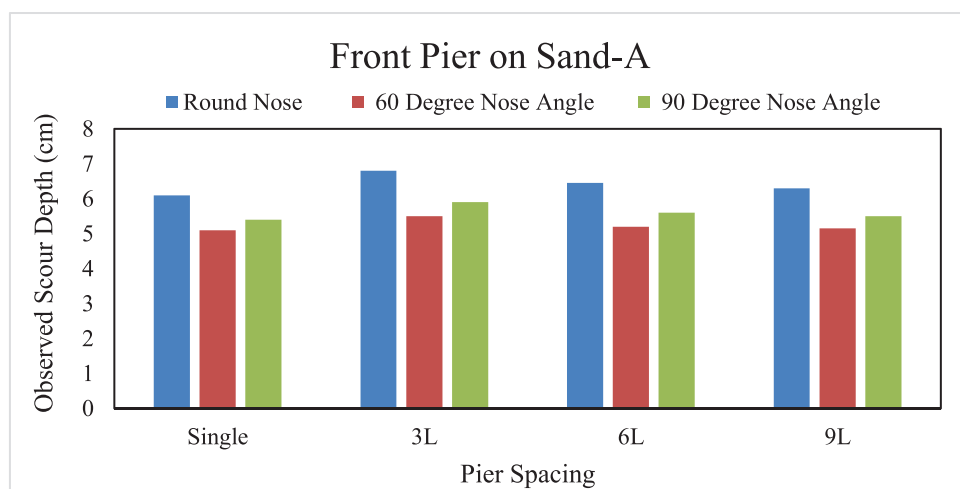
**Table 4.9** Summary of scour hole extent

| Run ID |                               | S/L | Extent of scour hole in the longitudinal direction (From pier face) |               |               |               | Extent of scour hole in the transverse direction (From pier face) |              |               |              |
|--------|-------------------------------|-----|---------------------------------------------------------------------|---------------|---------------|---------------|-------------------------------------------------------------------|--------------|---------------|--------------|
|        |                               |     | Front Pier                                                          |               | Rear Pier     |               | Front Pier                                                        |              | Rear Pier     |              |
|        |                               |     | u/s direction                                                       | d/s direction | u/s direction | d/s direction | Towards Right                                                     | Towards Left | Towards Right | Towards Left |
|        |                               |     | (cm)                                                                | (cm)          | (cm)          | (cm)          | (cm)                                                              | (cm)         | (cm)          | (cm)         |
| 1      | Round Nose Pier on Sand-      | S   | 10.4                                                                | N/A           | -             | -             | 8.3                                                               | 8.3          | -             | -            |
| 2      |                               | 3   | 10.12                                                               | 3.925         | 6.625         | N/A           | 10.25                                                             | 10.2         | 3             | 3.05         |
| 3      |                               | 6   | 9.925                                                               | 2.125         | 8.425         | N/A           | 8.25                                                              | 8.25         | 6.25          | 6.25         |
| 4      |                               | 9   | 9.3                                                                 | N/A           | 9.3           | N/A           | 11                                                                | 11           | 8.3           | 8.3          |
| 5      | 60° Nose Angle Pier on Sand-A | S   | 7.5                                                                 | 8.8           | -             | -             | 6.25                                                              | 6.3          | -             | -            |
| 6      |                               | 3   | 7.1                                                                 | 6.3           | 5.6           | N/A           | 8.75                                                              | 8.75         | 5.75          | 5.75         |
| 7      |                               | 6   | 8.5                                                                 | 8.3           | 7.5           | 1.9           | 9.25                                                              | 9.2          | 6.25          | 6.25         |
| 8      |                               | 9   | 10.5                                                                | 10.6          | 8.8           | 3.25          | 10.2                                                              | 10.2         | 8.5           | 8.5          |
| 9      | 90° Nose Angle Pier on Sand-A | S   | 8.6                                                                 | 7.3           | -             | -             | 10                                                                | 9.9          | -             | -            |
| 10     |                               | 3   | 8.4                                                                 | 8.9           | 4.8           | 4.4           | 9.25                                                              | 9.25         | 4.25          | 6.8          |
| 11     |                               | 6   | 8.6                                                                 | 10.4          | 4.9           | 4.9           | 9.75                                                              | 9.7          | 6.25          | 6.25         |
| 12     |                               | 9   | 9.8                                                                 | 8.5           | 5             | 6.9           | 11                                                                | 11           | 7             | 7            |
| 13     | Round Nose Pier on Sand-      | S   | 11                                                                  | N/A           | -             | -             | 10                                                                | 10           | -             | -            |
| 14     |                               | 3   | 10.5                                                                | N/A           | 7.7           | N/A           | 9.5                                                               | 9.3          | 8.5           | 8.5          |
| 15     |                               | 6   | 10.3                                                                | N/A           | 10.25         | N/A           | 9.4                                                               | 9.5          | 4.9           | 5            |
| 16     |                               | 9   | 11                                                                  | N/A           | 9             | N/A           | 9                                                                 | 9            | 8.9           | 9.9          |
| 17     | 60° Nose Angle Pier on        | S   | 7.1                                                                 | 2             |               |               | 7                                                                 | 7            | -             | -            |
| 18     |                               | 3   | 5.8                                                                 | 3.3           | 5.3           | 4.1           | 7                                                                 | 7            | 6.5           | 6.5          |
| 19     |                               | 6   | 5.3                                                                 | N/A           | 7             | N/A           | 6.7                                                               | 6.7          | 6.9           | 6.9          |
| 20     |                               | 9   | 5                                                                   | 3.2           | 5.5           | 5.2           | 7                                                                 | 7            | 7.2           | 7.2          |
| 21     | 90° Nose Angle Pier on        | S   | 6.7                                                                 | N/A           |               |               | 9.6                                                               | 9.6          | -             | -            |
| 22     |                               | 3   | 8.4                                                                 | 5.6           | 4.1           | N/A           | 9.2                                                               | 9.2          | 7.3           | 7.3          |
| 23     |                               | 6   | 9.1                                                                 | 2             | 8.8           | N/A           | 9.7                                                               | 9.7          | 9             | 9            |
| 24     |                               | 9   | 6.8                                                                 | 0.9           | 6.9           | N/A           | 9.5                                                               | 9.5          | 8.5           | 8.4          |

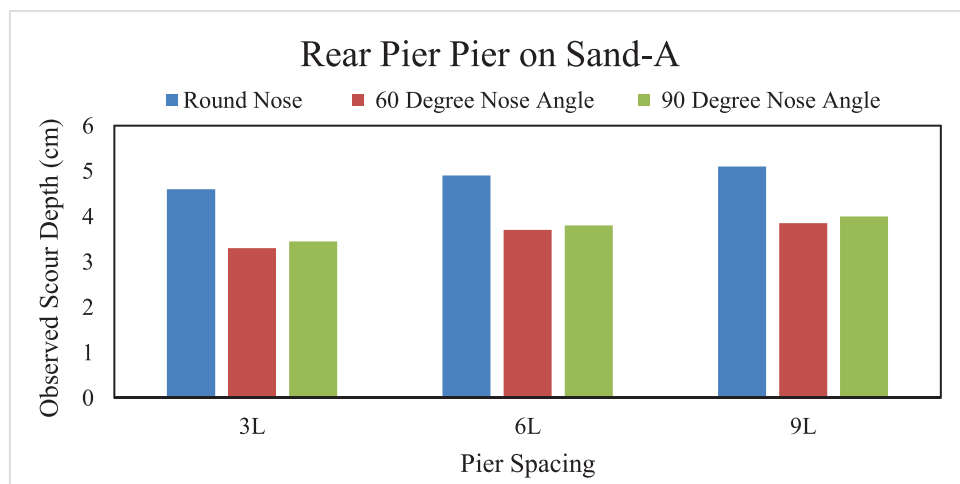
#### 4.11 Effect of Pier's Nose Shape on Scour Depth

As discussed earlier, all the experiments were conducted for a period of 6-h using three different pier's nose shape on Sand-A and Sand-B. From the experiments, it was observed that, pier's nose shape significantly affects maximum scour depth. In this study, piers with round nose showed maximum scour depth whereas piers with 60° nose

angle showed minimum scour depth. This observation is applicable for both front and rear pier. **Figure 4.31** represents the effect of pier's nose shape on scour depth on Sand-A for both front and rear pier. From which it can be observed that, for front piers placed at single, 3L, 6L and 9L C/C pier spacing arrangements, 6-h maximum scour depth were 19.61%, 23.64%, 24.03% and 22.33% higher respectively compared to the piers with  $60^\circ$  nose angle. Whereas for pier with  $90^\circ$  nose angle, 6-h maximum scour depth were 5.89%, 7.27%, 7.7% and 6.8% higher compared to the  $60^\circ$  nose angle pier for single, 3L, 6L and 9L C/C pier spacing arrangements respectively.



(a)



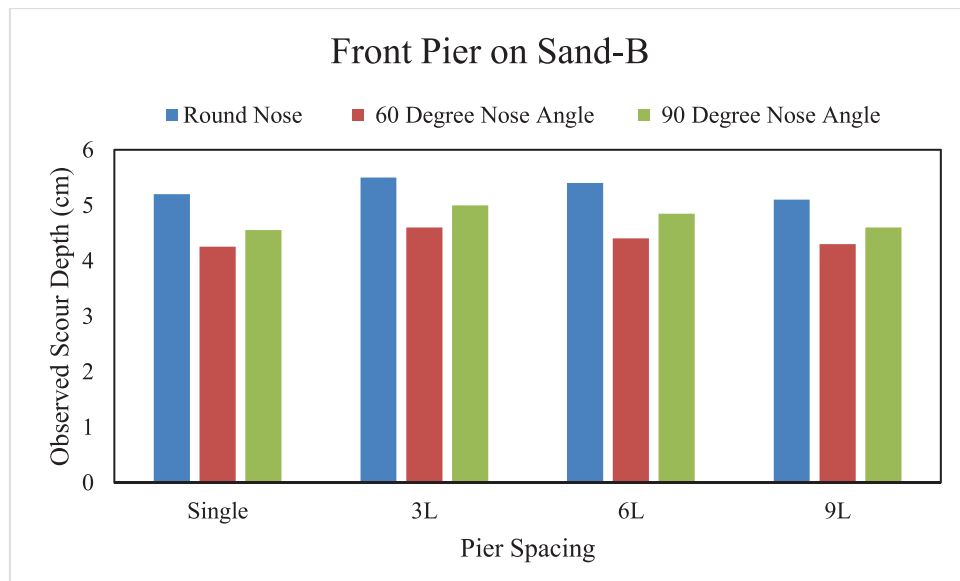
(b)

**Figure 4.31** Effect of pier's nose shape on scour depth on Sand-A: (a) Front Pier & (b) Rear Pier

For rear pier placed on Sand-A, 6-h maximum scour depth was 39.4%, 32.43% and 32.46% higher for round nose pier compared to  $60^\circ$  nose angle pier placed at 3L, 6L

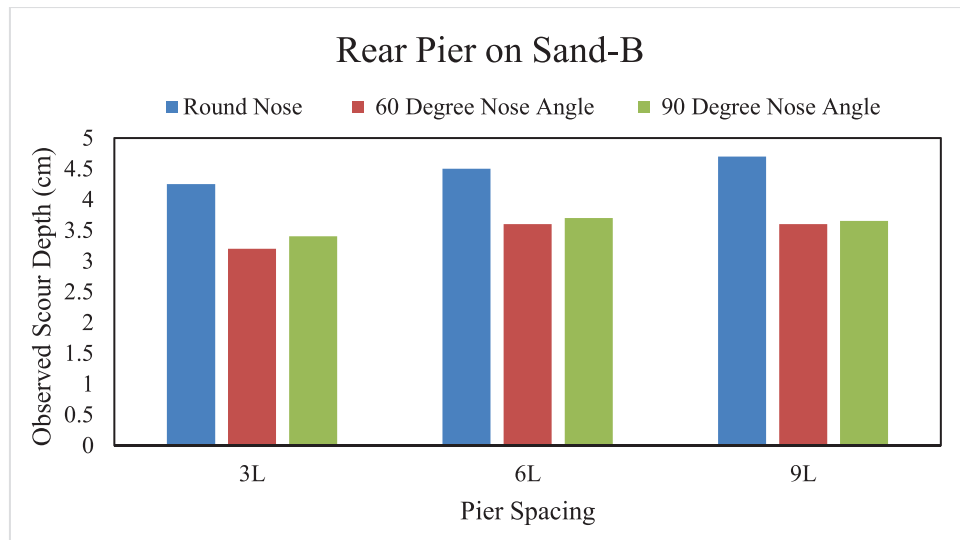
and 9L C/C pier spacing respectively, whereas for  $90^\circ$  nose angle, those values were 4.35%, 2.62% and 3.75% respectively.

**Figure 4.32** represents the effect of pier's nose shape on scour depth on Sand-B for both front and rear pier. From which it can be observed that, for front piers placed at single, 3L, 6L and 9L C/C pier spacing arrangements, 6-h maximum scour depth were 22.35%, 19.57%, 22.73% and 18.6% higher respectively compared to the piers with  $60^\circ$  nose angle. Whereas for pier with  $90^\circ$  nose angle, 6-h maximum scour depth were 7.05%, 8.7%, 10.22% and 6.98% higher compared to the  $60^\circ$  nose angle pier for single, 3L, 6L and 9L C/C pier spacing arrangements respectively. For rear pier placed on Sand-A, 6-h maximum scour depth was 32.81%, 25% and 30.56% higher for round nose pier compared to  $60^\circ$  nose angle pier placed at 3L, 6L and 9L C/C pier spacing respectively, whereas for  $90^\circ$  nose angle, those values were 6.25%, 2.78% and 1.39% respectively.



(a)





(b)

**Figure 4.32** Effect of pier's nose shape on scour depth on Sand-B: (a) Front Pier & (b) Rear Pier

In this study, pier's shape factor (Ratio of scour depth of any shape of pier to circular pier) had been developed. Basir (2022) conducted laboratory experiment using the similar setup used in this study to investigate local scour around circular pier. All the conditions except pier shape were similar to this study, so scour depth information of the circular pier of his study was applicable to this study.

To calculate the pier's shape factor only single pier arrangement had been considered. The detail calculation is shown in **Table 4.10**.

**Table 4.10** Calculation of pier's shape factor.

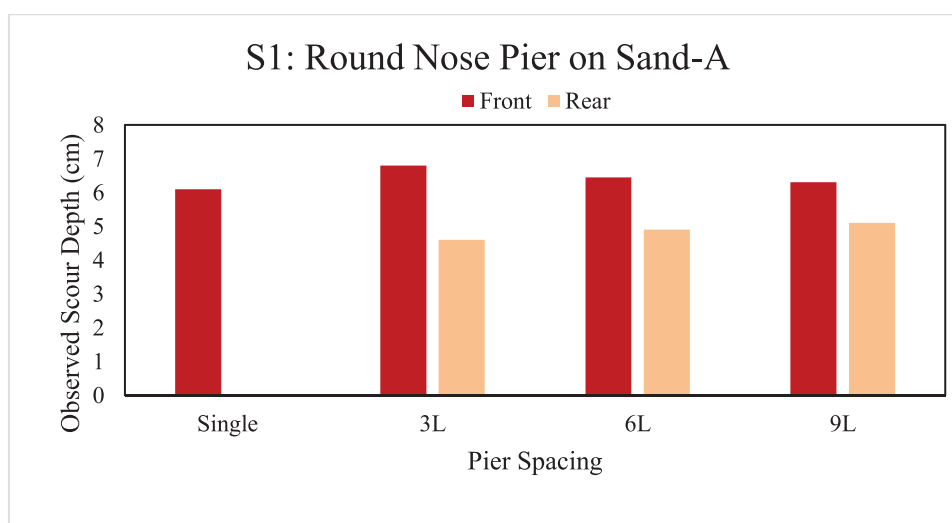
| Pier Shaper               | Scour Depth (cm) Sand-A | Scour Depth (cm) Sand-B | Shape Factor (Sand-A) | Shape Factor (Sand-B) | Average |
|---------------------------|-------------------------|-------------------------|-----------------------|-----------------------|---------|
| Circular Pier             | 7                       | 5.85                    | -                     | -                     | -       |
| Round Nose Pier           | 6.1                     | 5.2                     | 0.87                  | 0.89                  | 0.88    |
| 60 Degree Nose Angle Pier | 5.1                     | 4.25                    | 0.73                  | 0.73                  | 0.73    |
| 90 Degree Nose Angle Pier | 5.4                     | 4.55                    | 0.77                  | 0.78                  | 0.775   |

The shape factor for round nose, 60<sup>0</sup> nose angle and 90<sup>0</sup> nose angle were found as 0.88, 0.73 and 0.775. Previous studies of Al-Shukur and Obeid (2016) found pier's shape

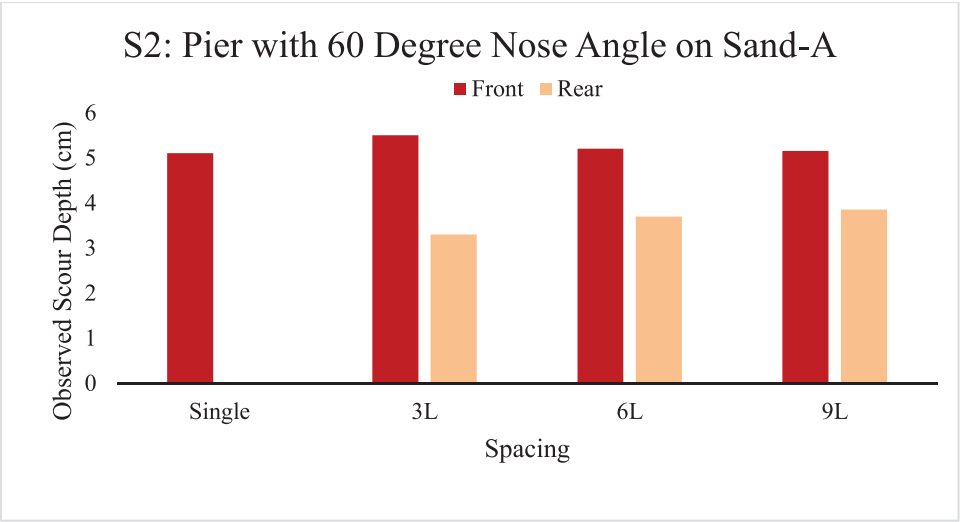
factor for oblong (round-nose) and sharp nose pier (similar to pier with  $60^\circ$  and  $90^\circ$  nose angle) as 0.85 and 0.733 respectively.

#### 4.12 Effect of Pier Spacing on Scour Depth

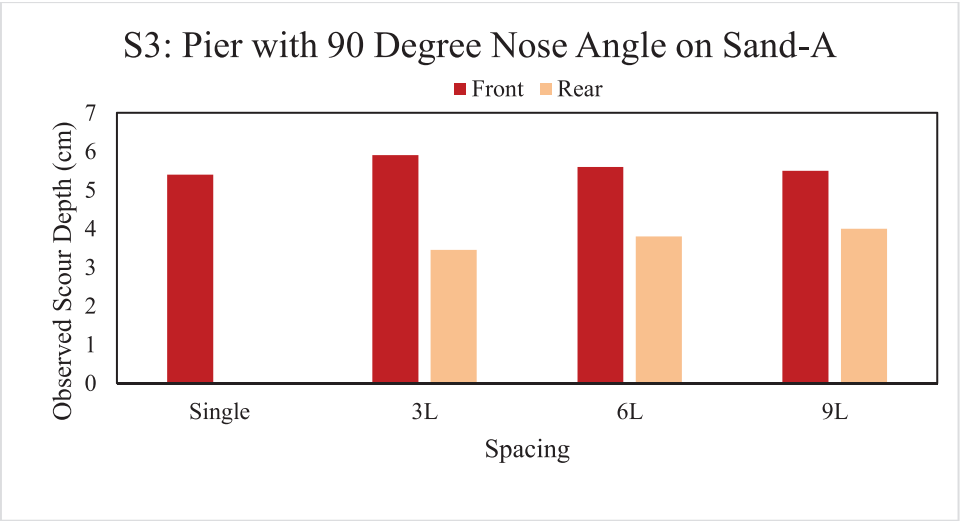
Along with pier's nose shape, the spacing between two piers when the piers are placed in tandem arrangements also affect scour depth around both front and rear pier. **Figure 4.33** represents the effect of pier spacing on maximum 6-h scour depth on Sand-A. From which it can be observed that, for front pier in tandem arrangement scour depth was higher compared to than that of single pier when the C/C spacing between the piers are 3L and 6L. Whereas, for 9L C/C pier spacing scour depth around front pier was almost equal to that of the single pier. Which concludes that, at 9L C/C pier spacing, front pier in tandem arrangements show almost identical scour depth as single pier arrangements. And for rear piers, maximum 6-h scour depth increased for almost all the cases with the increase of C/C pier spacing. Similar phenomenon was observed in both Sand-A and Sand-B. For round nose pier, placed on Sand-A, maximum 6-h scour depth around front pier were 11.41%, 5.74% and 3.28% higher compared to that of single pier at 3L, 6L and 9L C/C pier spacing. Whereas in case of rear pier, maximum 6-h scour depth were 75.4%, 80.32% and 83.6% of single pier scour depth when the piers were placed at 3L, 6L and 9L C/C pier spacing.



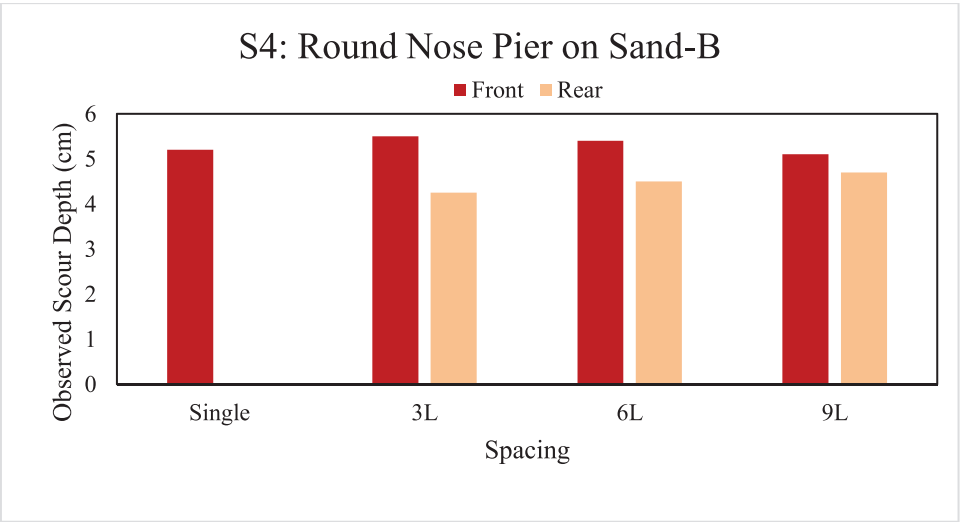
(a)



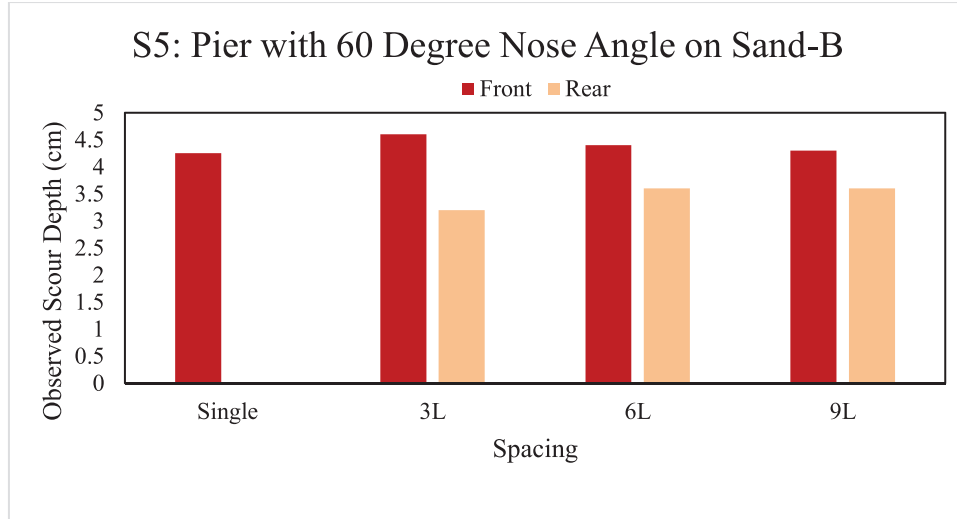
(b)



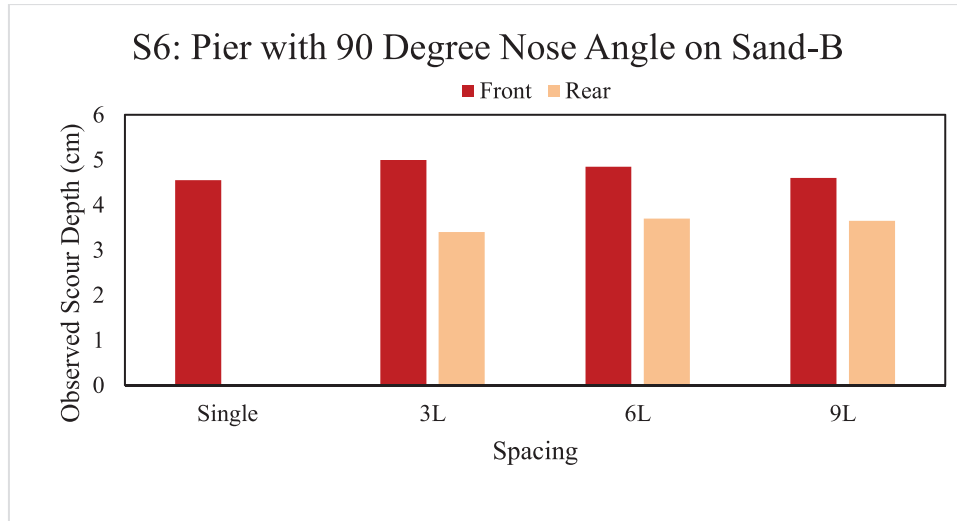
(c)



(d)



(e)



(f)

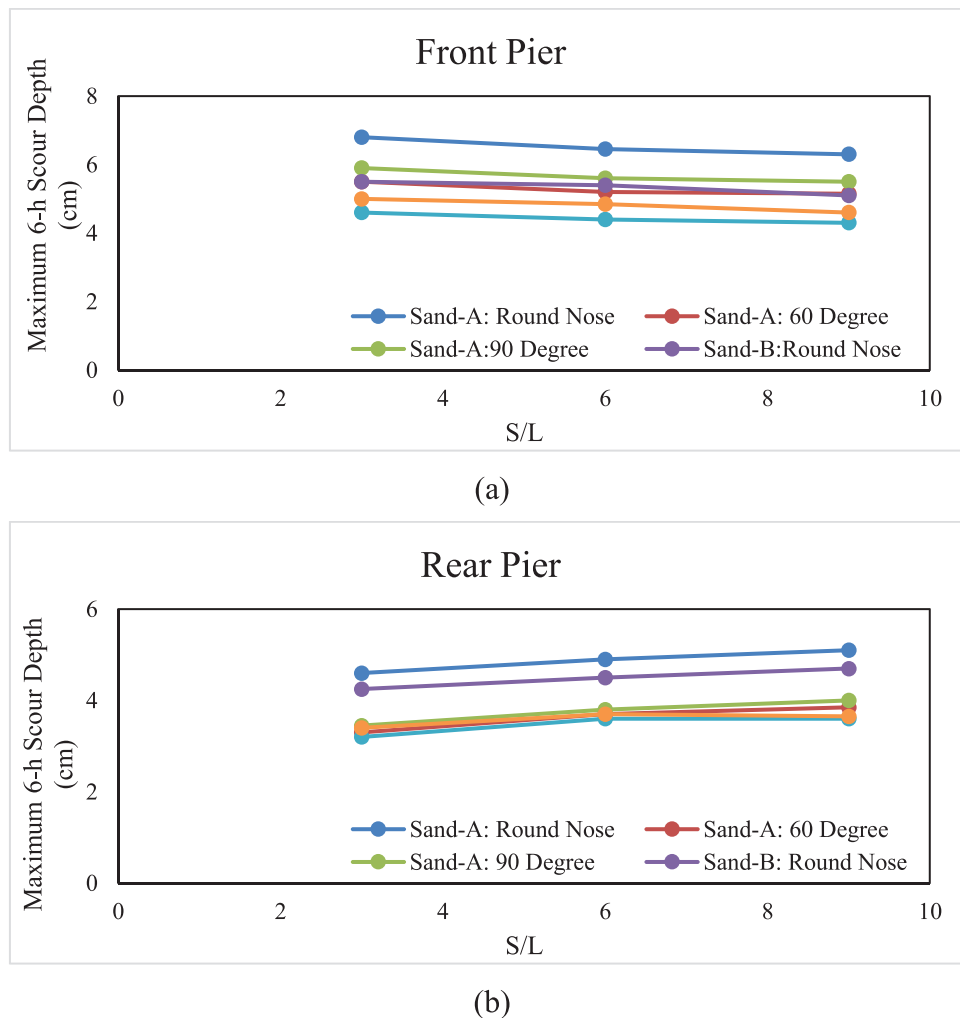
**Figure 4.33** Effect of pier spacing on maximum 6-h scour depth on Sand-A: (a) Round Nose Pier (b) Pier with 60° Nose Angle and (c) Pier with 90° Nose Angle and on Sand-B: (d) Round Nose Pier (e) Pier with 60° Nose Angle and (f) Pier with 90° Nose Angle

For 60° nose angle pier, placed on Sand-A, maximum 6-h scour depth around front pier were 7.84%, 1.96% and 0.98% higher compared to that of single pier at 3L, 6L and 9L C/C pier spacing. Whereas in case of rear pier, maximum 6-h scour depth were 64.7%, 72.54% and 75.5% of single pier scour depth when the piers were placed at 3L, 6L and 9L C/C pier spacing.

For 90° nose angle pier, placed on Sand-A, maximum 6-h scour depth around front pier were 9.25%, 3.7% and 1.85% higher compared to that of single pier at 3L, 6L and 9L C/C pier spacing. Whereas in case of rear pier, maximum 6-h scour depth were 63.89%,

70.37% and 74.1% of single pier scour depth when the piers were placed at 3L, 6L and 9L C/C pier spacing.

**Figure 4.34** represents the effect of pier spacing on maximum 6-h scour depth both for front and rear pier. For front pier, scour depth decreased with the increase of pier spacing but the rate of decrease was higher initially (up to  $S/L=6$ ). For rear pier, maximum 6-h scour depth increased with the increase of C/C pier spacing and the rate of increase was higher from  $S/L=3L$  to  $S/L=6L$  compared to  $S/L=6L$  to  $S/L=9L$ .



**Figure 4.34** Effect of pier spacing on maximum 6-h scour depth (a) Front Pier and (b) Rear Pier

Rahul and Baldev (2020) also reported that the maximum scour depth around the front pier was obtained when the C/C spacing between the piers was 3. With further increase of C/C spacing scour depth around front pier decreased.

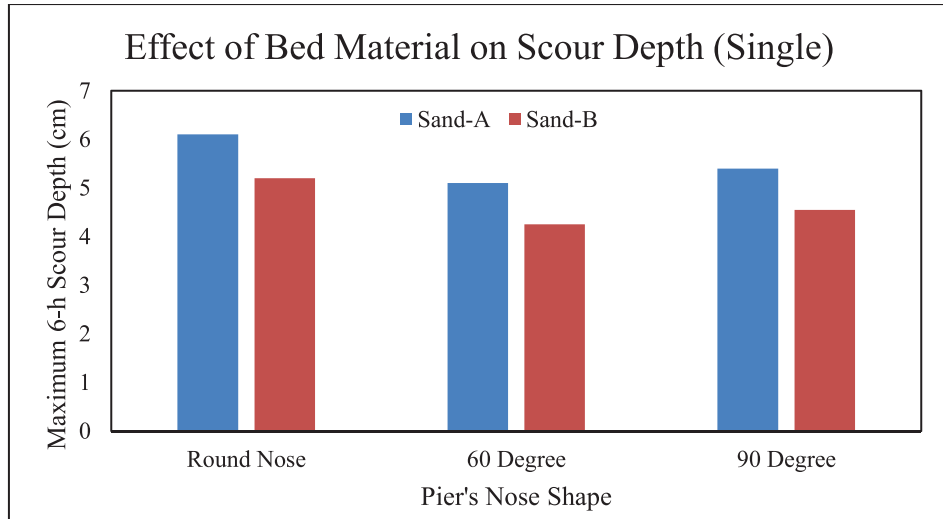
#### 4.13 Effect of Bed Material on Scour Depth

In this experiment, two different sizes of sediment were used named Sand-A ( $d_{50}=0.23\text{mm}$ ) and Sand-B ( $d_{50}=0.89$ ). When the value of the geometric standard deviation ( $\sigma_g < 1.5$ ), sediment had no effect on scour depth. Sand-A had a geometric standard deviation of 1.35 whereas, Sand-B had a geometric standard deviation of 2.1 which is greater than 1.5. So, Sand-B had effect on scour depth, and it was observed that maximum 6-h scour depth on Sand-A was higher in all scenarios compared to that of the Sand-B due to the accumulation of larger particles near the scour hole in the case of Sand-B. Which potentially reduces scour depth. This phenomenon is known as armoring effect. Funde et al. (2018) reported that scour depth would be smaller for higher geometric standard deviation of the bed material.

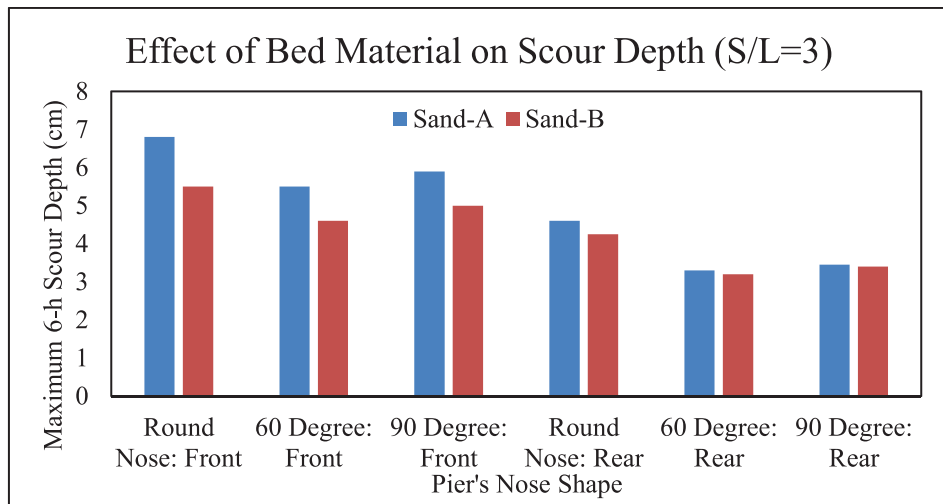
**Figure 4.35** represents the effect of bed material on scour depth around single pier and piers in tandem arrangement. In single pier configuration, for round nose, pier with  $60^\circ$  nose angle and pier with  $90^\circ$  nose angle, maximum 6-h scour depth was 17.3%, 20% and 18.68% higher in Sand-A compare to Sand-B.

In tandem pier arrangements, when the spacing between the piers was  $3L$  ( $S/L=3L$ ), maximum 6-h scour depth around front and rear pier were always higher in Sand-A. This difference in scour depth in two different types of sediment bed was more prominent for front pier compared to rear pier. For round nose pier placed at  $3L$ ,  $6L$  and  $9L$  C/C spacing, maximum 6-h scour depth around front pier was 23.6%, 19.44% and 23.5% higher in Sand-A than that of Sand-B respectively. For pier with  $60^\circ$  nose angle those values were 19.5%, 18.18% and 19.76% respectively. For pier with  $90^\circ$  nose angle those values were 18%, 15.5% and 19.55% respectively.

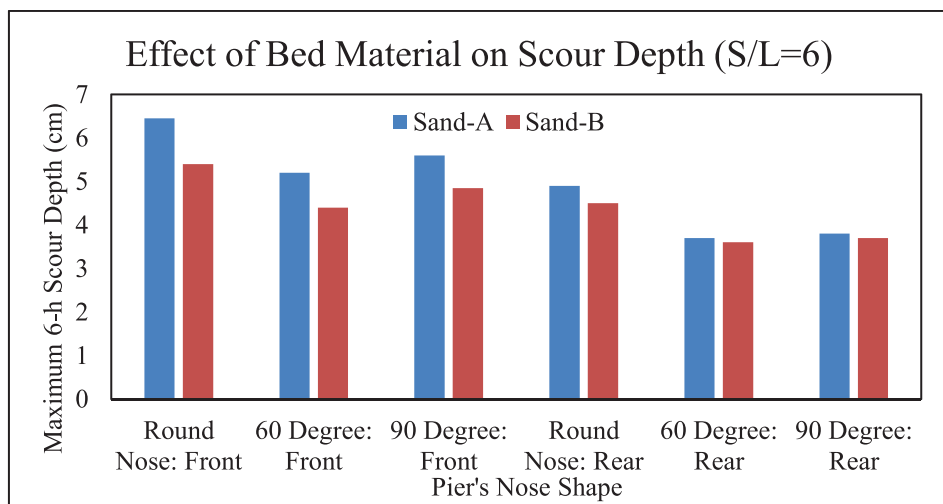
For round nose pier placed at  $3L$ ,  $6L$  and  $9L$  C/C spacing, maximum 6-h scour depth around rear pier was 8.2%, 8.8%% and 8.5% higher in Sand-A than that of Sand-B respectively. For pier with  $60^\circ$  nose angle those values were 3.1%, 2.7% and 6.9% respectively. For pier with  $90^\circ$  nose angle those values were 1.5%, 2.7% and 9.6% respectively. Those values indicates that, the effect of armoring was higher for rear pier than that of front pier. Besides, armoring effect was most dominant for piers with round nose.



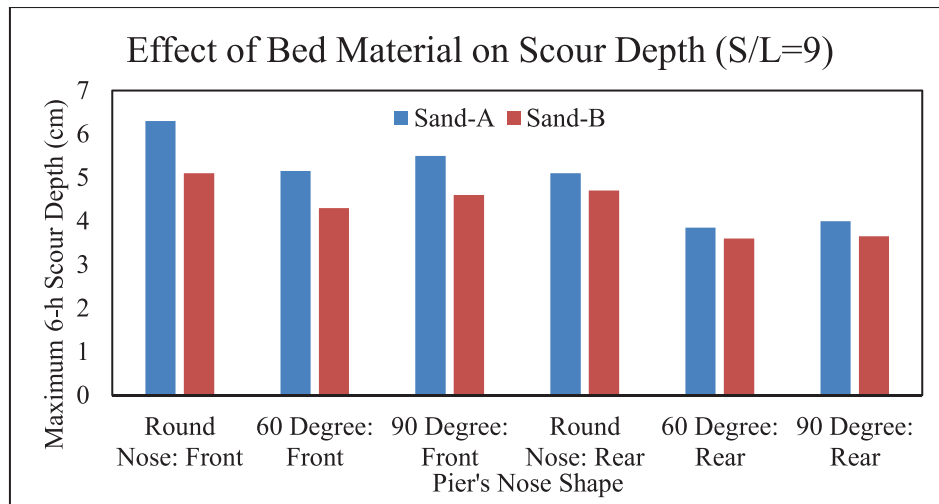
(a)



(b)



(c)



(d)

**Figure 4.35** Effect of bed material on maximum 6-h scour depth around (a) Single Pier, (b) Piers placed at 3L C/C spacing, (c) Piers placed 6L C/C spacing and (d) Piers placed at 9L C/C spacing.

#### 4.14 Scour Summary

**Table 4.11** represents the summary of maximum scour depth around piers in different configurations. From which it can be observed that, the maximum 6-h scour depth around front pier is higher than the rear pier, with increase of C/C pier spacing, scour depth around front pier decreased whereas scour depth around rear pier increased. At 9L C/C spacing, scour depth around front pier was almost similar to that of single pier. Which indicates that, when the C/C spacing between piers are greater or equal to 9L, the scour behavior around the front pier is almost identical to single pier and the mutual interference between the piers, placed in tandem arrangement decreased.

Moreover, in this study, three different pier's nose shape was used, among them piers with round nose had greater scour depth compared to other two shapes.



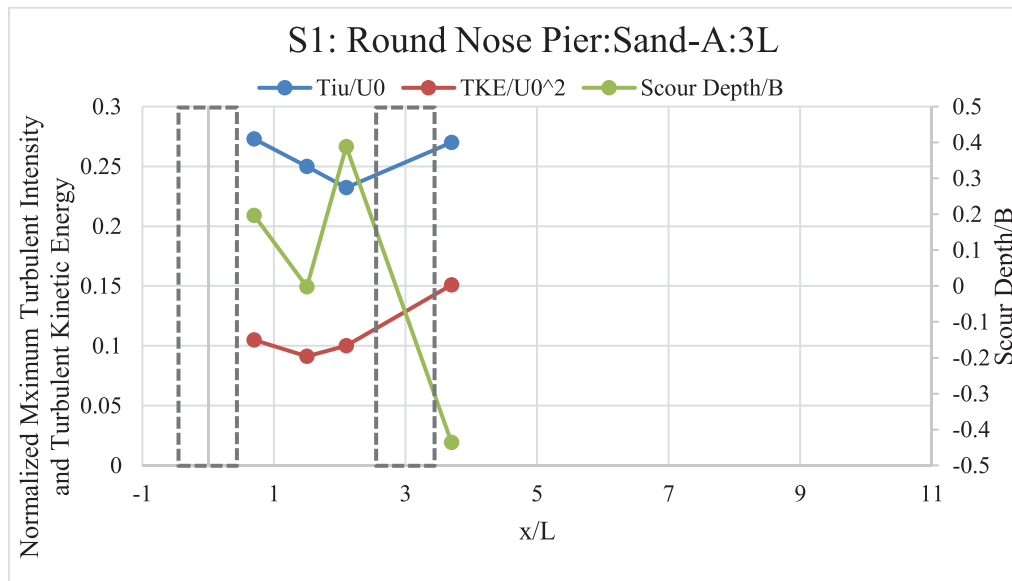
**Table 4.11** Summary of maximum scour depth around front and rear pier.

| Run ID |    | B    | S/L    | d <sub>s</sub> | d <sub>s1</sub> | d <sub>s2</sub> | d <sub>s1</sub> /B | d <sub>s2</sub> /B | d <sub>s1</sub> /d <sub>s</sub> | d <sub>s2</sub> /d <sub>s</sub> |
|--------|----|------|--------|----------------|-----------------|-----------------|--------------------|--------------------|---------------------------------|---------------------------------|
|        |    | (cm) |        | (cm)           | (cm)            | (cm)            |                    |                    |                                 |                                 |
| 1      | S1 | 5.5  | Single | 6.1            |                 |                 | 1.11               | -                  | -                               | -                               |
| 2      |    |      | 3      |                | 6.8             | 4.6             | 1.24               | 0.84               | 1.12                            | 0.76                            |
| 3      |    |      | 6      |                | 6.45            | 4.9             | 1.18               | 0.9                | 1.06                            | 0.81                            |
| 4      |    |      | 9      |                | 6.3             | 5.1             | 1.15               | 0.93               | 1.04                            | 0.84                            |
| 5      | S2 |      | Single | 5.1            |                 |                 | 0.93               | -                  | -                               | -                               |
| 6      |    |      | 3      |                | 5.5             | 3.3             | 1                  | 0.6                | 1.08                            | 0.65                            |
| 7      |    |      | 6      |                | 5.2             | 3.7             | 0.95               | 0.68               | 1.02                            | 0.73                            |
| 8      |    |      | 9      |                | 5.15            | 3.85            | 0.94               | 0.7                | 1.01                            | 0.76                            |
| 9      | S3 |      | Single | 5.4            |                 |                 | 0.99               | -                  | -                               | -                               |
| 10     |    |      | 3      |                | 5.9             | 3.45            | 1.08               | 0.63               | 1.1                             | 0.64                            |
| 11     |    |      | 6      |                | 5.6             | 3.8             | 1.02               | 0.7                | 1.04                            | 0.71                            |
| 12     |    |      | 9      |                | 5.5             | 4               | 1                  | 0.73               | 1.02                            | 0.75                            |
| 13     | S4 |      | Single | 5.2            |                 |                 | 0.95               | -                  | -                               | -                               |
| 14     |    |      | 3      |                | 5.5             | 4.25            | 1                  | 0.78               | 1.06                            | 0.82                            |
| 15     |    |      | 6      |                | 5.4             | 4.5             | 0.99               | 0.82               | 1.04                            | 0.87                            |
| 16     |    |      | 9      |                | 5.1             | 4.7             | 0.93               | 0.86               | 0.99                            | 0.91                            |
| 17     | S5 |      | Single | 4.25           |                 |                 | 0.78               | -                  | -                               | -                               |
| 18     |    |      | 3      |                | 4.6             | 3.2             | 0.84               | 0.59               | 1.09                            | 0.76                            |
| 19     |    |      | 6      |                | 4.4             | 3.6             | 0.8                | 0.66               | 1.04                            | 0.85                            |
| 20     |    |      | 9      |                | 4.3             | 3.6             | 0.79               | 0.66               | 1.02                            | 0.85                            |
| 21     | S6 |      | Single | 4.55           |                 |                 | 0.83               | -                  | -                               | -                               |
| 22     |    |      | 3      |                | 5               | 3.4             | 0.91               | 0.62               | 1.1                             | 0.76                            |
| 23     |    |      | 6      |                | 4.85            | 3.7             | 0.89               | 0.68               | 1.07                            | 0.83                            |
| 24     |    |      | 9      |                | 4.6             | 3.65            | 0.84               | 0.67               | 1.02                            | 0.82                            |

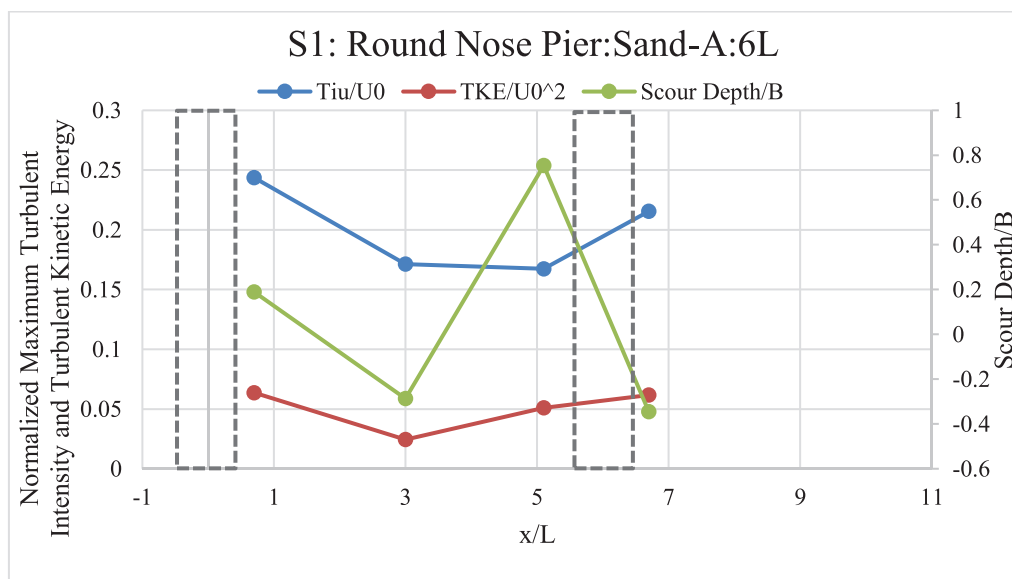
#### 4.15 Variation of Turbulence Parameters and Scour Depth

**Figure 4.36** represents the variation of normalized maximum turbulent intensity and turbulent kinetic energy along with dimensionless scour depth along the centerline of the flume for round nose piers on Sand-A at 3L, 6L and 9LC/C spacing. Earlier discussion reveals that turbulent intensity and turbulent kinetic energy were higher at the downstream end of the pier compared to the upstream. Whereas, scour depth was higher at the upstream of the pier compared to the downstream. From **Figure 4.36** it can be observed that maximum normalized turbulent kinetic energy and turbulent intensity follows similar trends along the centerline of the flume for all runs and maximum values of normalized maximum turbulent intensity and turbulent kinetic

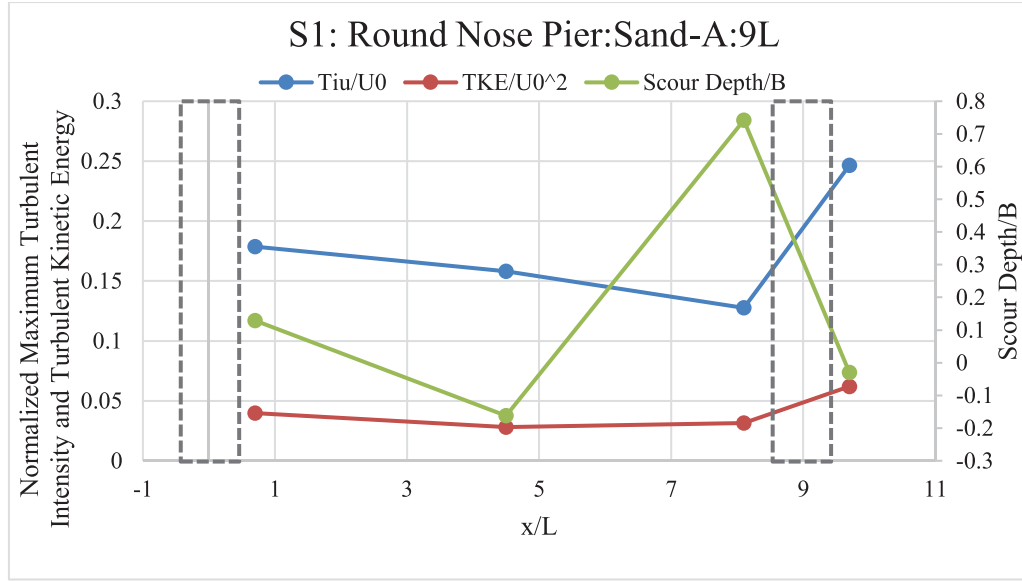
energy was observed either at section-2 or section-5 (downstream end of the pier), whereas scour depth at the upstream of the pier was always higher than that of the downstream of the pier. Besides, at mid-section (section-3) maximum turbulent intensity and maximum turbulent kinetic energy both are lower compared to section -2 and scour depth is lowest. For almost all experimental runs, at section-2 and section-3, the higher scour depth was obtained at which turbulent kinetic energy were observed. For other experiments, the  $TI_u/U_{0\max}$  and  $TKE/U_0^2$  along with scour depths are presented in **Figure M. 1** to **Figure M.5** of **Appendix-M**.



(a)



(b)



(c)

**Figure 4.36** Variation of normalized maximum turbulent intensity and turbulent kinetic energy along the centerline of the flume: (a) S1:3L (b) S1:6L and (c) S1:9L

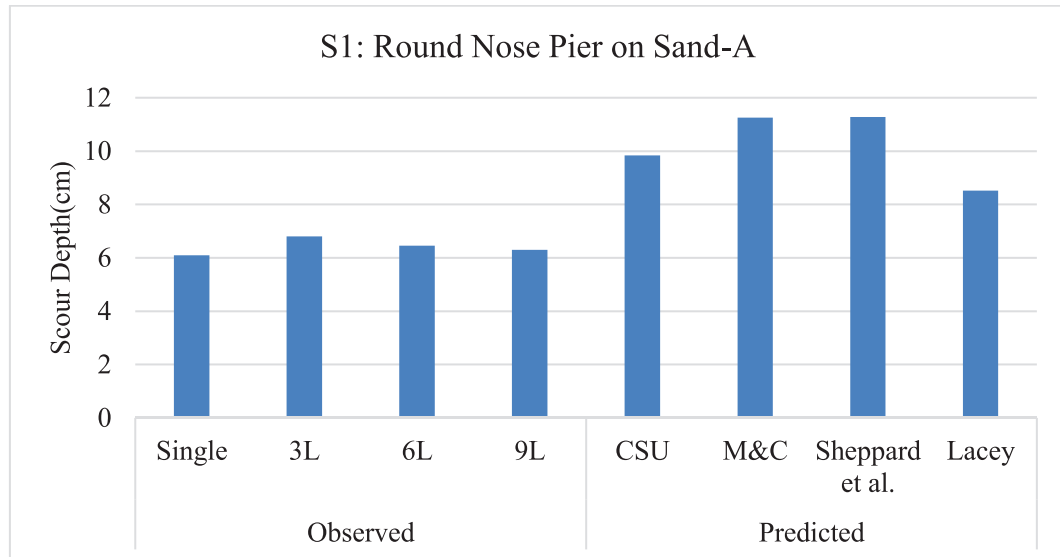
#### 4.16 Comparison of Observed and Predicted Scour Depth

In this study, three existing scour depth predictive equations named Colorado State University (CSU) or HEC-18 equation, Melville and Coleman (2000) equation (M&C) and Sheppard et. al (2004) equation and Lacey equation had been used to calculate scour depth around single piers and two piers placed at various spacing in tandem arrangements on both Sand-A and Sand-B.

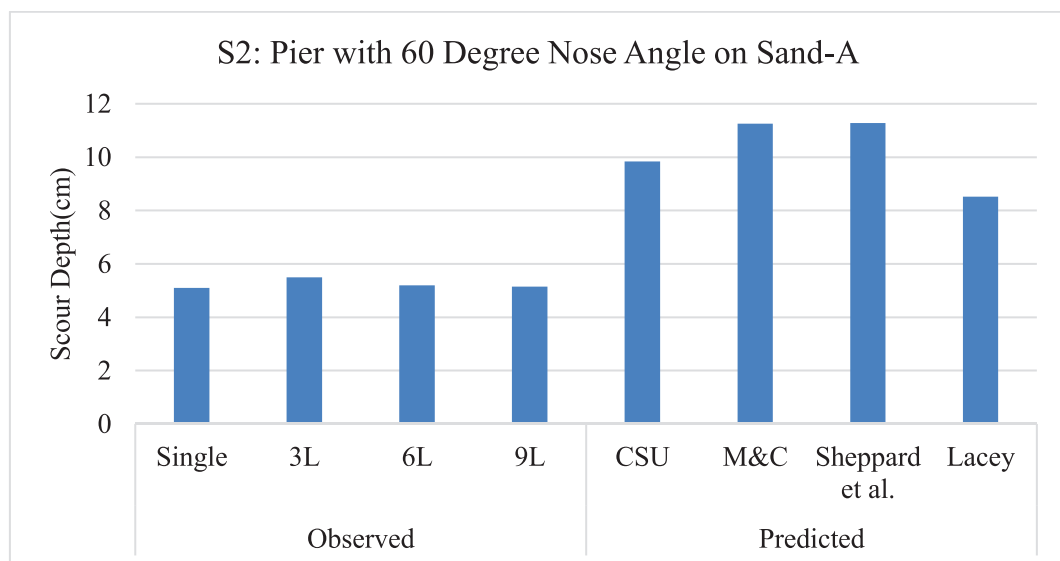
**Figure 4.37 & Figure 4.38** represent the comparison between observed maximum 6-h scour depth and predicted maximum equilibrium scour depth on Sand-A and Sand-B respectively. The predicted scour depths are for 5.5 cm single cylindrical piers. It can be observed that all the scour depth predicting equation over predicted scour depth. Among the single pier scour depth predicting equations, Lacey's equation showed better result.

For Sand-A, the over prediction derived from 2 factors. The 1<sup>st</sup> one is that the equation used for scour depth prediction are for cylindrical pier, whereas scour depth for pier with 60° and 90° nose angle is lower compared to the cylindrical piers. The 2<sup>nd</sup> factor is the duration of the run. Each of the experiment was conducted for 6-h duration. The longer the duration the higher would be the observed scour depth. So, the 6-h maximum scour depth is always lower than the equilibrium scour depth. In single pier scenarios

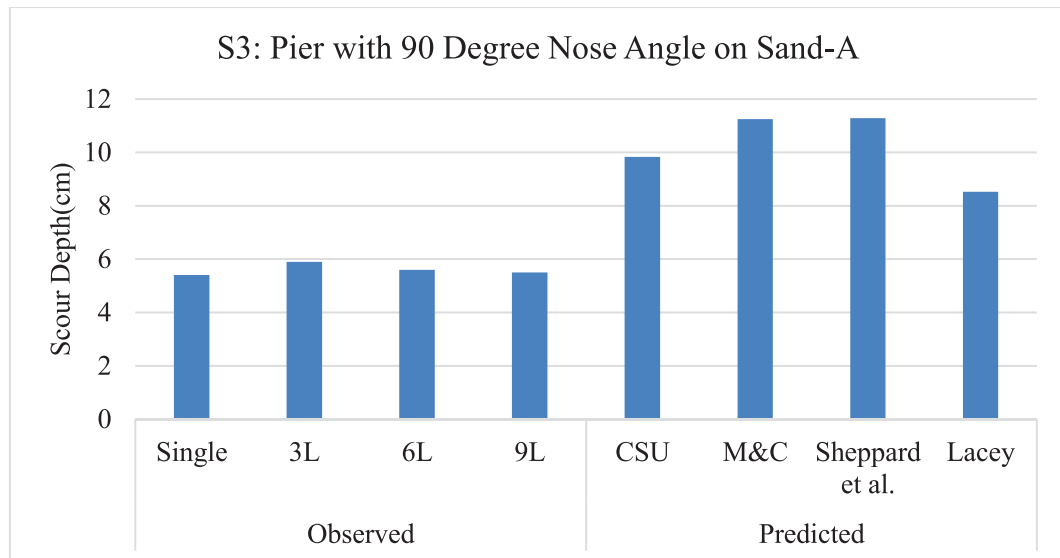
on Sand-A for round nose piers, CSU, M&C, Sheppard et al., and Lacey's equation overpredict scour depth by 61.2%, 84.50%, 84.98%, and 39.69% respectively.



(a)

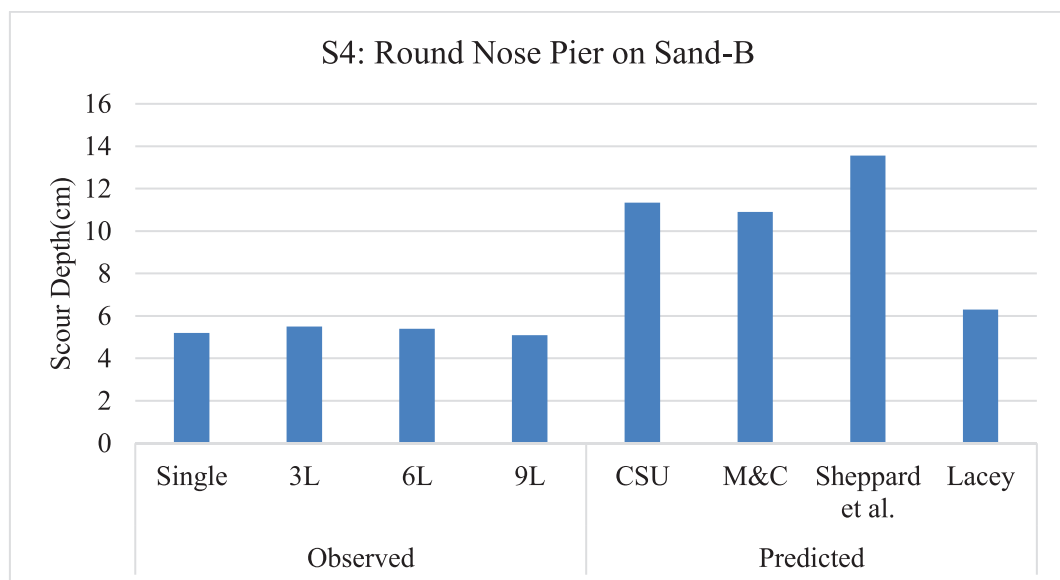


(b)

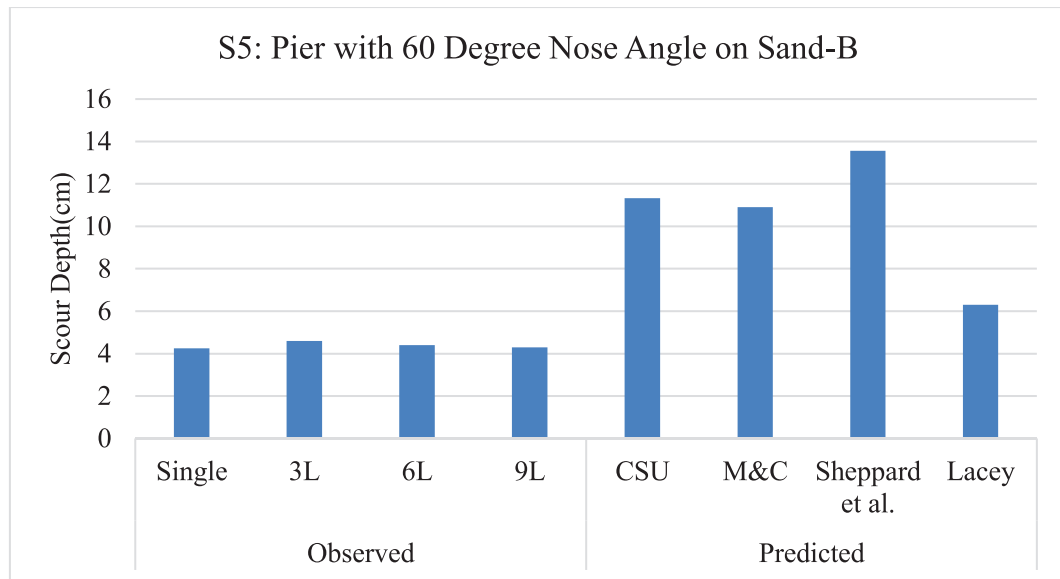


(c)

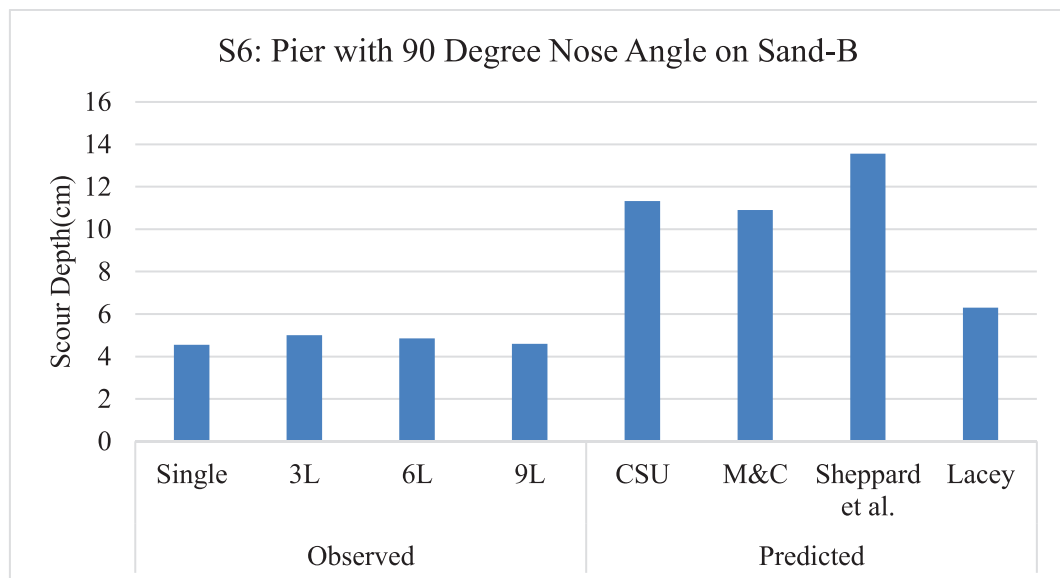
**Figure 4.37** Comparison of observed maximum 6-h scour depth with predicted equilibrium scour depth using single pier equation for 5.5 cm cylindrical pier on Sand-A: (a) Round Nose Pier (b) Pier with 60° Nose Angle & (c) Pier with 90° Nose Angle



(a)



(b)



(c)

**Figure 4.38** Comparison of observed maximum 6-h scour depth with predicted equilibrium scour depth using single pier equation for 5.5 cm cylindrical pier on Sand-B: (a) Round Nose Pier (b) Pier with 60° Nose Angle & (c) Pier with 90° Nose Angle

For piers with 60° nose angle on Sand-A, CSU, M&C, Sheppard et al., and Lacey's equations overpredict scour depth by 92.8456%, 120.68%, 121.26% and 67% respectively. For piers with 90° nose angle on Sand-A, CSU, M&C, Sheppard et al., and Lacey's equations overpredict scour depth compared to observed maximum 6-h scour depth by 82.14%, 108.42%, 57.78% and respectively.

For Sand-B, the over prediction derived from 3 factors. The 1<sup>st</sup> two factors were discussed earlier. The 3<sup>rd</sup> one is the armoring effect (accumulation of larger particles in the scour hole). The equation used for equilibrium scour depth prediction does not incorporate the effect of armoring, but during the experimental run larger particle accumulation near the scour hole was observed which further reduced observed scour depth. In single pier scenarios on Sand-B for round nose piers, CSU, M&C, Sheppard et al., and Lacey's equations overpredict scour depth by 117.972%, 109.569%, 160.698% and 21.17% respectively.

For piers with 60<sup>0</sup> nose angle on Sand-B, CSU, M&C, Sheppard et al., and Lacey's equations overpredict scour depth by 166.969%, 156.414%, 218.971% and 48.25% respectively. For piers with 90<sup>0</sup> nose angle on Sand-B, CSU, M&C, Sheppard et al., and Lacey's equations overpredict scour depth compared to observed maximum 6-h scour depth by 149.111%, 139.507%, 197.64% and 38.48% respectively.

#### 4.17 Development of Correction Factor on CSU Equation

In this study, correction factors to the CSU equation for predicting scour depth around single pier have been developed.

$$\frac{ds}{h} = 2.0K_1K_2K_3K_4 \left(\frac{D}{h}\right)^{0.65} F_r^{0.43} \quad (4.1)$$

Equation 4.1 is suggested by the Federal Highway Administration for predicting scour depth around single pier. This equation is also known as Colorado State University (CSU) or HEC-18 equation. In this equation, D is the pier diameter, h is the flow depth, ds is the scour depth, K<sub>1</sub> is the shape factor, K<sub>2</sub> is the flow skew angle factor, K<sub>3</sub> is the dune factor, K<sub>4</sub> is the correction factor for armoring by bed material size, and F<sub>r</sub> is the Froude number.

The shape factor K<sub>1</sub> have been computed earlier where the shape factor for Round Nose, Pier's with 60<sup>0</sup> nose angle and Pier's with 90<sup>0</sup> have been computed as 0.88, 0.73 and 0.775 respectively. The diameter of the pier is equivalent to the width of the pier.

To use this equation for the pier groups in a tandem arrangement, spacing between the pier (S) needs to incorporate into the single pier equation. This has been done by adding an additional dimensionless parameter (S/L) to the CSU equation. So, the new form of the CSU equation can be written as

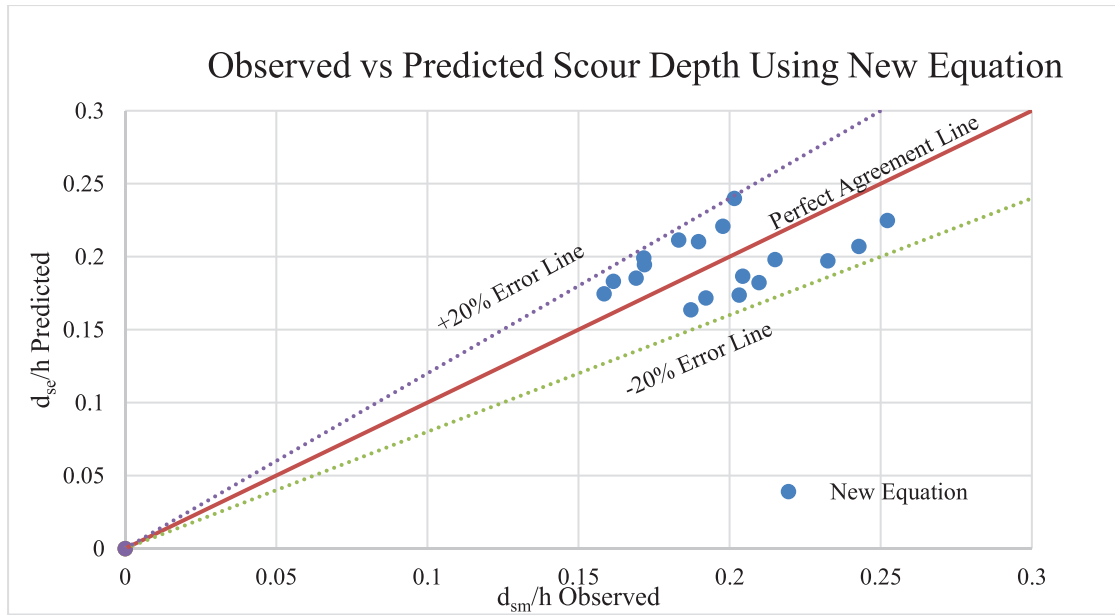
$$\frac{ds}{h} = \left[ 2.0K_1K_2K_3K_4 \left( \frac{D}{h} \right)^{0.65} F_r^{0.43} \right] \times \left[ \left( \frac{S}{L} \right)^a \right] \quad (4.2)$$

Where, S is the C/C spacing between piers, L is the pier length and a is an exponent for pier spacing (S/L). The value of the exponents a has been calculated by nonlinear regression analysis using SPSS and obtained as -0.172.

So, the new CSU equation for two piers placed in tandem arrangements at varying spacing can be written as

$$\frac{ds}{h} = \left[ 2.0K_1K_2K_3K_4 \left( \frac{D}{h} \right)^{0.65} F_r^{0.43} \right] \times \left[ \left( \frac{S}{L} \right)^{-0.172} \right] \quad (4.3)$$

**Figure 4.39** represents the comparison between the observed and predicted scour depth using the new CSU equation from which it can be observed that all the values lie within  $\pm 20\%$  error line.



**Figure 4.39** Comparison of observed and predicted scour depth using the new CSU equation.



## CHAPTER 5

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

In this study, three different shapes of pier (round nose pier, pier with  $60^\circ$  nose angle, and pier with  $90^\circ$  nose angle) were used to investigate the variation of turbulence parameters along the center-line of the flume and scour development both in single and tandem pier arrangement. In tandem pier arrangement, two identical piers were placed in Sand-A ( $d_{50} = 0.23$  mm) and Sand-B ( $d_{50} = 0.89$  mm) at different C/C pier spacing (3L, 6L, and 9L). The key findings of this study can be summarized as follows:

1. For both single and tandem pier arrangements, the analysis displays the logarithmic streamwise velocity profiles, with the greatest velocity being observed at  $z/h = 0.1-0.15$ . In addition, flow reversal was seen at Section-2 and Section-5 of the tandem pier, where it was lowest for the  $60^\circ$  nose angle pier and nearly identical for both  $90^\circ$  nose angle pier & round nose pier.
2. At the u/s of the front pier, normalized streamwise turbulent intensity was higher near the bed and decreased towards the surface. At the d/s of both front pier and rear pier normalized streamwise turbulent intensity increased towards the surface. For all shapes of pier, average of the maximum normalized streamwise turbulent intensity was highest at Section-2, then decreased up to Section-4 and again increased at Section-5. Besides lowest streamwise turbulent intensity was observed for pier with  $60^\circ$  nose angle.
3. Value of the normalized turbulent kinetic energy was higher at the d/s of a pier compare to the u/s due to strong flow circulation. At the u/s of the front pier its value was higher near the bed and decreased towards the surface. In the mid-section its value reaches the lowest. It was also found that, turbulent kinetic energy and turbulent intensity showed similar pattern in almost all cases.
4. At the u/s of the front pier, the values of Reynolds Shear Stress (RSS) had higher magnitude near the bottom due to flow reversal and close to zero near the surface. At the d/s of the pier, its showed oscillatory nature due to flow separation and vortex shedding. In general, round nose pier showed highest RSS.

5. Comparison between CFD simulation and experimental observation showed that in general CFD simulation showed lower turbulent kinetic energy compare to experimental investigation.
6. Piers with round noses had the highest scour depth, while for 60° nose angles had the lowest. Frontal scour was more significant for round nose pier, while side scour was more prominent for piers with 60° and 90° nose angles. The shape factor for round nose, pier with 60° nose angle and pier with 90° angle were found as 0.88, 0.73 and 0.775.
7. Scour depth was influenced by the spacing between two piers in tandem arrangements. For instance, as pier spacing was increased, the front pier's scour depth reduced while increased for the rear pier. Scour depth around the front pier was greater in 3L and 6L C/C spacing than in single pier scenarios and was approximately similar to the single pier at 9L C/C spacing.
8. Scour depth on Sand-A ( $d_{50} = 0.23$  mm) was higher compare to the Sand-B ( $d_{50} = 0.89$  mm). It was observed that, for Sand-B, heavier particles were accumulated near the scour hole as the geometric standard deviation of Sand-B was higher than Sand-A. This accumulation resulted in the decrease of scour depth.
9. Round nose and 90° nose angle pier had almost circular scour hole at lower spacing, whereas 60° nose angle pier had slightly conical shape of scour hole.
10. Comparison between the scour depth obtained from the experimental runs with the existing scour depth predictive equations revealed that all the equations overpredict scour depth and the overprediction increased for sand with higher geometric standard deviation.
11. A correction factor to the existing CSU single-pier equation was developed to predict the scour depths for pier groups in tandem arrangements which can be written as follows:

$$\frac{ds}{h} = \left[ 2.0K_1K_2K_3K_4 \left( \frac{D}{h} \right)^{0.65} F_r^{0.43} \right] \times \left[ \left( \frac{S}{L} \right)^{-0.172} \right]$$

The findings of this study can be used for validating computation fluid dynamics (CFD) model, and hence the model can be used for different experimental scenarios by varying pier spacing, flow depth, sediment size etc.

## **5.2 Recommendations for Future Work**

1. In this study only three C/C spacing was used, using a wider range of spacing at finer interval can be performed to better understand the effect of pier spacing on scour development.
2. For understanding the effect of geometric standard deviation on scour depth and for analyzing the armoring effect, more sediment bed with a wider range of geometric standard deviation can be used for conduction of laboratory experiments.
3. As turbulent parameters vary within a very short distance, collection of three-dimensional instantaneous velocity components data at finer interval will provide better understanding regarding flow field around the piers.
4. The findings of this study can be used for validating computation fluid dynamics (CFD) model, and hence the model can be used for different experimental scenarios by varying pier spacing, flow depth, sediment size etc.

## REFERENCES

- Al-Shukur, A.-H.K., & Obeid, Z.H., 2016. Experimental Study of Bridge Pier Shape to Minimize Local Scour. *IJCIET\_07\_01\_013 International Journal of Civil Engineering and Technolog.* 7(1), 162–171.
- Ataie-Ashtiani, B., & Aslani-Kordkandi, A., 2013. Flow Field Around Single and Tandem Piers. *Flow, Turbulence and Combustion.* 90(3), 471–490. <https://doi.org/10.1007/s10494-012-9427-7>
- Ataie-Ashtiani, B., Baratian-Ghorghi, Z., & Beheshti, A.A., 2010. Experimental Investigation of Clear-Water Local Scour of Compound Piers. *Journal of Hydraulic Engineering.* 136(6), 343–351. <https://doi.org/10.1061/ASCE0733-94292010136:6343>
- Ataie-Ashtiani, B., & Beheshti, A.A., 2006. Experimental Investigation of Clear-Water Local Scour at Pile Groups. *Journal of Hydraulic Engineering.* 132(10), 1100–1104. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2006\)132](https://doi.org/10.1061/(ASCE)0733-9429(2006)132)
- Basir, Md.S., 2022. Experimental Investigation of Local Scour around Two Cylinder-Shaped Pier in Tandem Arrangements. M.Sc Thesis, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh.
- Beheshti, A.A., Ataie-Ashtiani, B., & Khanjani, M.J., 2013. Discussion of “Clear-Water Local Scour around Pile Groups in Shallow-Water Flow” by Ata Amini, Bruce W. Melville, Thamer M. Ali, and Abdul H. Ghazali. *Journal of Hydraulic Engineering.* 139(6), 679–680.
- Bento, A.M., Viseu, T., Pêgo, J.P., & Couto, L., 2021. Experimental Characterization of the Flow Field Around Oblong Bridge Piers. *Fluids.* 6(11). <https://doi.org/10.3390/fluids6110370>
- Breusers, H.N.C., Nicollet, G., & Shen, H.W., 1977a. Local Scour Around Cylindrical Piers. *Journal of hydraulic research.* 15(3), 211–252.
- Breusers, H.N.C., Nicollet, G., & Shen, H.W., 1977b. Local Scour Around Cylindrical Piers. *Journal of Hydraulic Research.* 15(3), 211–252.
- Breusers, H.N.C., & Raudkivi, A.J., 1991. Scouring. IAHR Hydraulic Structures Design Manual 2. *AA Balkema, Rotterdam, The Netherlands.*

- Chavan, R., 2018. Hydrodynamics and Morphology around Bridge Piers in Seepage Affected Alluvial Channel. Ph.D. Thesis, Indian Institute of Technology, Guwahati, India.
- Chien, N., & Wan, Z., 1983. *Mechanics of Sediment Transport*. ASCE Press, Reston, Virginia.
- Chiew, Y.-M., & Lim, F.-H., 2000. Failure Behavior of Riprap Layer at Bridge Piers Under Live-Bed Conditions. *Journal of Hydraulic Engineering*. 126(1), 43–55.
- Coleman, S.E., 2005. Clearwater Local Scour at Complex Piers. *Journal of Hydraulic Engineering*. 131(4), 330–334.
- Coleman, S.E., & Melville, B.W., 2001. Case Study: New Zealand Bridge Scour Experiences. *Journal of Hydraulic engineering*. 127(7), 535–546.
- Dargahi, B., 1990a. Controlling Mechanism of Local Scouring. *Journal of Hydraulic Engineering*. 116(10), 1197–1214.
- Dargahi, B., 1990b. Controlling Mechanism of Local Scouring. *Journal of Hydraulic Engineering*. 116(10), 1197–1214.
- Dey, S., Bose, S.K., & Sastry, G.L.N., 1995. Clear Water Scour at Circular Piers: A Model. *Journal of Hydraulic Engineering*. 121(12), 869–876. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1995\)121:12\(869\)](https://doi.org/10.1061/(ASCE)0733-9429(1995)121:12(869))
- Dongguang, G., Pasada, L., & Nordin, C.F., 1993. Pier Scour Equations Used in the People's Republic of China: Review and Summary.
- Elliott, K.R., & Baker, C.J., 1985. Effect of Pier Spacing on Scour Around Bridge Piers. *Journal of Hydraulic Engineering*. 111(7), 1105–1109. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1985\)111:7\(1105\)](https://doi.org/10.1061/(ASCE)0733-9429(1985)111:7(1105))
- Ettema, R., Constatinescu, G., & Melville, B., 2011. Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions. Transportation Research Board, National Academies of Sciences, Engineering, and Medicine. <https://doi.org/10.17226/22886>
- Fael, C., Lança, R., & Cardoso, A., 2016. Effect of Pier Shape and Pier Alignment on the Equilibrium Scour Depth at Single Piers. *International Journal of Sediment Research*. 31(3), 244–250. <https://doi.org/10.1016/j.ijsrc.2016.04.001>

- Funde, K.B., Gidde, M., & Patil, P.D., 2018. Effect of Different Shapes of Different Shapes of Bridge Piers to Minimize Local Scour. *International Journal of Civil Engineering and Technology (IJCIET)*. 9(1), 628–638.
- Garde, R.J., & Raju, K.G.R., 2000. *Mechanics of Sediment Transportation and Alluvial Stream Problems*. Taylor & Francis.
- Ghasemi, M., & Soltani-Gerdefaramarzi, S., 2017. The Scour Bridge Simulation Around a Cylindrical Pier Using Flow-3D. *Journal of Hydrosiences and Environment*. 1(2), 46–54.
- Graf, W.H., & Istiarto, I., 2002. Flow Pattern in the Scour Hole Around a Cylinder. *Journal of Hydraulic Research*. 40(1), 13–20.
- Hannah, C., 1978. Scour at Pile Groups. M.Sc. Thesis, University of Canterbury, Christchurch, New Zealand.
- Hosseini, R., & Amini, A., 2015. Scour Depth Estimation Methods Around Pile Groups. *KSCE Journal of Civil Engineering*. 19, 2144–2156.
- Jalal, H.K., & Hassan, W.H., 2020. Effect of Bridge Pier Shape on Depth of Scour, in: IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing. <https://doi.org/10.1088/1757-899X/671/1/012001>
- Keshavarzi, A., Shrestha, C.K., Melville, B., Khabbaz, H., Ranjbar-Zahedani, M., & Ball, J., 2018b. Estimation of Maximum Scour Depths at Upstream of Front and Rear Piers for Two In-Line Circular Columns. *Environmental Fluid Mechanics*. 18(2), 537–550. <https://doi.org/10.1007/s10652-017-9572-6>
- Khaple, S., Hanmaiahgari, P.R., Gaudio, R., & Dey, S., 2017. Interference of an Upstream Pier on Local Scour at Downstream Piers. *Acta Geophysica*. 65(1), 29–46. <https://doi.org/10.1007/s11600-017-0004-2>
- Kirkil, G., Constantinescu, S.G., & Ettema, R., 2008. Coherent Structures in the Flow Field Around a Circular Cylinder with Scour Hole. *Journal of Hydraulic Engineering*. 134(5), 572–587.
- Kothyari, U.C., & Kumar, A., 2012. Temporal Variation of Scour Around Circular Compound Piers. *Journal of Hydraulic Engineering*. 138(11), 945–957. [https://doi.org/10.1061/\(asce\)hy.1943-7900.0000593](https://doi.org/10.1061/(asce)hy.1943-7900.0000593)

- Lacey, G. (1930). Stable Channels in Alluvium (includes appendices). In *Minutes of the Proceedings of the Institution of Civil Engineers* (Vol. 229, No. 1930, pp. 259-292). Thomas Telford-ICE Virtual Library.
- Lee, S.O., & Sturm, T.W., 2009. Effect of Sediment Size Scaling on Physical Modelling of Bridge Pier Scour. *Journal of hydraulic engineering*. 135(10), 793–802.
- Marsh, N.A., Western, A.W., & Grayson, R.B., 2004. Comparison of Methods for Predicting Incipient Motion for Sand Beds. *Journal of Hydraulic Engineering*. 130(7), 616–621. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2004\)130:7\(616\)](https://doi.org/10.1061/(ASCE)0733-9429(2004)130:7(616))
- Melville, B., 1992. Local Scour at Bridge Abutments. *Journal of Hydraulic Engineering*. 118(4), 615–631. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1992\)118:4\(615\)](https://doi.org/10.1061/(ASCE)0733-9429(1992)118:4(615))
- Melville, B., 1975. Local Scour at Bridge Sites. Ph.D. Thesis, University of Auckland, New Zealand.
- Mia, Md.F., & Nago, H., 2003. Design Method of Time-Dependent Local Scour at Circular Bridge Pier. *Journal of Hydraulic Engineering*. 129(6), 420–427. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:6\(420\)](https://doi.org/10.1061/(ASCE)0733-9429(2003)129:6(420))
- Nazariha, M., 1996. Design Relationships for Maximum Local Scour Depth for Bridge Pier Groups. Ph.D. Thesis, University of Ottawa, Ottawa, Canada K1N 6N5.
- Nezu, I., & Nakagawa, H., 1993. *Turbulence in Open Channel Flows*, 1st ed, Taylor & Francis. CRC Press. <https://doi.org/10.1201/9780203734902>
- Nowrin, S.N., 2020. Experimental Study on Turbulent Flow around a Pair of Cylinders Placed along Plane of Symmetry in a Rectangular Open Channel. M.Sc Thesis, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh.
- Omara, H., Elsayed, S.M., Abdeelaal, G.M., Abd-Elhamid, H.F., & Tawfik, A., 2019. Hydromorphological Numerical Model of The Local Scour Process Around Bridge Piers. *Arabian Journal for Science and Engineering*. 44(5), 4183–4199.
- Ozturk, N.A., Akkoca, A., & Sahin, B., 2008. Flow Details of a Circular Cylinder Mounted on a Flat Plate. *Journal of Hydraulic Research*. 46(3), 344–355.
- Rahul, M., & Baldev, S., 2020. Prediction of Scour Depth Around Bridge Piers in Tandem Arrangement Using M5 and ANN Regression Models. *Archives of*



- Materials Science and Engineering*. 102(2), 49–58.  
<https://doi.org/10.5604/01.3001.0014.1524>
- Rao, S.K., Sumner, D., & Balachandar, R., 2004. A Visualization Study of Fluid-Structure Interaction Between a Circular Cylinder and a Channel Bed. *Journal of Visualization*. 7(3), 187–199.
- Richardson, E.V., & Davis, S.R., 2001. Evaluating Scour at Bridges. Hydraulic Engineering Circular No. 18, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.
- S V S N D L, P., & Kumar, S., 2018. Simulation of Flow Behaviour Around Bridge Piers Using ANSYS-CFD.
- Salim, M., & Jones, J.S.J., 1998. Scour around Exposed Pile Foundations, in: Compilation of Conf. Scour Papers. ASCE, Reston, VA.
- Shahhosseini, M., & Guoliang, Y., 2019. Experimental Study on the Effects of Pier Shape and Skew Angle on Pier Scour, in: Journal of Physics: Conference Series. Institute of Physics Publishing. <https://doi.org/10.1088/1742-6596/1300/1/012031>
- Shahhosseini, M., & Yu, G., 2019. Experimental Study on the Effects of Pier Shape and Skew Angle on Pier Scour, in: *Journal of Physics: Conference Series*. IOP Publishing, p. 012031.
- Sheppard, D.M., Odeh, M., & Glasser, T., 2004. Large Scale Clear-Water Local Pier Scour Experiments. *Journal of Hydraulic Engineering*. 130(10), 957–963.  
[https://doi.org/10.1061/\(ASCE\)0733-9429\(2004\)130:10\(957\)](https://doi.org/10.1061/(ASCE)0733-9429(2004)130:10(957))
- Shrestha, C.K., 2015. Bridge Pier Flow Interaction and Its Effect on the Process of Scouring. PhD Thesis. University of Technology Sydney (UTS).
- Sontek, 2001. ADV Field Operation Manual. SonTek/YSI, San Diego, USA.
- Strom, K.B., & Papanicolaou, A.N., 2007. ADV Measurements around a Cluster Microform in a Shallow Mountain Stream. *Journal of Hydraulic Engineering*. 133(12), 1379–1389. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:12\(1379\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:12(1379))
- Sturm, T.W., 2001. *Open Channel Hydraulics*. McGraw-Hill New York.



- Vijayasree, B.A., Eldho, T.I., Mazumder, B.S., & Ahmad, N., 2019. Influence of Bridge Pier Shape on Flow Field and Scour Geometry. *International Journal of River Basin Management*. 17(1), 109–129.  
<https://doi.org/10.1080/15715124.2017.1394315>
- Vittal, N., Kothiyari, U.C., & Haghighat, M., 1994. Clear-Water Scour around Bridge Pier Group. *Journal of Hydraulic Engineering*. 120(11), 1309–1318.  
[https://doi.org/10.1061/\(ASCE\)0733-9429\(1994\)120:11\(1309\)](https://doi.org/10.1061/(ASCE)0733-9429(1994)120:11(1309))
- Yanmaz, A.M., & Altinbilek, H.D., 1991. Study of TimeDepenbent Local Scour around Bridge Piers. *Journal of Hydraulic Engineering*. 117(10), 1247–1268.  
[https://doi.org/10.1061/\(ASCE\)0733-9429\(1991\)117:10\(1247\)](https://doi.org/10.1061/(ASCE)0733-9429(1991)117:10(1247))
- Zhang, R., 2007. River dynamics. Wuhan University Press, Wuhan, China.
- Zhao, S., Ji, C., Sun, Z., Yu, H., & Zhang, Z., 2022. Effects of the Gap on the Local Scour Around Two Tandem Piles in Shallow Flows. *Ocean Engineering*. 246, 110575.
- Zhou, Y., & Yiu, M.W., 2006. Flow Structure, Momentum and Heat Transport in a Two-Tandem-Cylinder Wake. *Journal of Fluid Mechanics*. 548, 17–48.
- Zobeyer, H., Baki, A.B.M., & Nowrin, S.N., 2021. Interactions between Tandem Cylinders in an Open Channel: Impact on Mean and Turbulent Flow Characteristics. *Water (Switzerland)*. 13(13), 1-13  
<https://doi.org/10.3390/w13131718>

## APPENDICES

### Appendix-A Pictures Collected During the Experiments.



(a)



(b)

**Figure A. 1** Placement of pier on sediment bed: (a) Round Nose Pier (b) Pier with  $90^0$  Nose Angle.



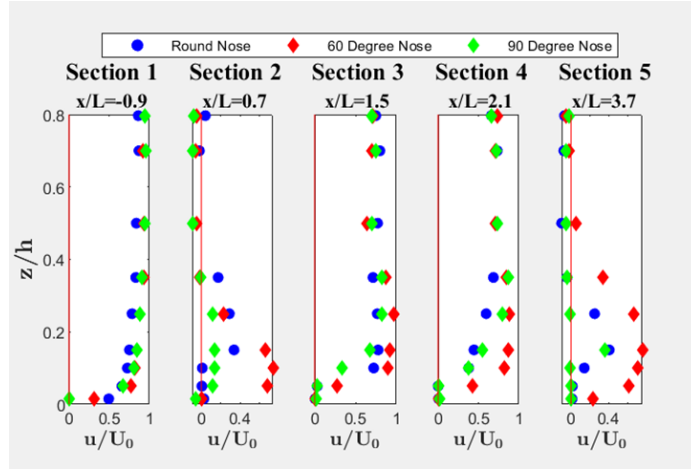
(a)



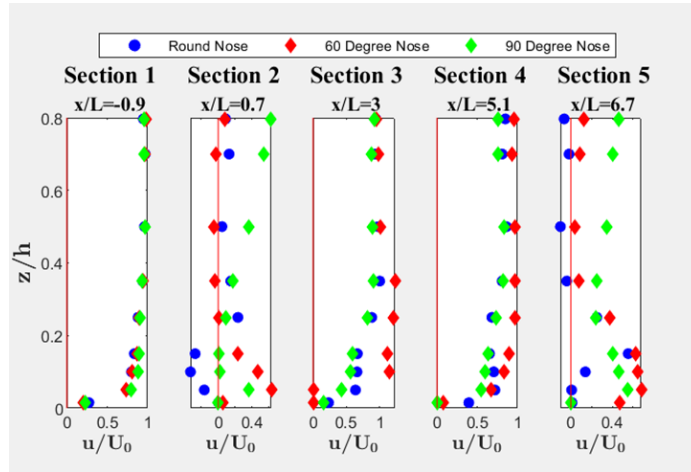
(b)

**Figure A. 2** Scour around piers: (a) Sand-A (b) Sand-B.

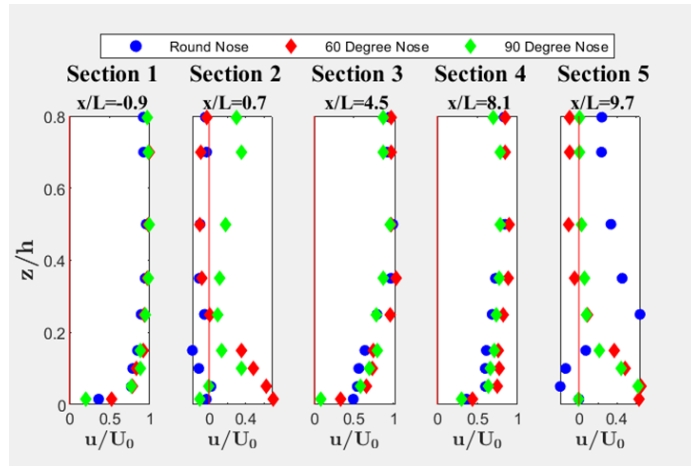
## Appendix-B Variation of Normalized Streamwise Velocity along the Centerline



(a)



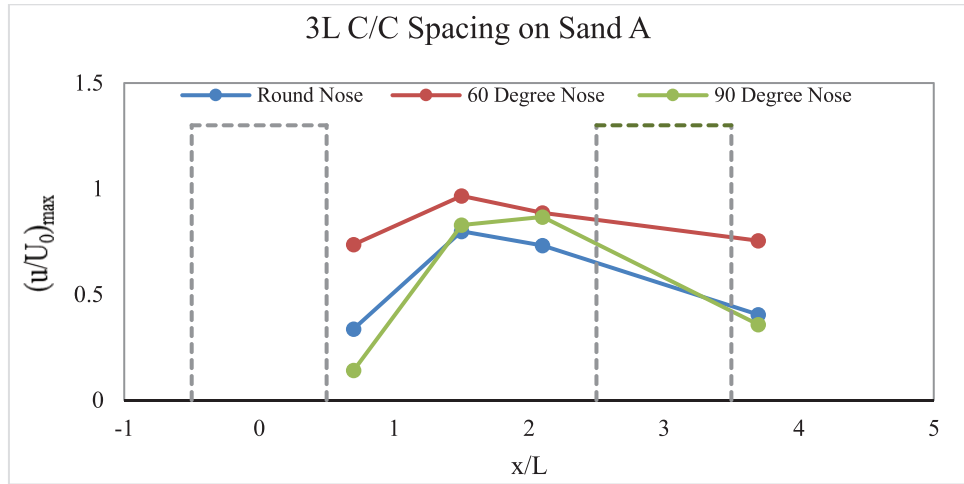
(b)



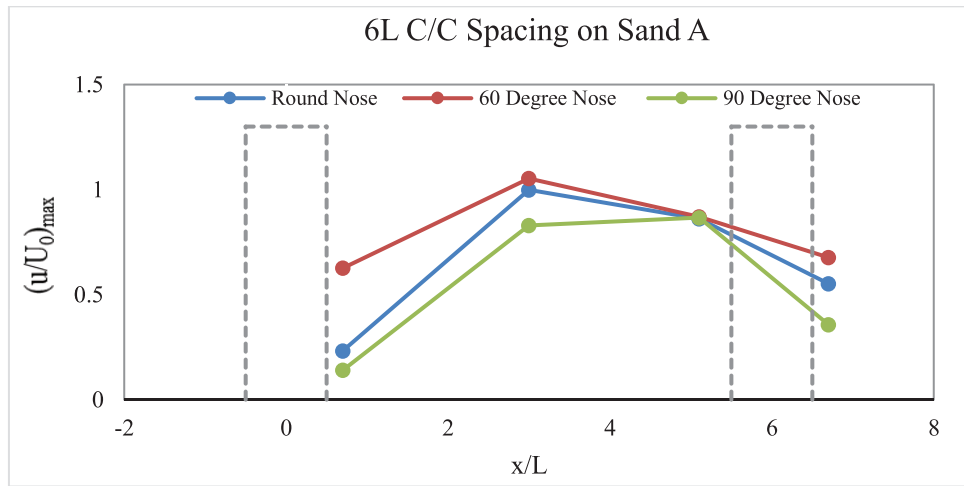
(c)

**Figure B. 1** Variation of normalized streamwise velocity component along the centerline in tandem arrangements on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) 3L C/C spacing (b) 6L C/C spacing (c) 9L C/C spacing.

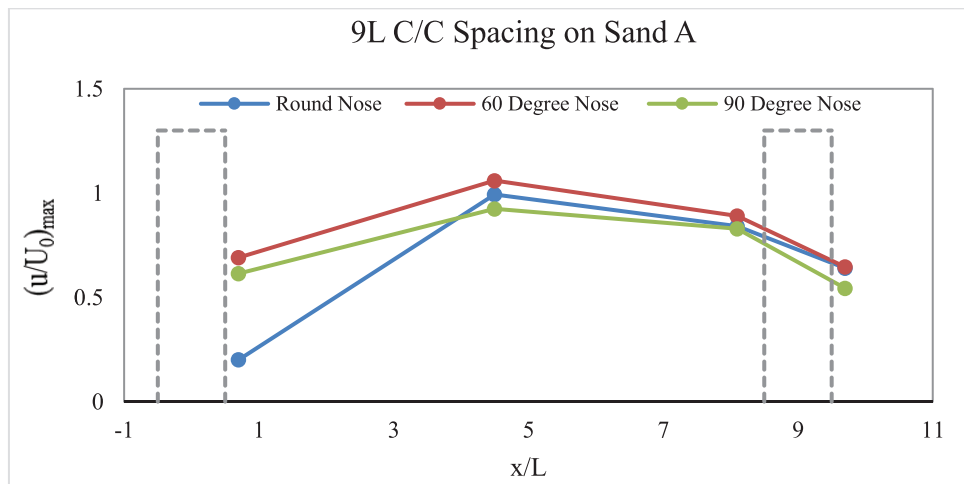
## Appendix-C Effect of Pier Nose Shape on Maximum Streamwise Velocity



(a)



(b)

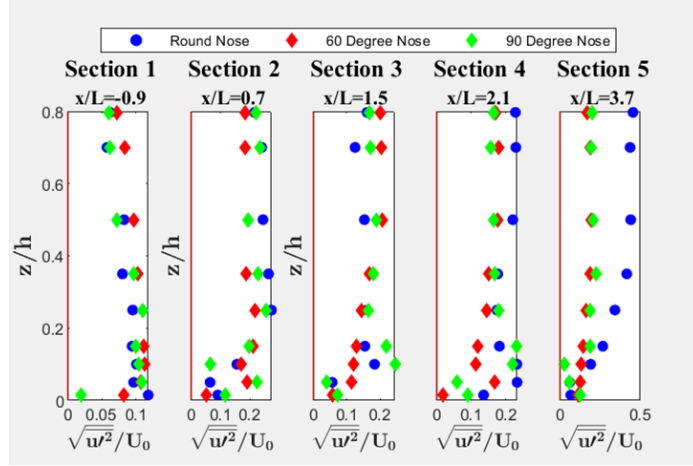


(c)

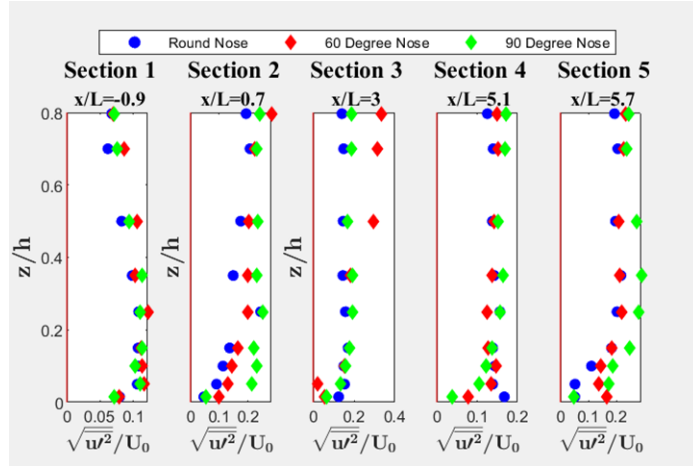
**Figure C. 1** Effect of pier nose shape on maximum normalized streamwise velocity on Sand-A ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.



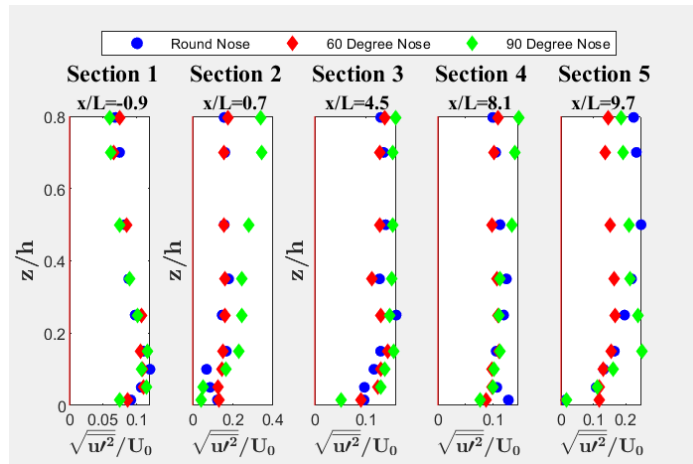
Appendix-D Variation of Normalized Streamwise Turbulence Intensity ( $TI_u$ ) along the Centerline.



(a)



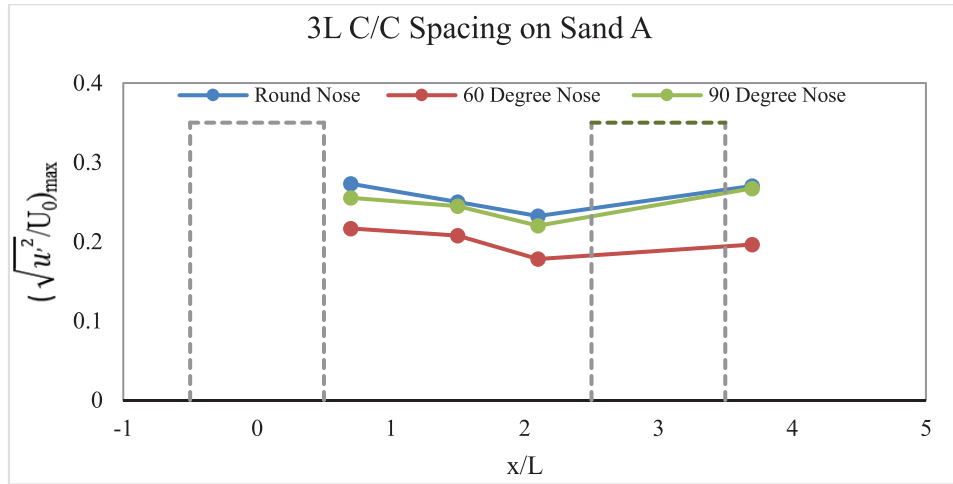
(b)



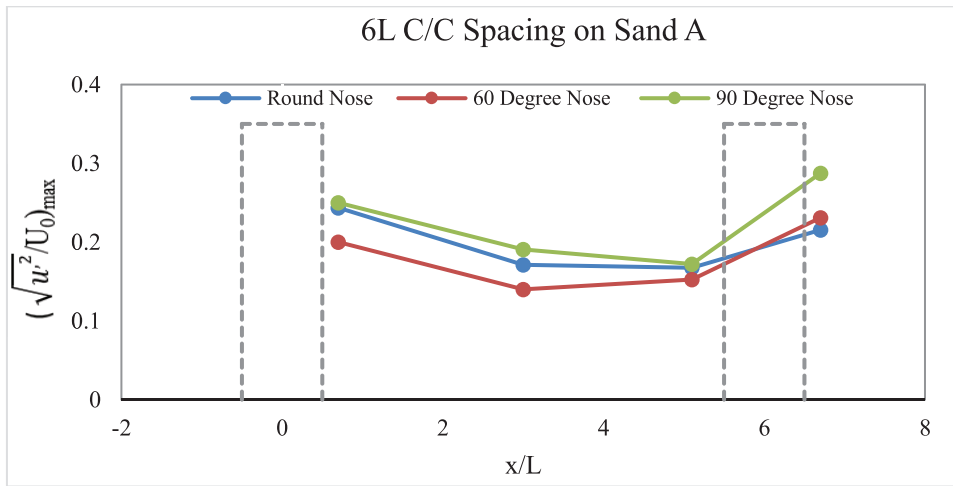
(c)

**Figure D. 1** Variation of normalized streamwise turbulent intensity along the centerline in tandem arrangements on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) 3L C/C spacing (b) 6L C/C spacing (c) 9L C/C spacing.

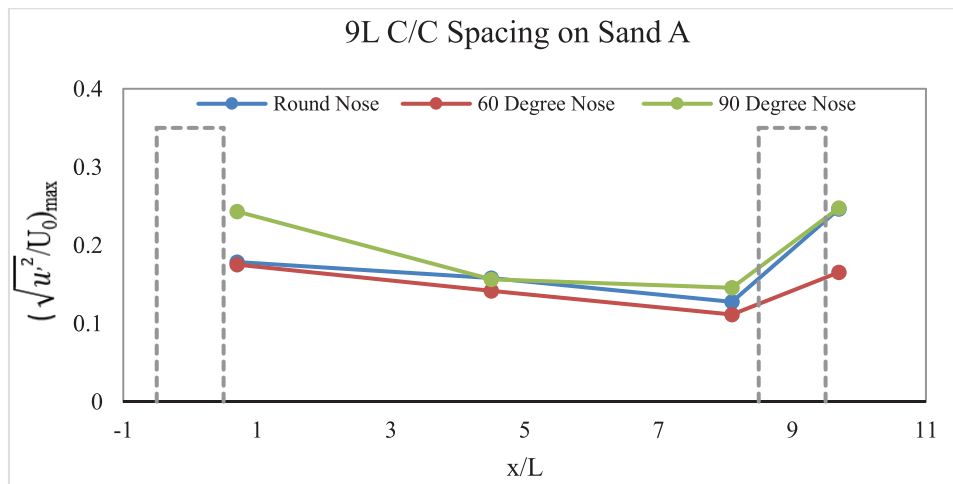
## Appendix-E Effect of Pier Nose Shape on Maximum Turbulent Intensity



(a)



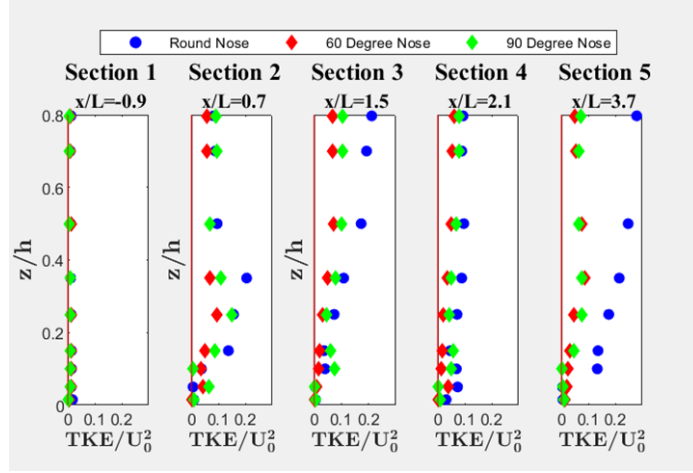
(b)



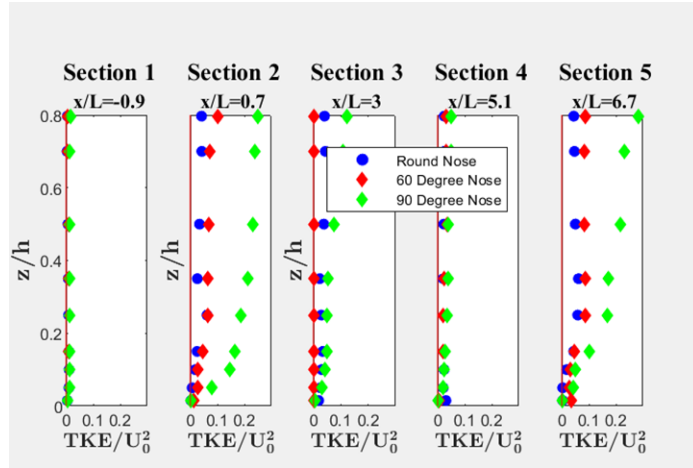
(c)

**Figure E. 1** Effect of pier nose shape on maximum normalized streamwise turbulent intensity on Sand-A ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

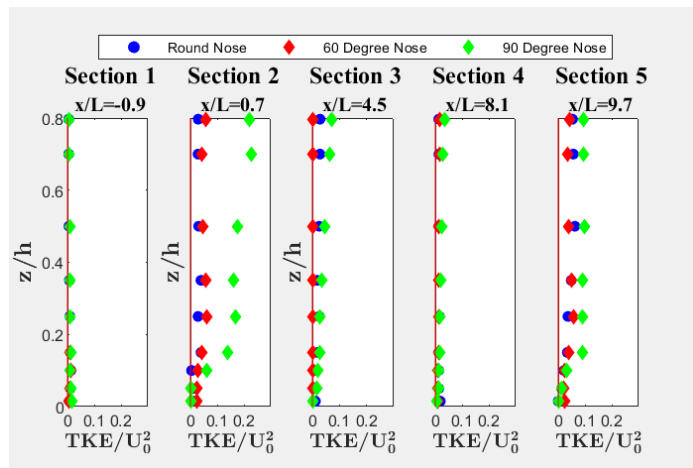
## Appendix-F Variation of Normalized Turbulent Kinetic Energy (TKE) along the Centerline.



(a)



(b)

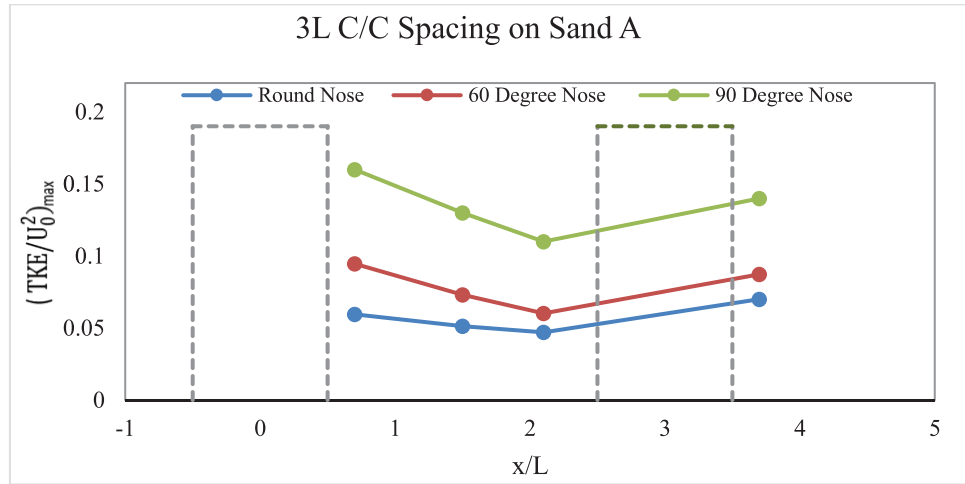


(c)

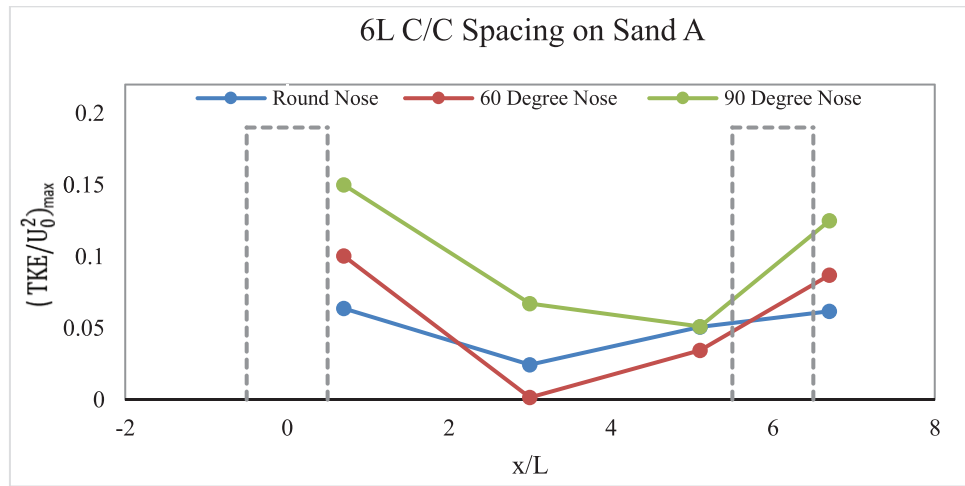
**Figure F. 1** Variation of normalized turbulent kinetic energy along the centerline in tandem arrangements on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) 3L C/C spacing (b) 6L C/C spacing (c) 9L C/C spacing



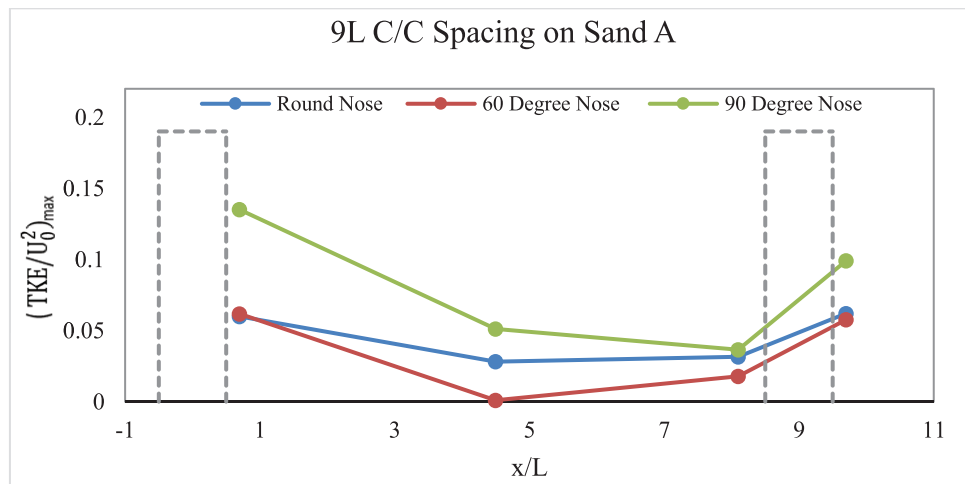
## Appendix-G Effect of Pier Nose Shape on Maximum Turbulent Kinetic Energy



(a)



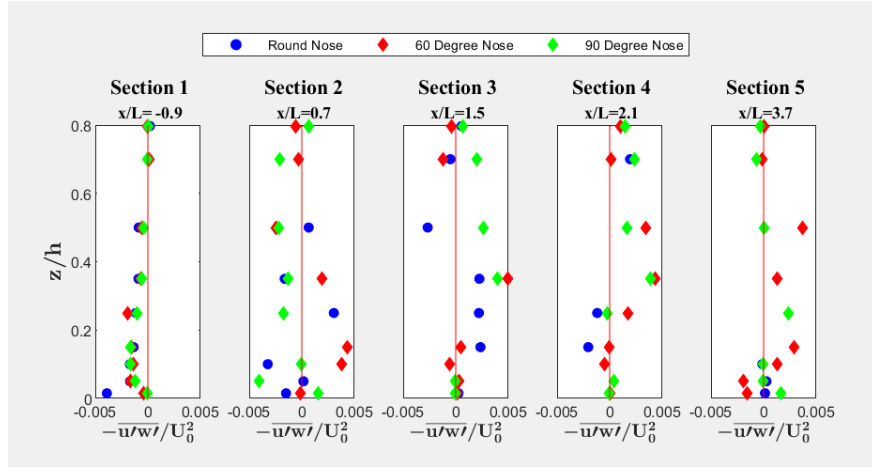
(b)



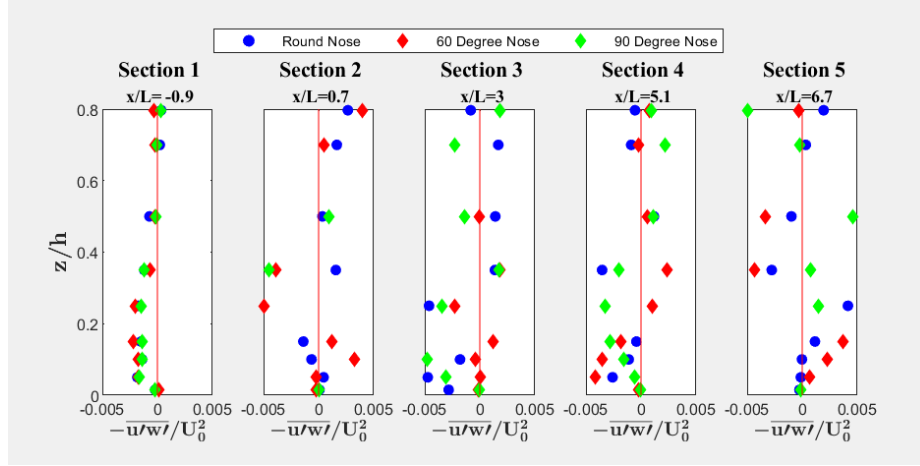
(c)

**Figure G. 1** Effect of pier nose shape on maximum normalized turbulent kinetic energy on Sand-A ( $d_{50}=0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

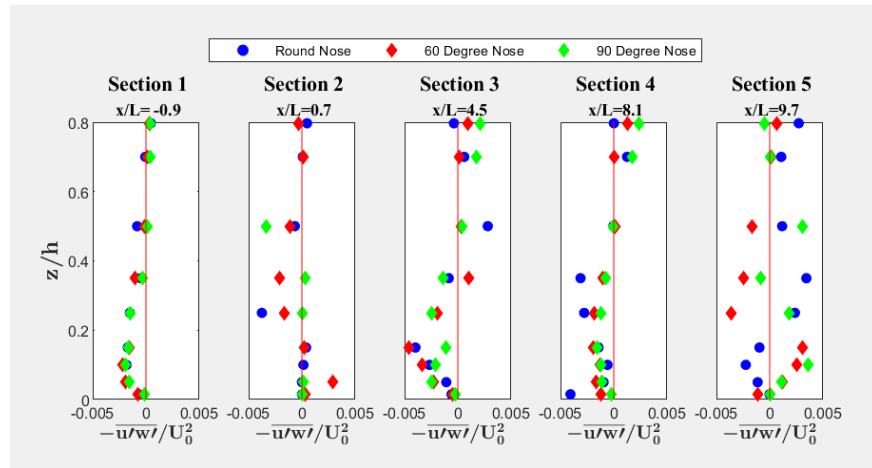
Appendix-H Variation of Normalized Reynolds Shear Stress ( $-\overline{u'w'}$ ) along the Centerline.



(a)



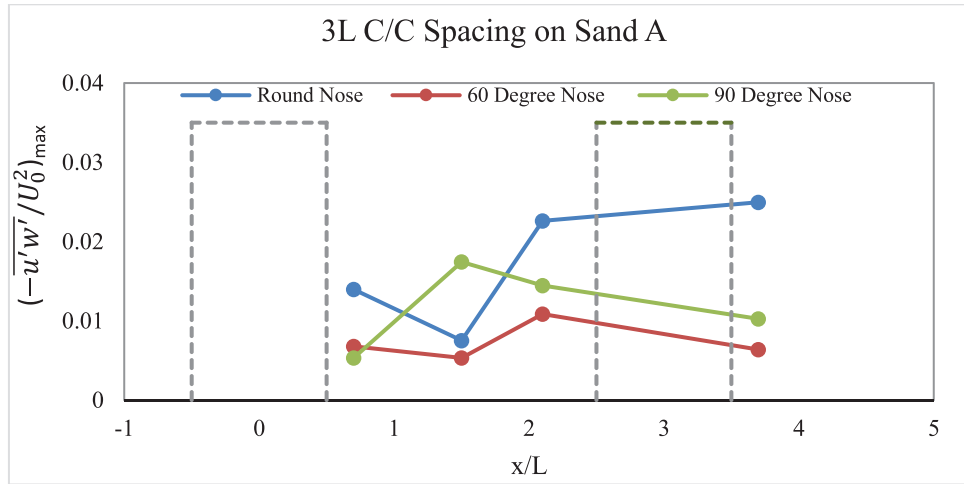
(b)



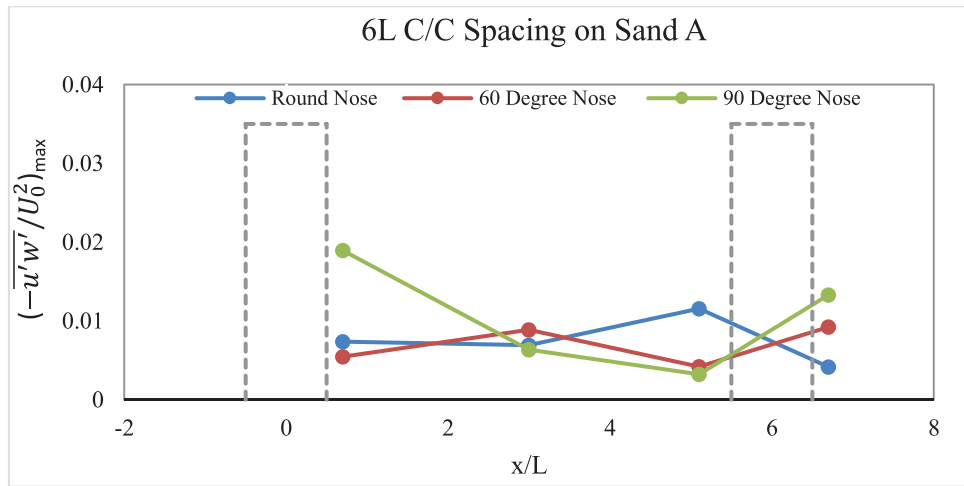
(c)

**Figure H. 1** Variation of normalized Reynolds Shear Stress along the centerline in tandem arrangements on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) 3L C/C spacing (b) 6L C/C spacing (c) 9L C/C spacing

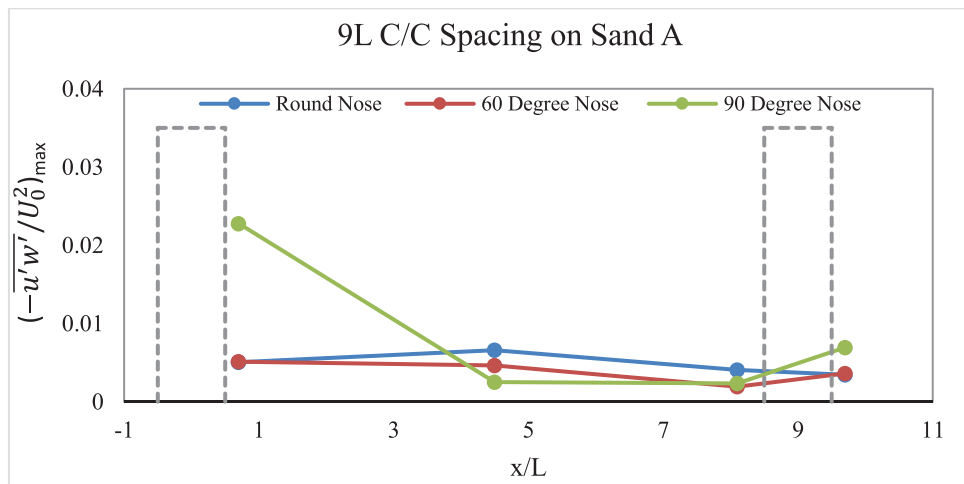
## Appendix-I Effect of Pier Nose Shape on Maximum Reynolds Shear Stress



(a)



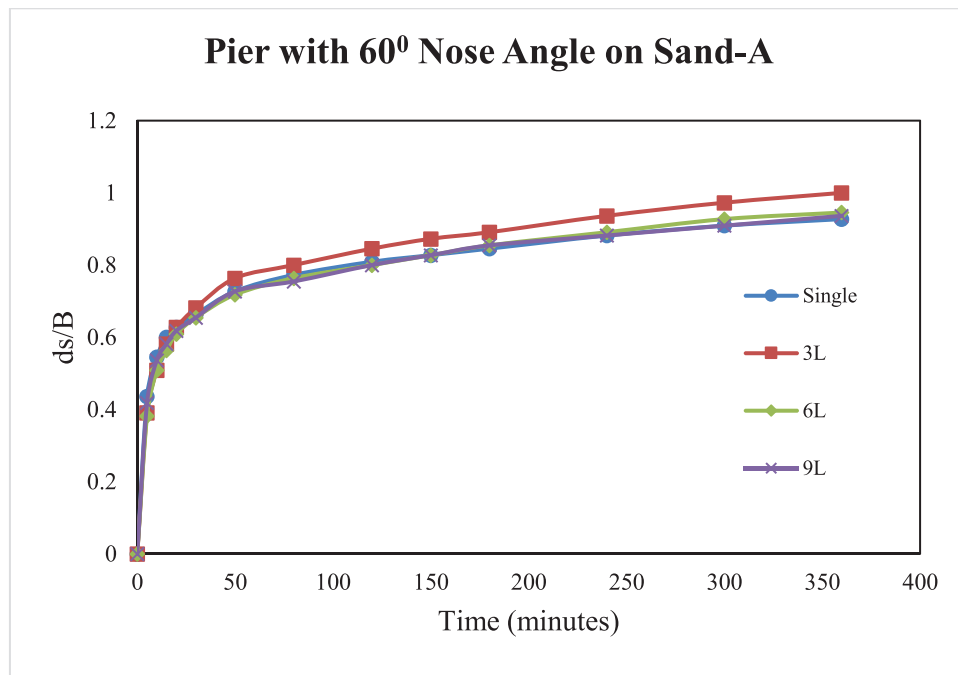
(b)



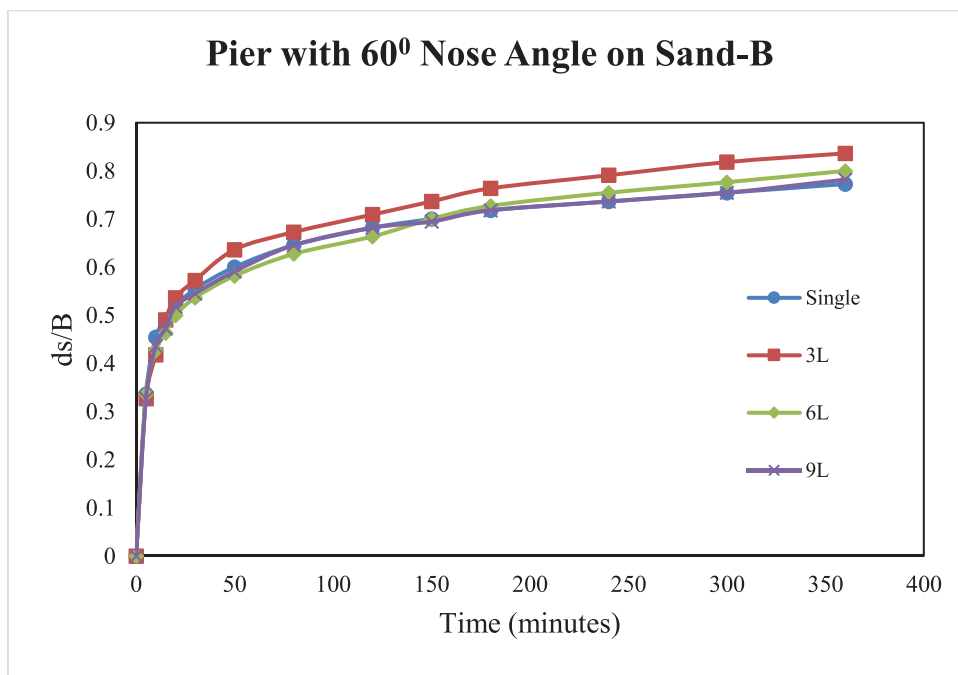
(c)

**Figure I. 1** Effect of pier nose shape on maximum normalized Reynolds Shear Stress on Sand-A ( $d_{50} = 0.89$  mm): (a) 3L C/C Spacing (b) 6L C/C Spacing (c) 9L C/C Spacing.

## Appendix-J Temporal Development of Scour Depth

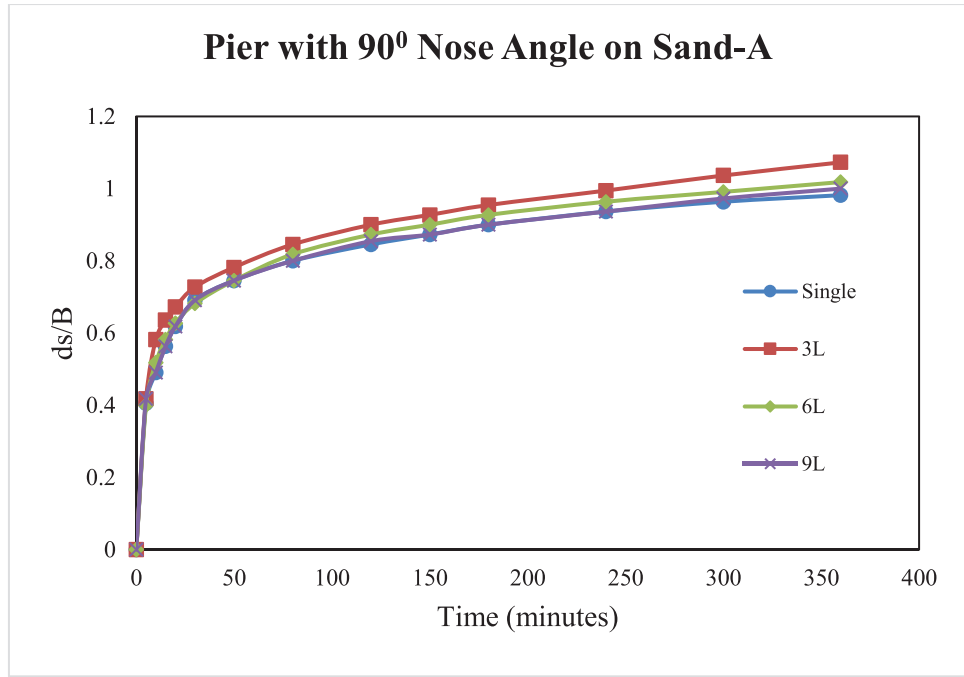


(a)

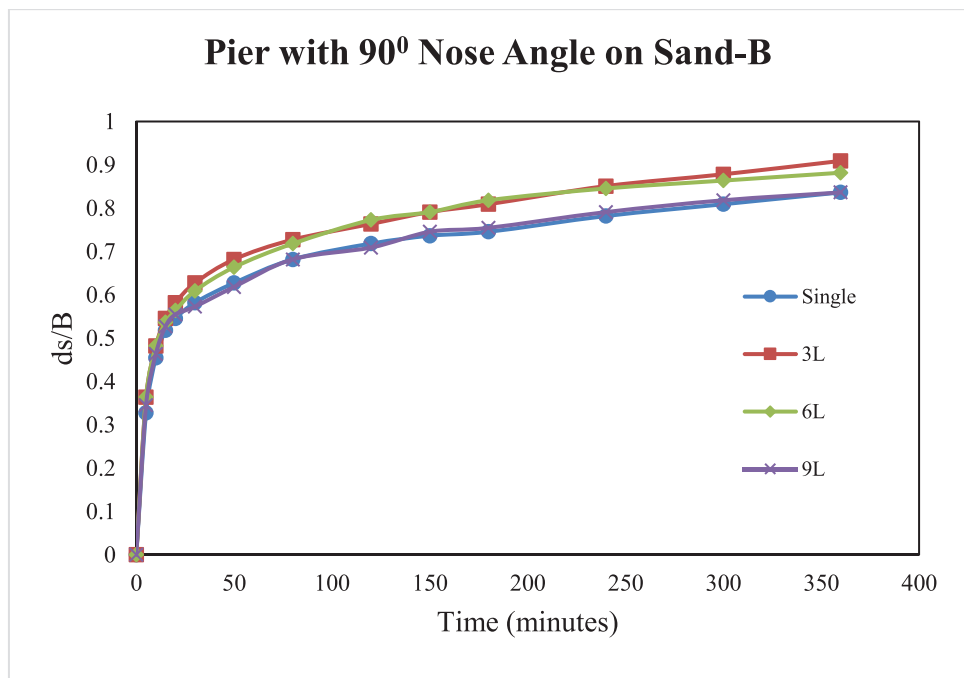


(b)

**Figure J. 1** Temporal development of scour depth around front piers placed at different spacing (a) pier with 60° Nose Angle on Sand-A ( $d_{50}=0.23$  mm) (b) pier with 60° nose angle on Sand-B ( $d_{50}=0.89$  mm).



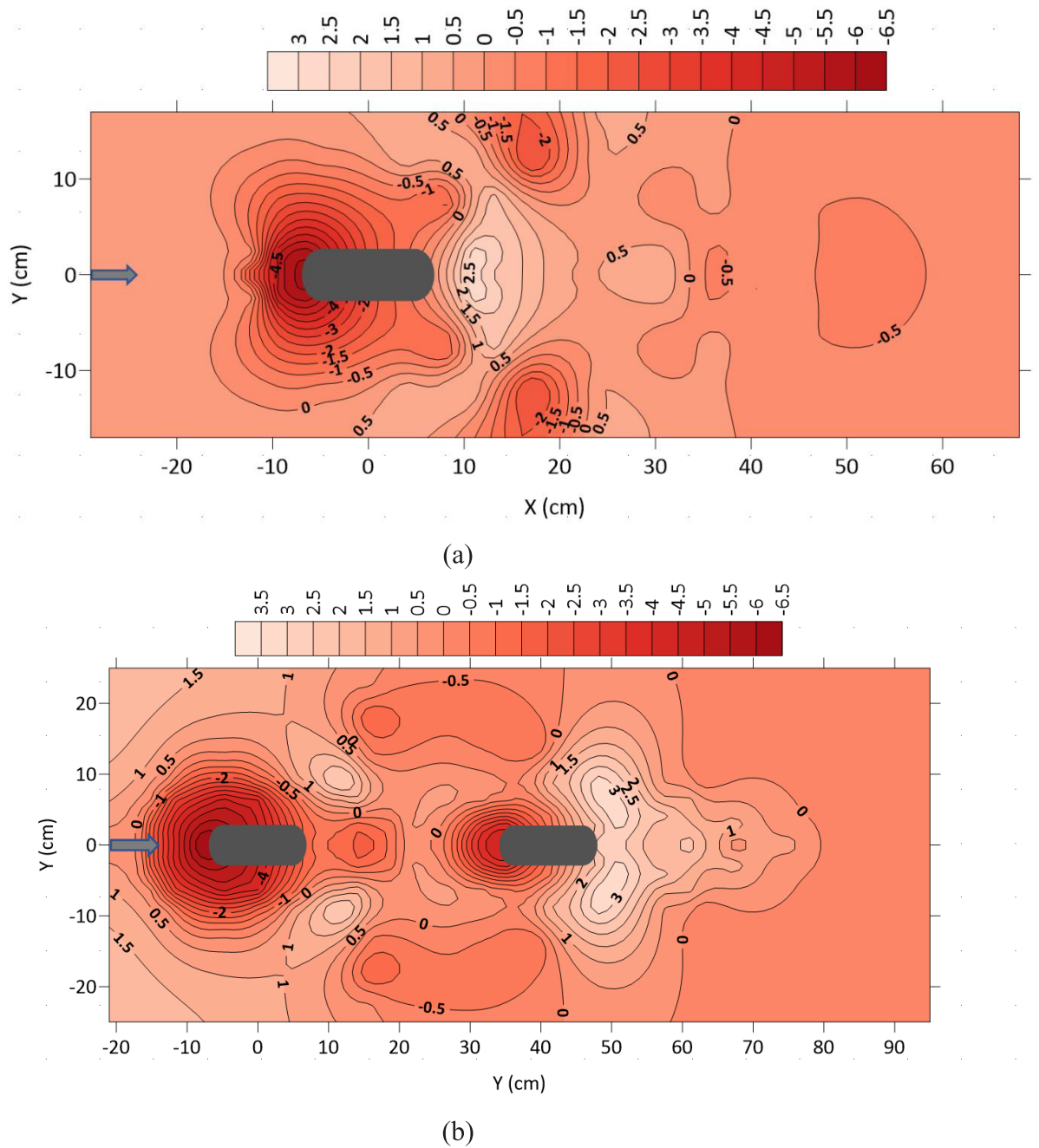
(a)



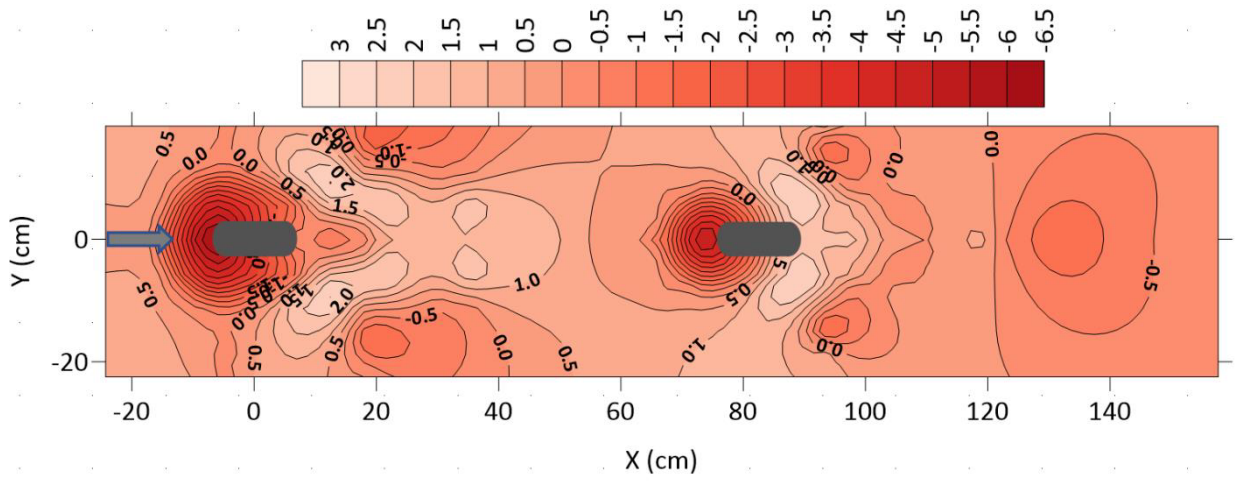
(b)

**Figure J. 2** Temporal development of scour depth around front piers placed at different spacing (a) Pier with 90° Nose Angle on Sand-A ( $d_{50}=0.23$  mm) (b) pier with 60° nose angle on Sand-B ( $d_{50}=0.89$  mm).

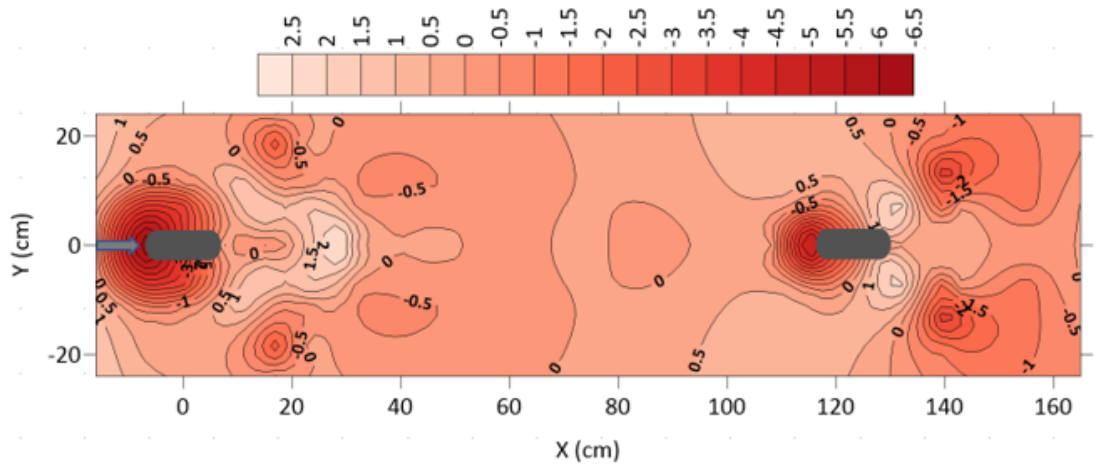
# Appendix-K Contours of Bed Surface Elevation around Single and Tandem Piers in Sand-A and Sand-B



**Figure K. 1** Contours of bed elevation at the end of run around Round Nose pier in Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) Single (b) 3L C/C spacing.

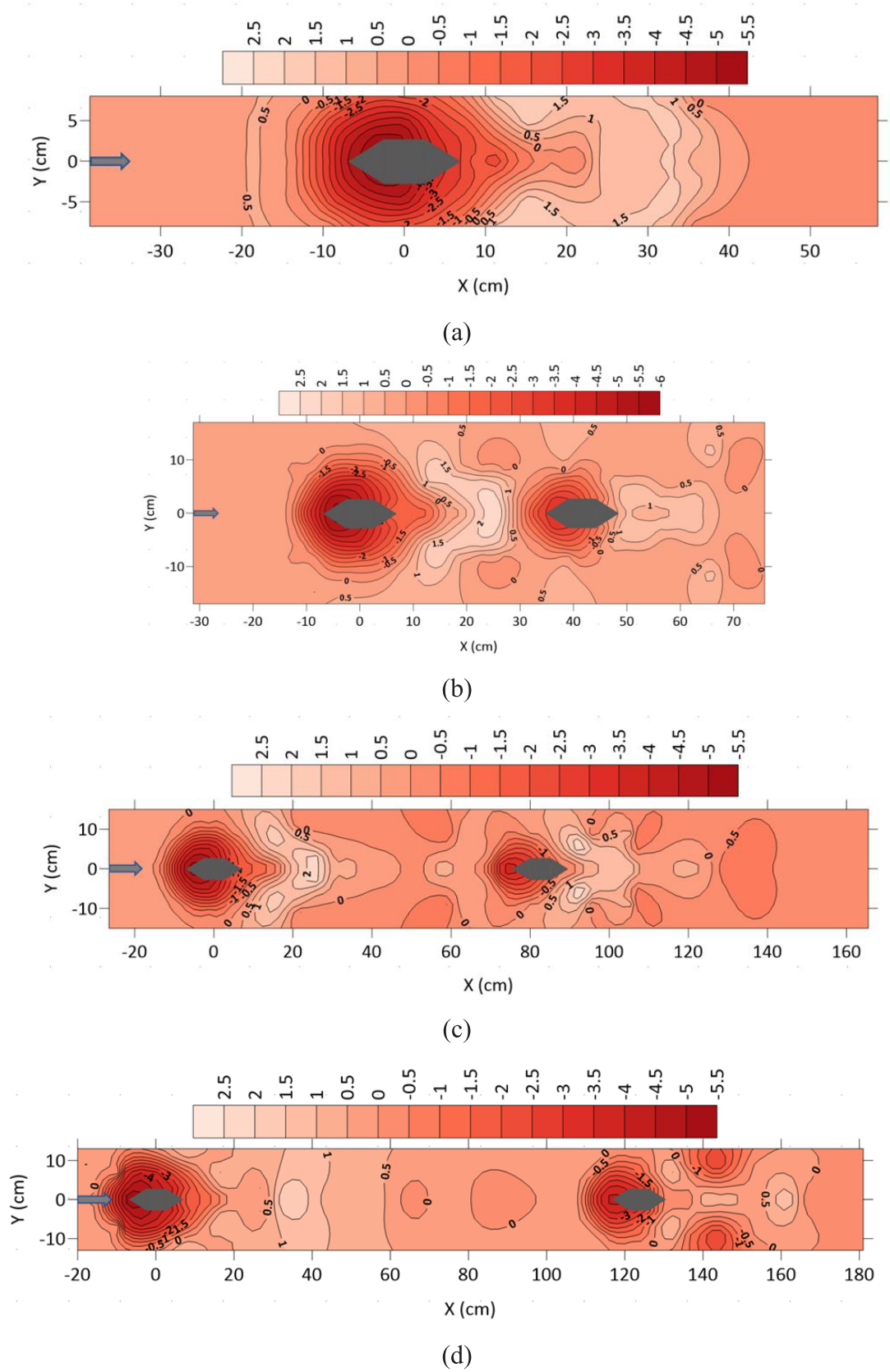


(a)



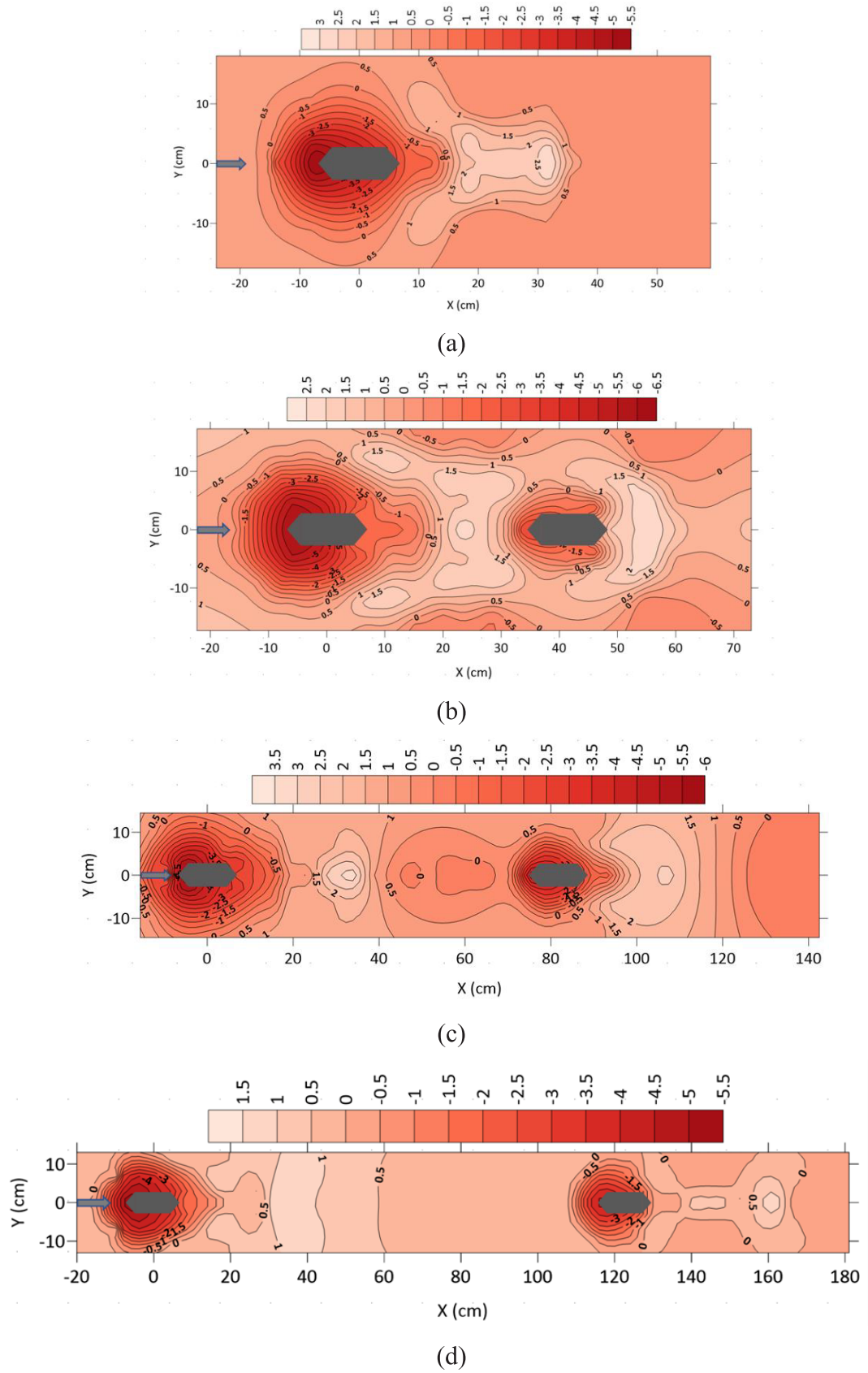
(b)

**Figure K. 2** Contours of bed elevation at the end of run around Round Nose pier in Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) 6L C/C spacing (b) 9L C/C spacing.

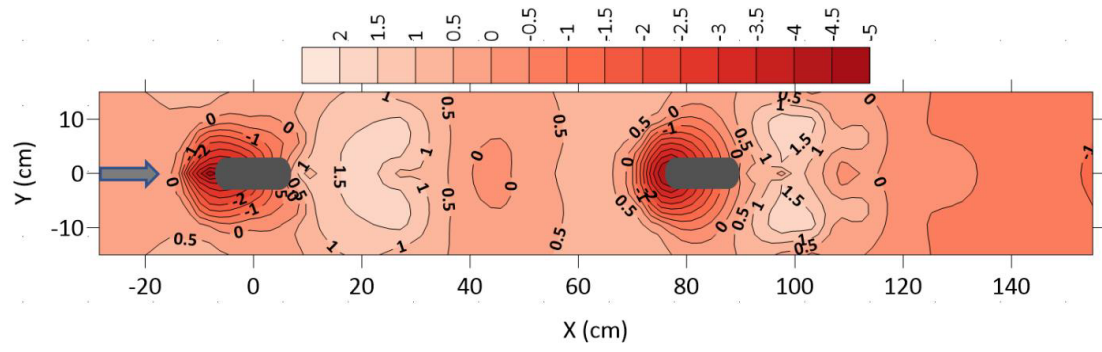


**Figure K. 3** Contours of bed elevation at the end of run around Pier with 60° Nose Angle in Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) Single (b) 3L C/C spacing(c) 6L C/C spacing (d) 9L C/C spacing.

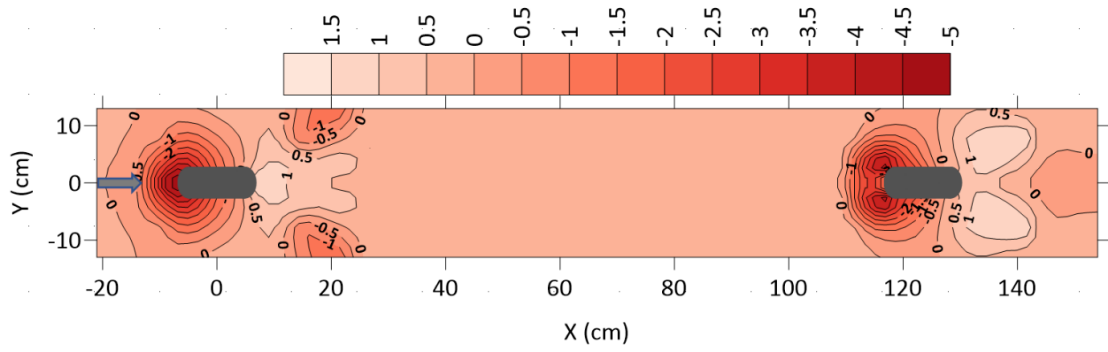




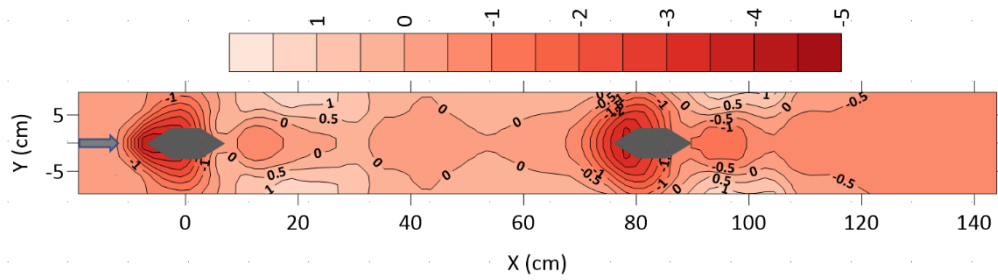
**Figure K. 4** Contours of bed elevation at the end of run around Pier with 90<sup>0</sup> Nose Angle in Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) Single (b) 3L C/C spacing(c) 6L C/C spacing (d) 9L C/C spacing.



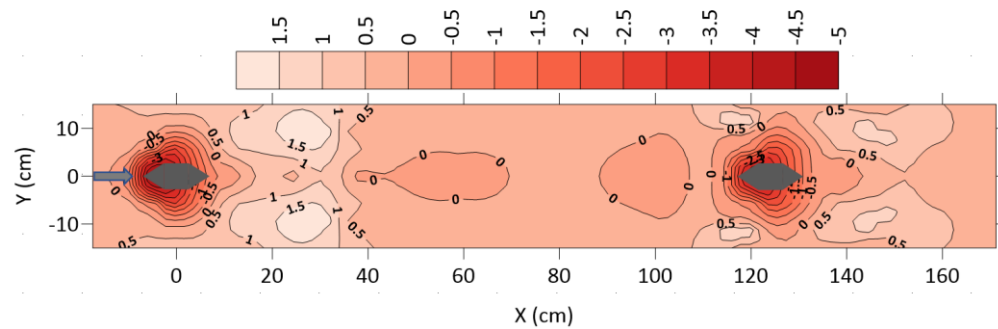
(a)



(b)

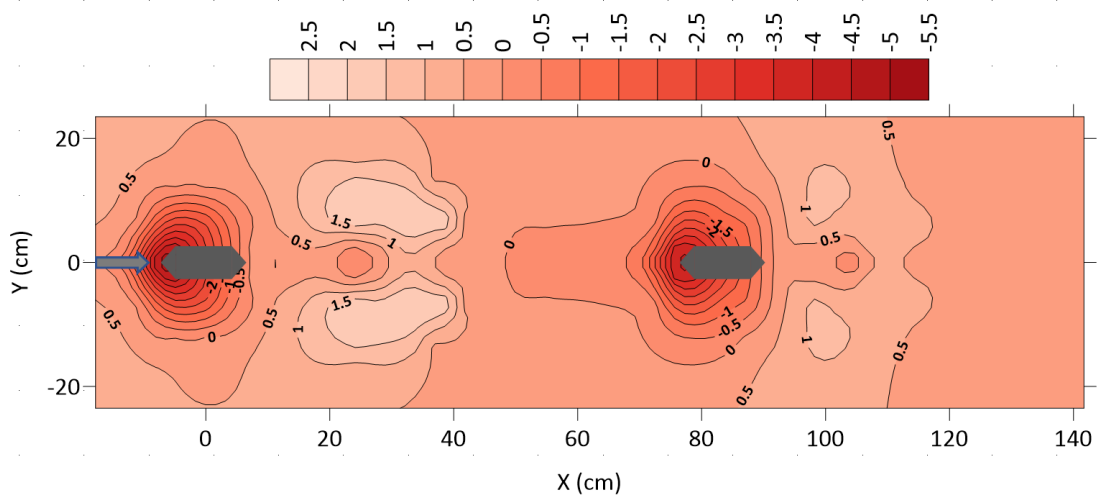


(c)

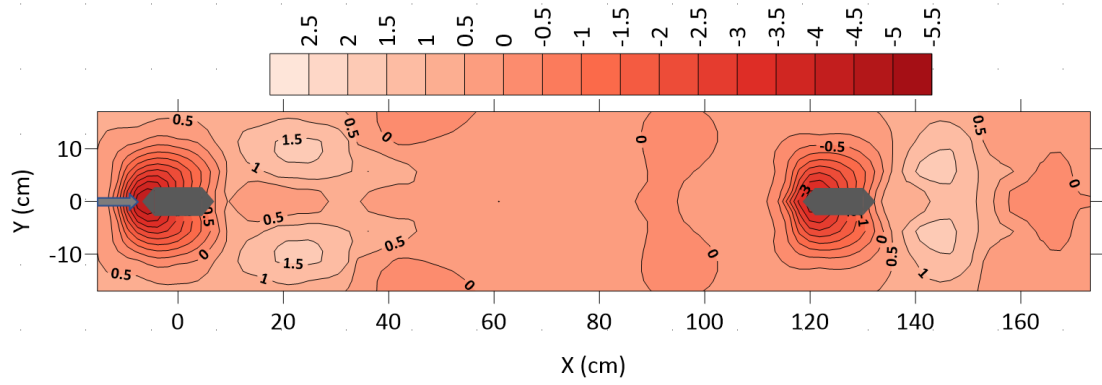


(d)

**Figure K. 5** Contours of bed elevation at the end of run in Sand-B ( $d_{50} = 0.0.89\text{mm}$ ): Round Nose Pier (a) 6L C/C spacing (b) 9L C/C spacing. Pier with  $60^\circ$  Nose Angle (c) 6L C/C spacing (d) 9L C/C spacing.



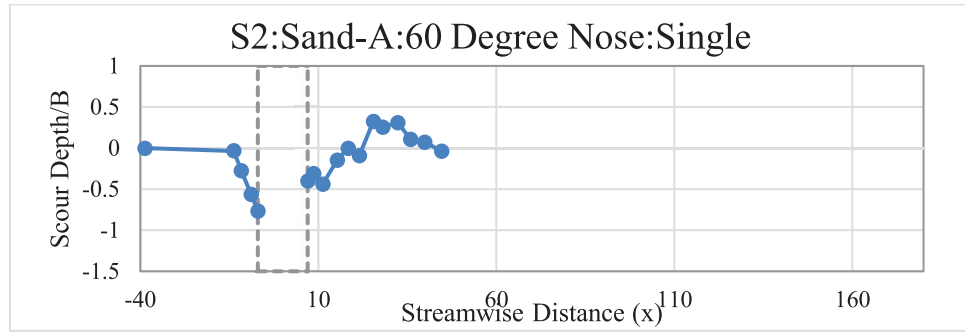
(a)



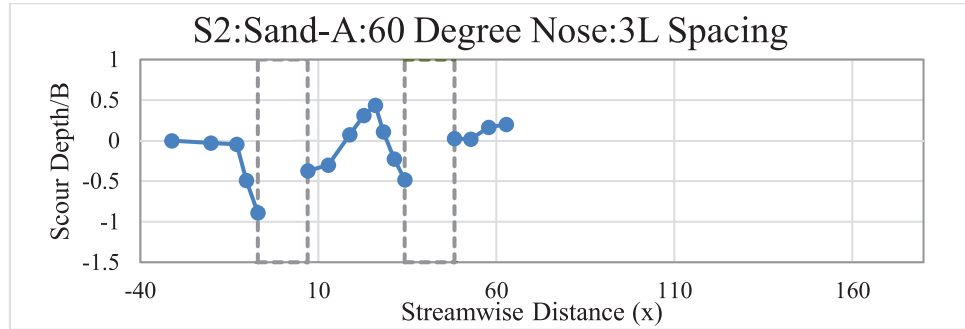
(b)

**Figure K. 6** Contours of bed elevation at the end of run around Pier with 90<sup>0</sup> Nose Angle in Sand-B ( $d_{50} = 0.089\text{mm}$ ): (a) 6L C/C spacing (b) 9L C/C spacing.

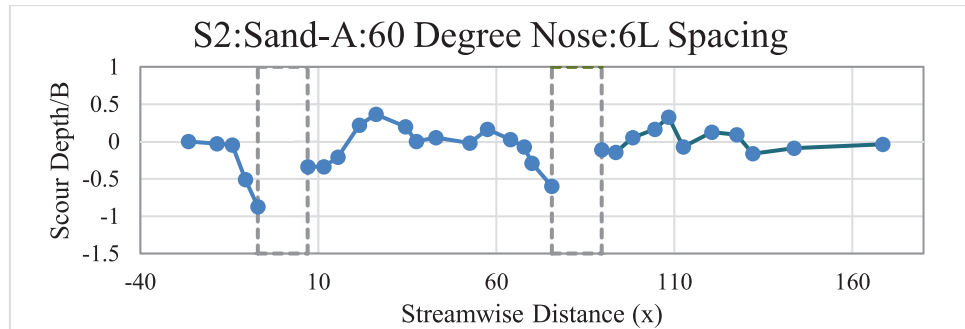
## Appendix-L Scour along Longitudinal Direction in the Centerline of the Flume



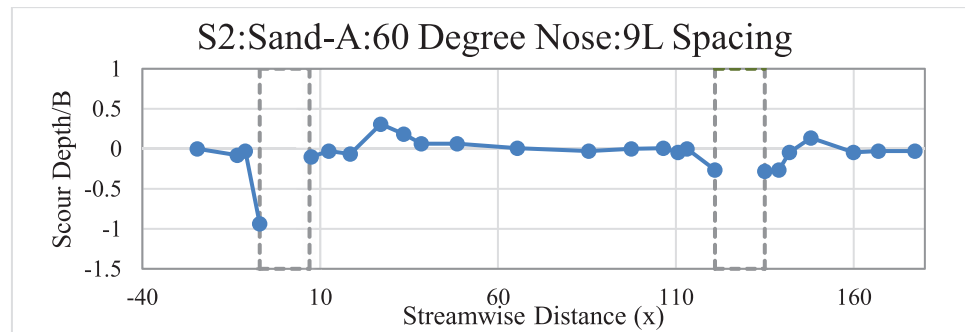
(a)



(b)

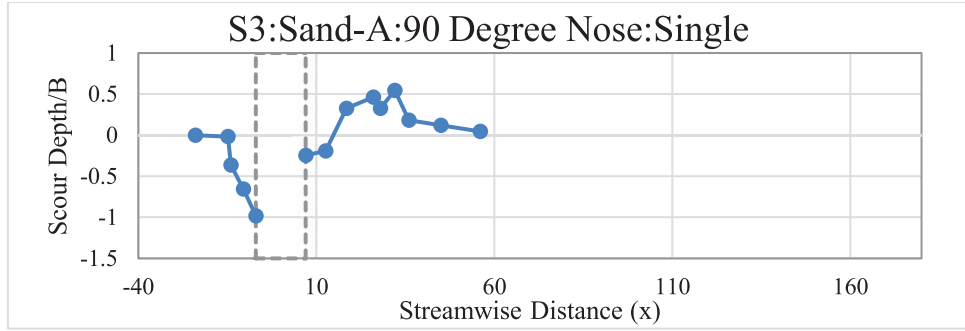


(c)

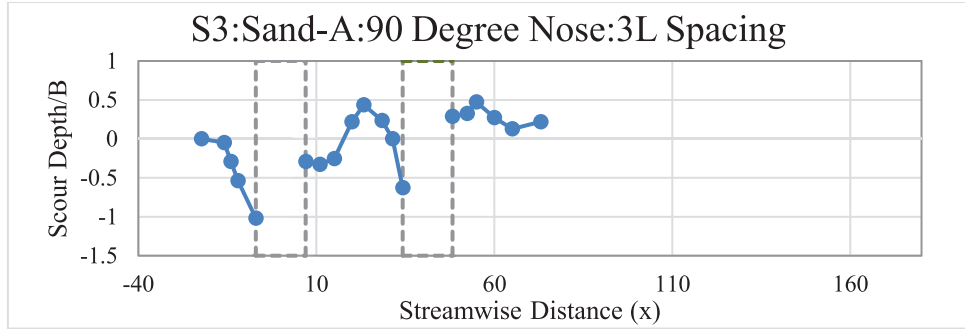


(d)

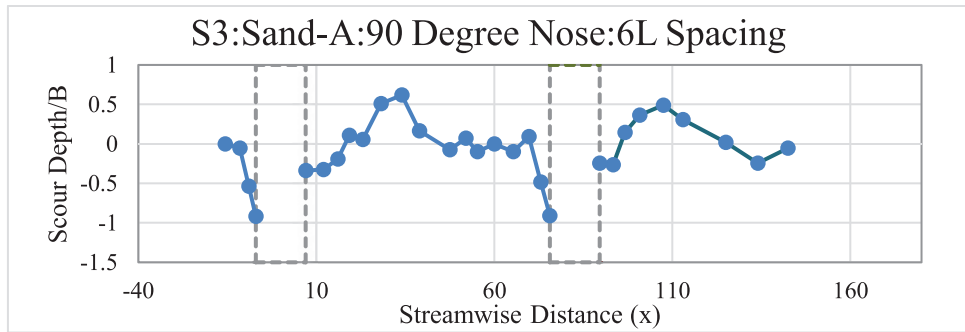
**Figure L. 1** Scour development along longitudinal direction for Pier with 60° Nose Angle on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) Single (b) 3L C/C spacing (c) 6L C/C spacing (d) 9L C/C spacing.



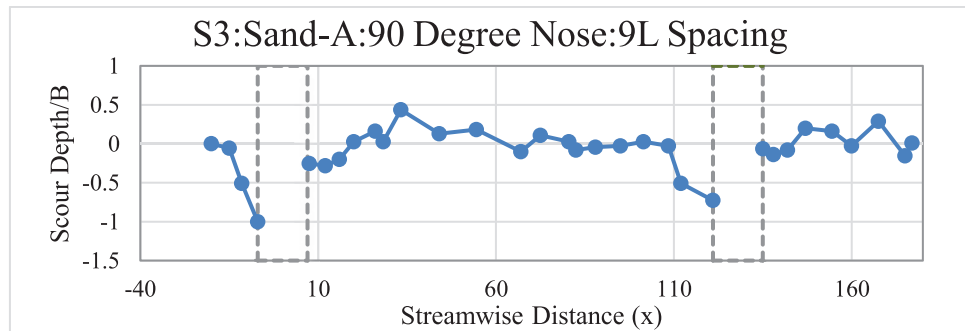
(a)



(b)

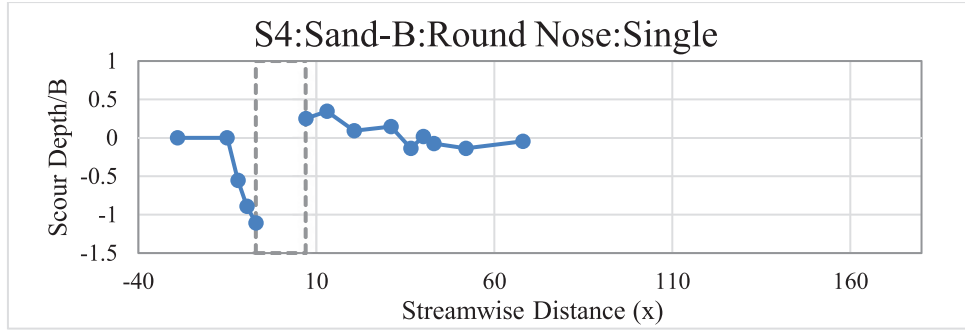


(c)

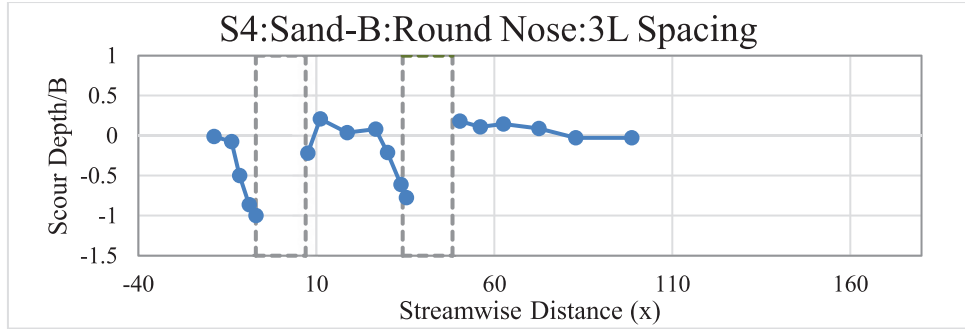


(d)

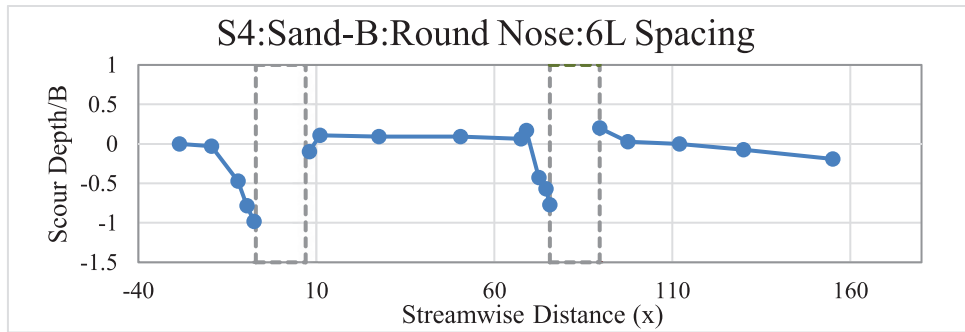
**Figure L. 2** Scour development along longitudinal direction for Pier with 90° Nose Angle on Sand-A ( $d_{50} = 0.23\text{mm}$ ): (a) Single (b) 3L C/C spacing (c) 6L C/C spacing (d) 9L C/C spacing.



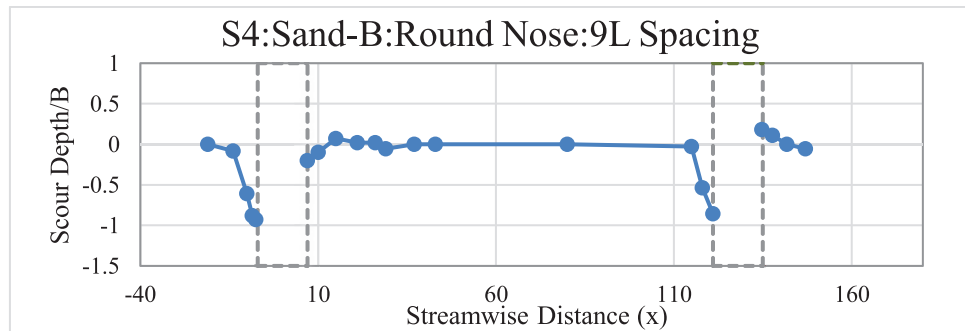
(a)



(b)

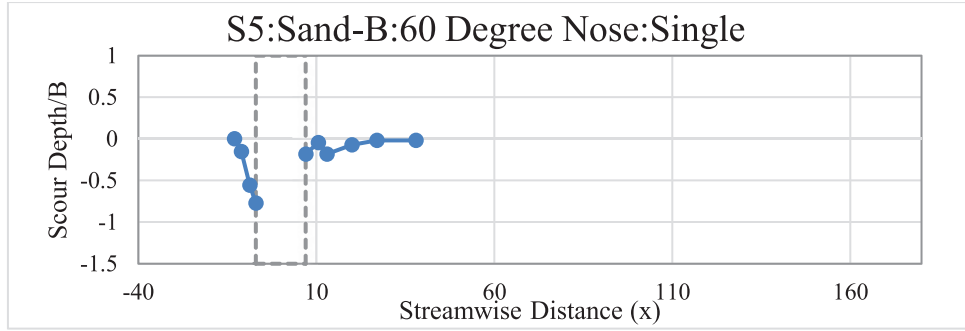


(c)

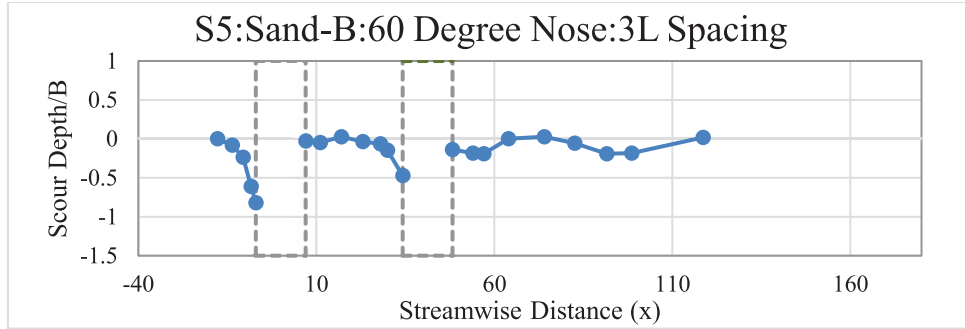


(d)

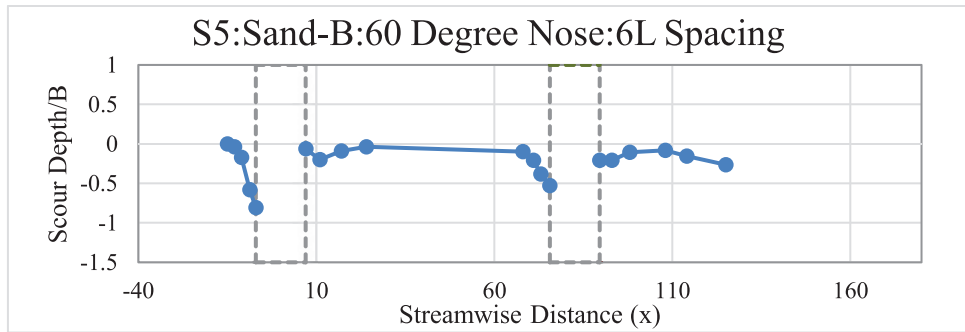
**Figure L. 3** Scour development along longitudinal direction for Round Nose Pier on Sand-B ( $d_{50} = 0.89\text{mm}$ ): (a) Single (b) 3L C/C spacing (c) 6L C/C spacing (d) 9L C/C spacing.



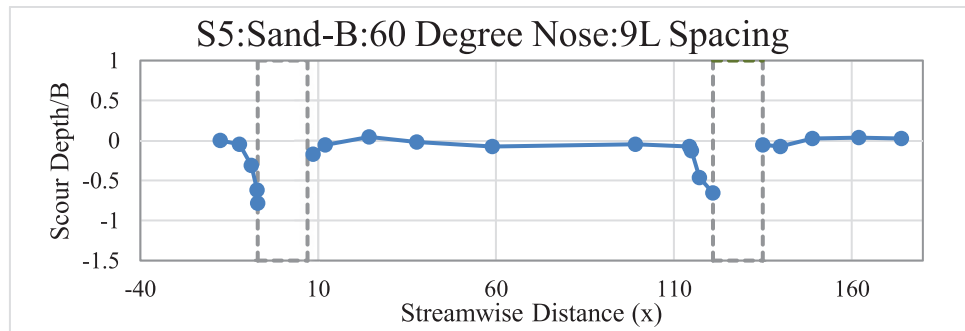
(a)



(b)

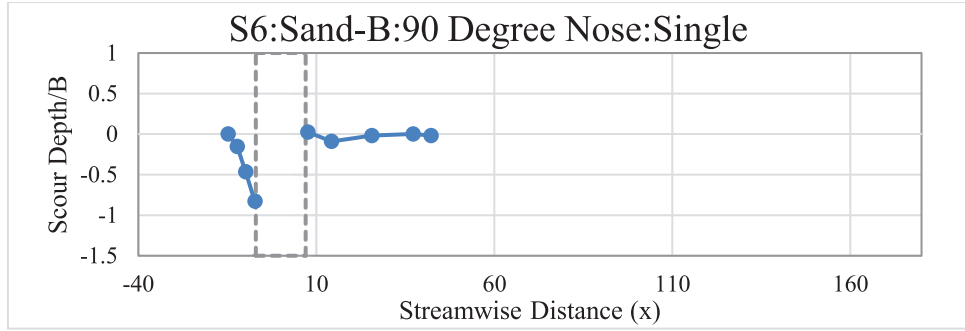


(c)

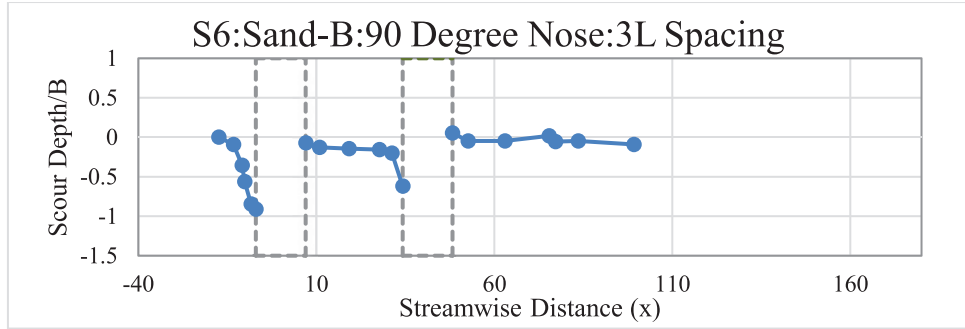


(d)

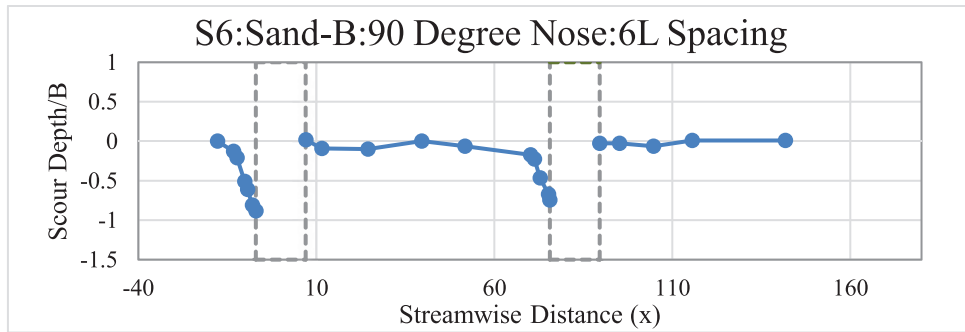
**Figure L. 4** Scour development along longitudinal direction for Pier with 60° Nose Angle on Sand-B ( $d_{50} = 0.89\text{mm}$ ): (a) Single (b) 3L C/C spacing (c) 6L C/C spacing (d) 9L C/C spacing.



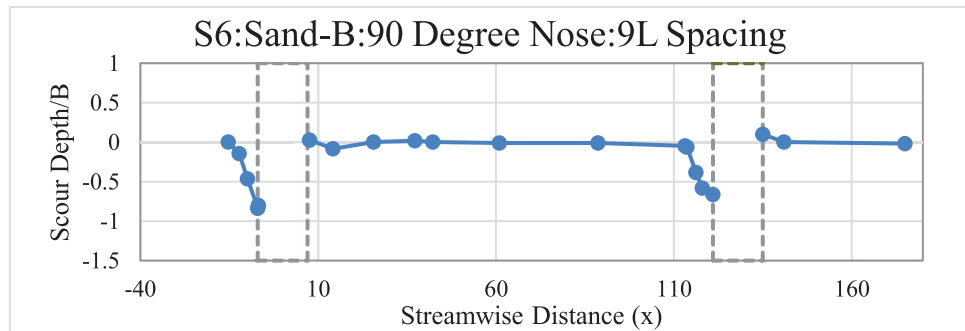
(a)



(b)



(c)

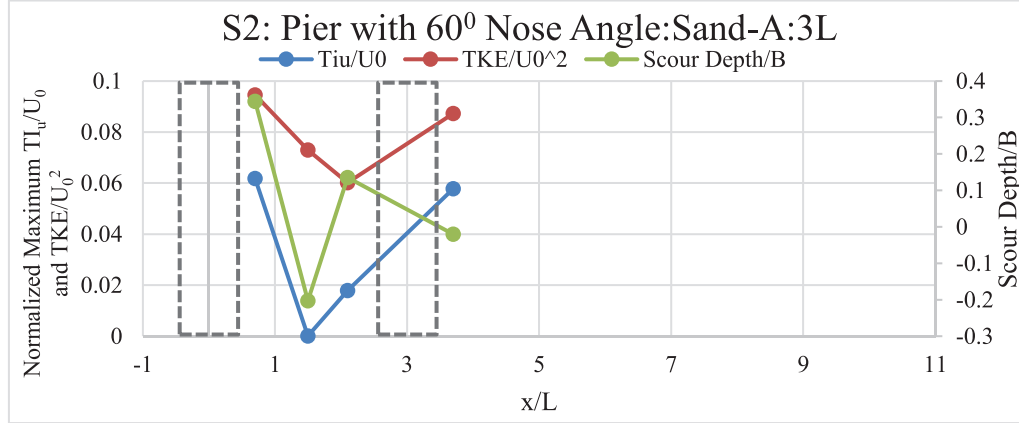


(d)

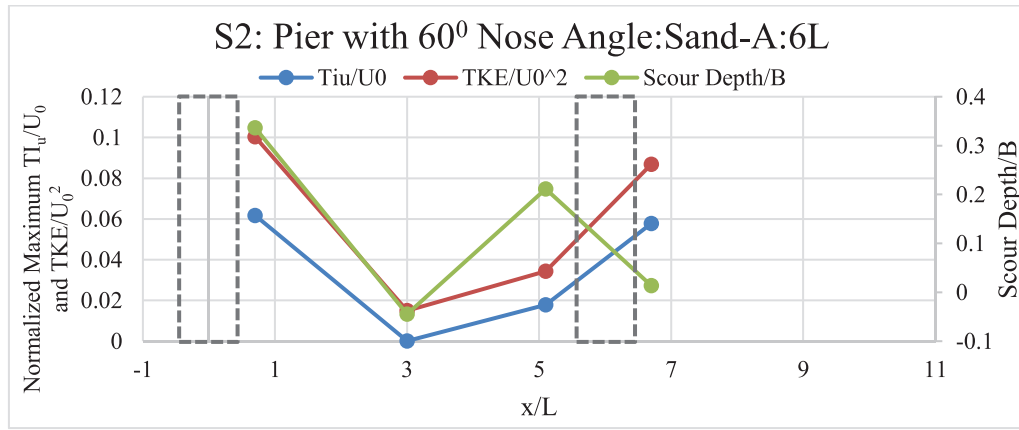
**Figure L. 5** Scour development along longitudinal direction for Pier with 90<sup>0</sup> Nose Angle on Sand-B ( $d_{50} = 0.89\text{mm}$ ): (a) Single (b) 3L C/C spacing (c) 6L C/C spacing (d) 9L C/C spacing.



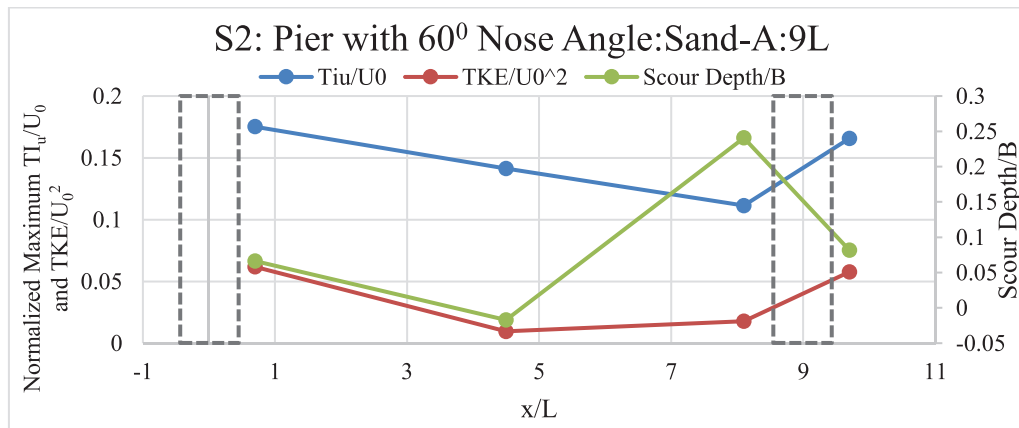
# Appendix-M Variation of Maximum Turbulence Intensity and Turbulent Kinetic Energy along with Scour Depth in the Plane of Symmetry (POS)



(a)

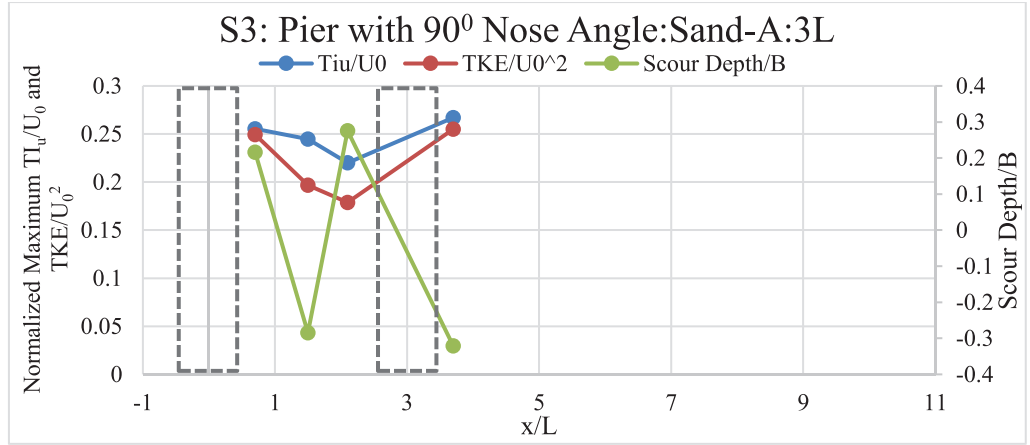


(b)

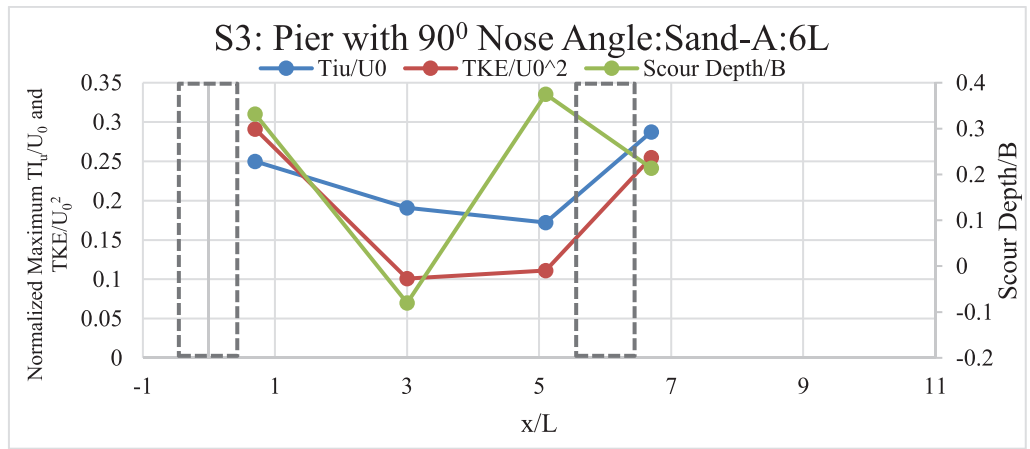


(c)

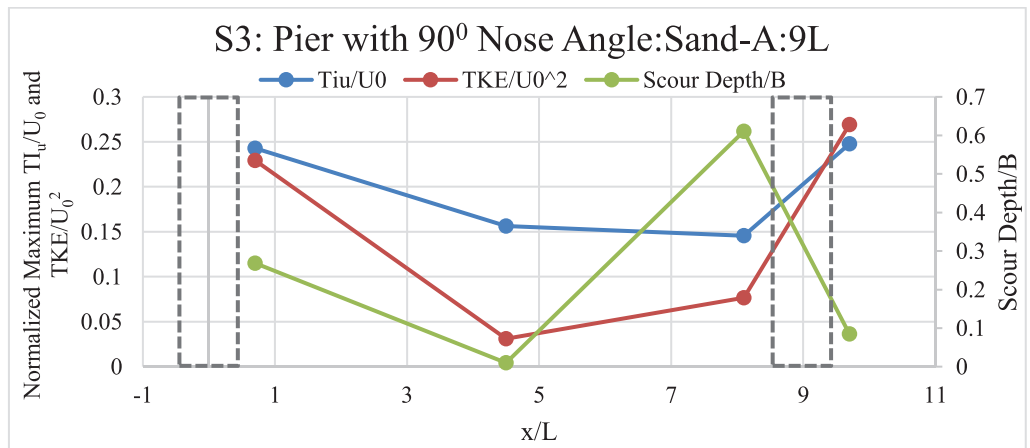
**Figure M. 1** Variation of normalized maximum turbulence intensity and turbulent kinetic energy along with scour depth in the plane of symmetry in Sand-A ( $d_{50} = 0.23\text{mm}$ ) for Pier with 60° Nose Angle: (a) 3L(b) 6L (c) 9L.



(a)

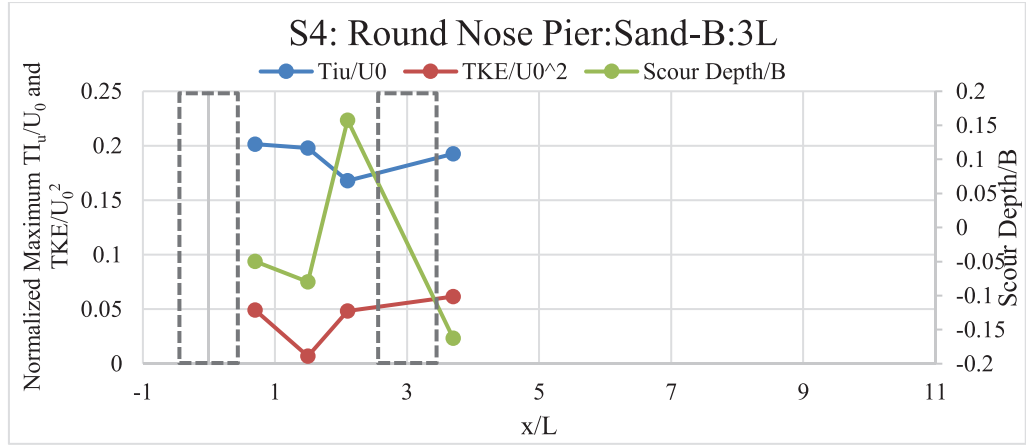


(b)

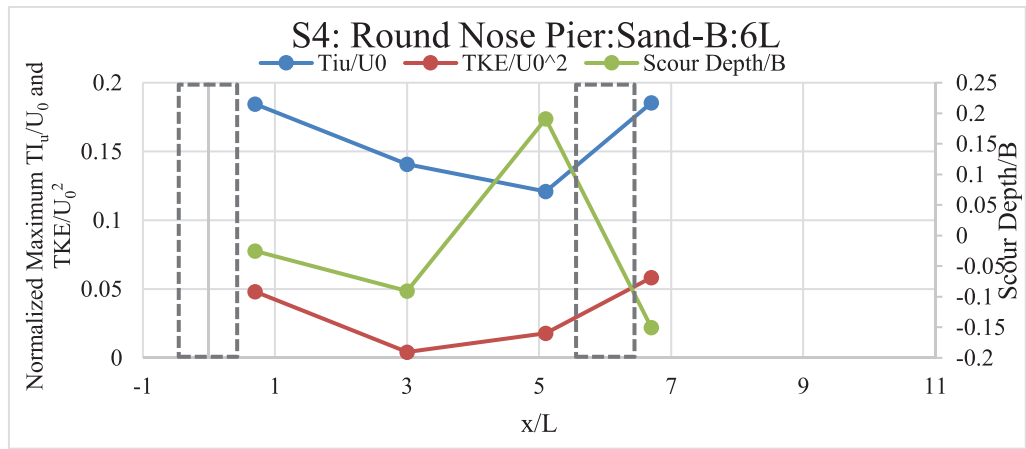


(c)

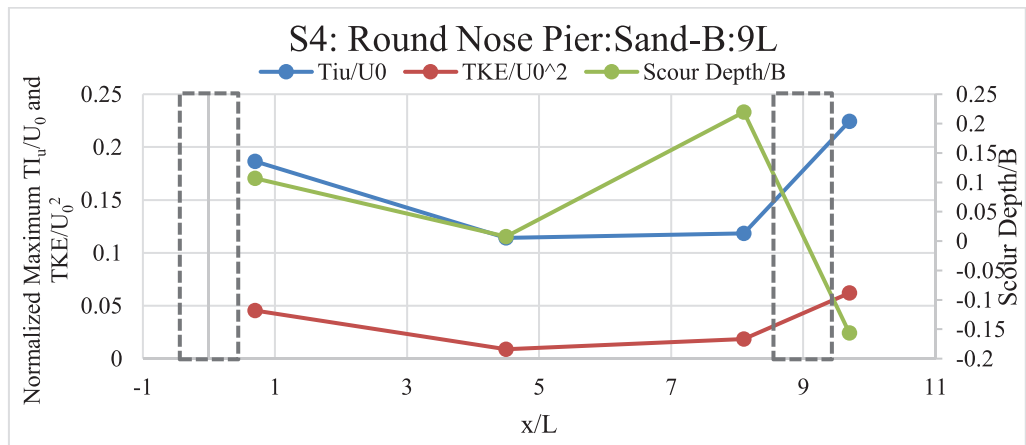
**Figure M. 2** Variation of normalized maximum turbulence intensity and turbulent kinetic energy along with scour depth in the plane of symmetry in Sand-A ( $d_{50} = 0.23\text{mm}$ ) for Pier with 90° Nose Angle: (a) 3L(b) 6L (c) 9L.



(a)

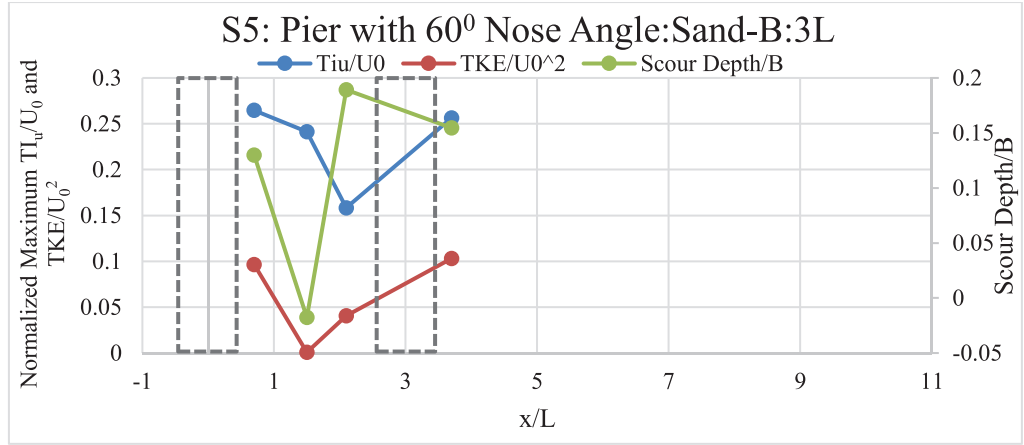


(b)

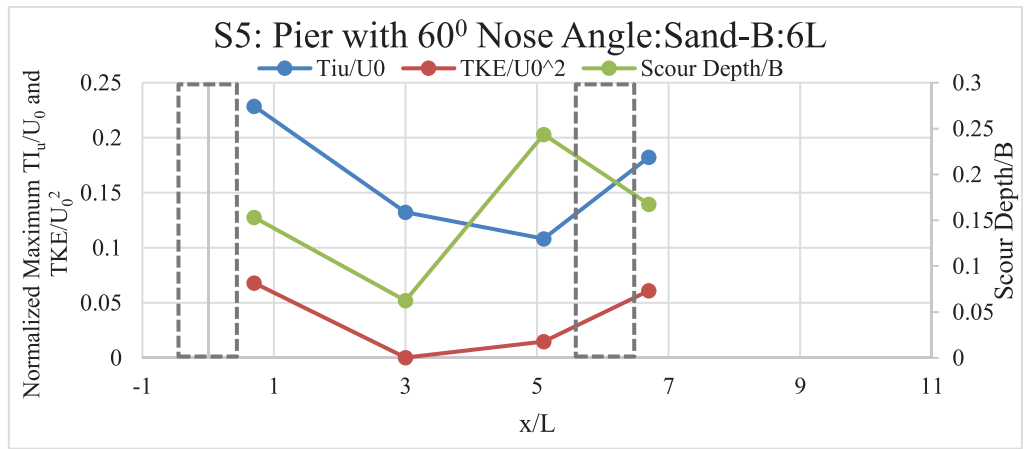


(c)

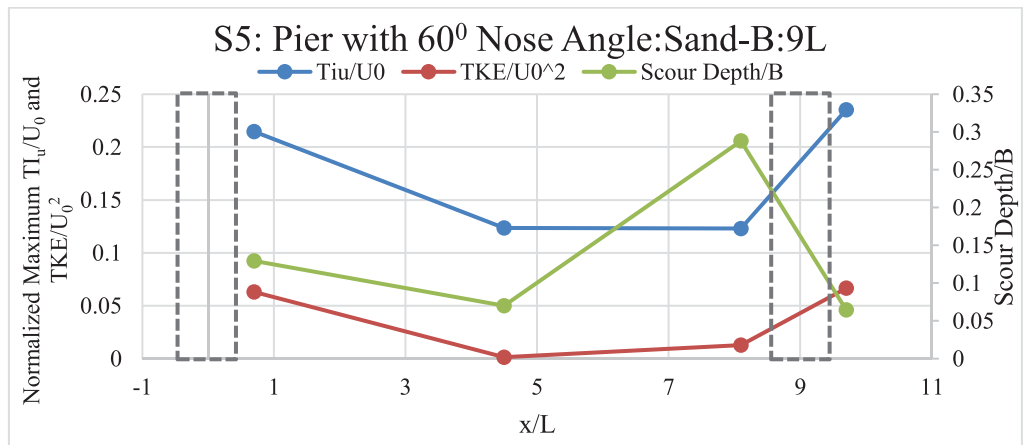
**Figure M.3** Variation of normalized maximum turbulence intensity and turbulent kinetic energy along with scour depth in the plane of symmetry in Sand-B ( $d_{50} = 0.89\text{mm}$ ) for Round Nose Pier: (a) 3L(b) 6L (c) 9L.



(a)

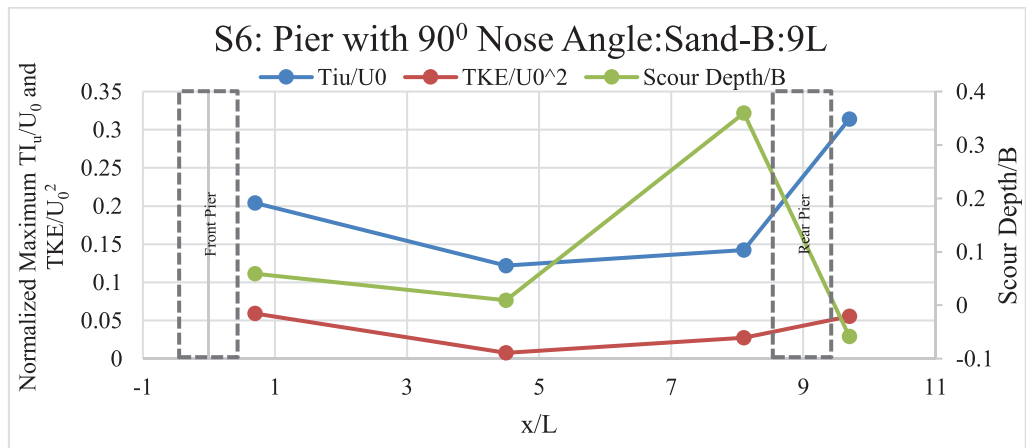
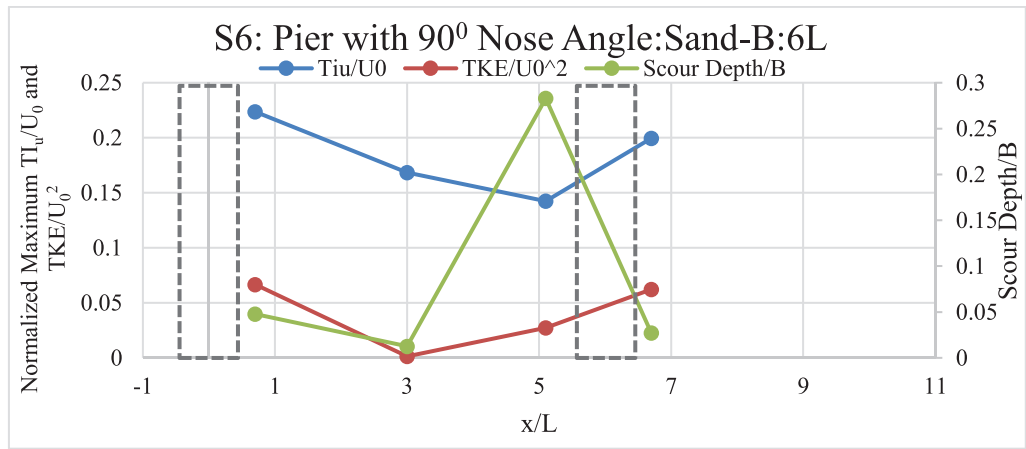
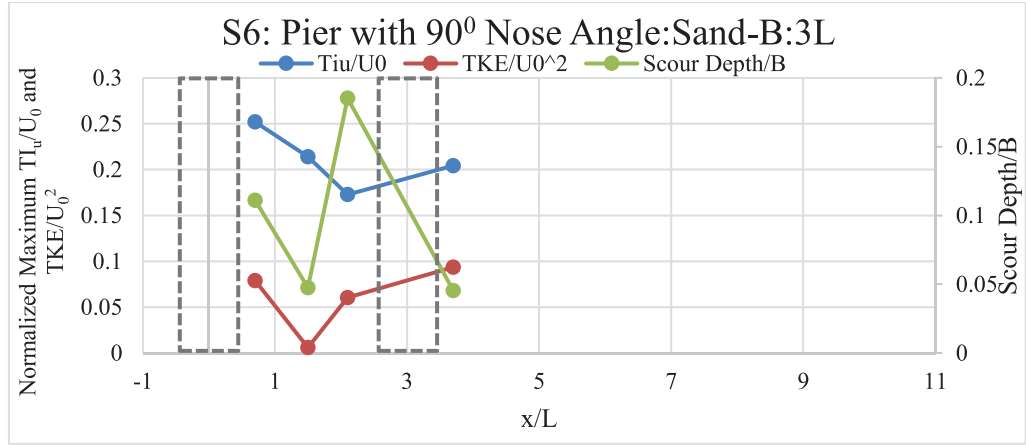


(b)



(c)

**Figure M.4** Variation of normalized maximum turbulence intensity and turbulent kinetic energy along with scour depth in the plane of symmetry in Sand-B ( $d_{50} = 0.89\text{mm}$ ) for Pier with 60° Nose Angle: (a) 3L (b) 6L (c) 9L.



**Figure M.5** Variation of normalized maximum turbulence intensity and turbulent kinetic energy along with scour depth in the plane of symmetry in Sand-B ( $d_{50} = 0.89\text{mm}$ ) for Pier with 90° Nose Angle: (a) 3L(b) 6L (c) 9L.