SAND BED MORPHODYNAMICS UNDER WATER WAVES AND VEGETATED CONDITIONS

BY

BLAKE J. LANDRY

DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

Doctoral Committee:

Professor Marcelo H. García, Chair
Professor James Best
Dr. Joseph Calantoni
Professor Gary Parker
ABSTRACT

The littoral zone plays an integral role in the success of today’s thriving society, providing a stable food supply as well as points of trade/transport for goods around the world. Key environmental processes in this region such as sediment transport, wave attenuation, and boundary layer development are directly governed by the presence of bathymetric features, which include large-scale sand bars upon which smaller-scale sand ripples are superimposed, as well as the presence of submarine vegetation. As a result, understanding the complex interaction among these features is imperative to determining coastline morphological changes and protecting coastal zones and society as a whole due to our strong dependence on the region.

The experimental large-scale laboratory work presented herein provides new insight into the complex sediment dynamics within this region. Specifically, this study explores the impact of spatial variability in the wave envelope on bed evolution, sand ripple geometric characteristics, and migration velocities as well as effects that vegetation imparts on the sediment dynamics. Key results of the study show that it is of the utmost importance to fully resolve the wave conditions along the entire domain of a facility to understand local morphodynamics. The study reports that mild wave reflections of 20% can generate 55% variability in the small-scale bedform geometries. Analysis of high-resolution temporal and spatial bathymetry measurements shows that ripple velocities under partially progressive waves are related to the local near-bed Lagrangian mass transport velocities within the bottom boundary layer.

Additional laboratory experiments with near-deeply submerged vegetated canopies (current work has a ratio of mean still water depth to plant height, $H_p/h_p = 7.9$) using idealized vegetation (6.35-mm diameter rigid wooden cylinders) beneath standing water waves provide evidence that significant modifications in bathymetry can result without vegetation directly attenuat-
ing the surface waves. While the introduction of vegetation decreases the bar
growth rate, the final equilibrium bar height can be increased due to local-
ization of flow velocities within the intra-canopy (i.e., enhanced streaming).
In vegetated conditions with high lateral density (i.e., one plant diameter on-
center), bar crests formed near wave antinodes rather than under wave nodes,
which is indicative of a change in the dominant mode of sediment transport
from bedload to suspended load. Ultimately, the study demonstrates that
bottom roughness can be controlled with the help of vegetation to provide a
sustainable means of altering sediment transport, adding valuable insight to
aid in coastal erosion mitigation efforts.
To my wife and parents, for their love and support of the philosophy “per sapientiam felicitas,” I will be forever grateful.
ACKNOWLEDGMENTS

I would like to express deep gratitude to my advisor, Professor Marcelo García for his continued support, guidance, and availability, despite his persistently busy and demanding schedule. Also, I would like to thank my committee members: Professor James Best, Dr. Joseph Calantoni, and Professor Gary Parker for all their valuable discussions, comments, and suggestions.

I would like to thank the numerous undergraduate research assistants, specifically Kevin Bane, Gerald Kujawa, Fangzhou “Albert” Liu, and Brett Zitny for their unwavering dedication along with physical and mental energy during the countless hours they aided in preparing and conducting experiments as well as assisting in processing the plethora of data that was generated. Also, I would like to thank James Palmer III for insight in helping with various electronic issues and design of the directional trigger.

I would like to acknowledge funding from the Office of Naval Research, Grant Numbers: N00014-08-1-0421, N00014-01-1-0540 (DURIP), and N00014-06-1-0661 (DURIP).

On a personal note, I would like to thank all my officemates/colleagues over the years: Javier Ancalle, Yovanni Catano, Jose Mier, Ezequiel Martin, Nils Oberg, Francisco Pedocchi, Octavio Sequeiros, Andrew Waratuke, and David Waterman, for their valuable professional comments as well as their friendship. Finally, my sincere gratitude goes to my mother and grandmother for their enduring support and encouragement throughout all my pursuits, both academic and non-academic. Finally, I would like to thank my wife for being a true companion through this incredible journey even down to the point of spending many a late night assisting with various experimental measurements. Together we can truly appreciate the philosophy “per sapientiam felicitas” - “through knowledge, happiness”.

v
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2</td>
<td>Introduction</td>
<td>76</td>
</tr>
<tr>
<td>6.3</td>
<td>Experimental Dataset</td>
<td>77</td>
</tr>
<tr>
<td>6.4</td>
<td>Dataset Analysis</td>
<td>78</td>
</tr>
<tr>
<td>6.5</td>
<td>Measured Ripple Geometric Characteristics</td>
<td>80</td>
</tr>
<tr>
<td><strong>CHAPTER 7</strong></td>
<td>EFFECT OF WATER WAVE ENVELOPE VARIATION ON SAND RIPPLE MIGRATIONS</td>
<td>88</td>
</tr>
<tr>
<td>7.1</td>
<td>Abstract</td>
<td>88</td>
</tr>
<tr>
<td>7.2</td>
<td>Introduction</td>
<td>89</td>
</tr>
<tr>
<td>7.3</td>
<td>Experimental Dataset</td>
<td>90</td>
</tr>
<tr>
<td>7.4</td>
<td>Data Analysis of the Dataset</td>
<td>94</td>
</tr>
<tr>
<td>7.5</td>
<td>Results</td>
<td>96</td>
</tr>
<tr>
<td>7.6</td>
<td>Discussion</td>
<td>103</td>
</tr>
<tr>
<td>7.7</td>
<td>Conclusion</td>
<td>113</td>
</tr>
<tr>
<td><strong>CHAPTER 8</strong></td>
<td>EFFECTS OF VEGETATION ON SAND BAR FORMATION</td>
<td>115</td>
</tr>
<tr>
<td>8.1</td>
<td>Abstract</td>
<td>115</td>
</tr>
<tr>
<td>8.2</td>
<td>Introduction</td>
<td>116</td>
</tr>
<tr>
<td>8.3</td>
<td>Experimental Details</td>
<td>119</td>
</tr>
<tr>
<td>8.4</td>
<td>Results</td>
<td>127</td>
</tr>
<tr>
<td>8.5</td>
<td>Discussion</td>
<td>133</td>
</tr>
<tr>
<td>8.6</td>
<td>Conclusion</td>
<td>140</td>
</tr>
<tr>
<td><strong>CHAPTER 9</strong></td>
<td>CONCLUSIONS AND FUTURE WORK</td>
<td>143</td>
</tr>
<tr>
<td>9.1</td>
<td>Summary of Main Results</td>
<td>143</td>
</tr>
<tr>
<td>9.2</td>
<td>Technical Contributions</td>
<td>145</td>
</tr>
<tr>
<td>9.3</td>
<td>Future Work</td>
<td>146</td>
</tr>
<tr>
<td><strong>APPENDIX A</strong></td>
<td>DIRECTION SENSING TRIGGERING SYSTEM (DSTS) CIRCUIT DESIGN</td>
<td>148</td>
</tr>
<tr>
<td><strong>APPENDIX B</strong></td>
<td>DIRECTIONS FOR PROCESSING BAR IMAGES</td>
<td>151</td>
</tr>
<tr>
<td><strong>APPENDIX C</strong></td>
<td>WAVE AND RIPPLE VELOCITY PLOTS</td>
<td>154</td>
</tr>
<tr>
<td><strong>APPENDIX D</strong></td>
<td>EFFECTS OF VEGETATION ON BAR GROWTH</td>
<td>239</td>
</tr>
<tr>
<td>D.1</td>
<td>Tank Conditions</td>
<td>239</td>
</tr>
<tr>
<td>D.2</td>
<td>Bar Evolution Stacks</td>
<td>245</td>
</tr>
<tr>
<td>D.3</td>
<td>Laser Bathymetry Scans of Final Bedforms</td>
<td>251</td>
</tr>
<tr>
<td><strong>REFERENCES</strong></td>
<td></td>
<td>261</td>
</tr>
<tr>
<td><strong>AUTHOR’S BIOGRAPHY</strong></td>
<td></td>
<td>270</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Fitting results from WaveAR for wave measurements displayed in Figure 5.5.</td>
<td>72</td>
</tr>
<tr>
<td>7.1</td>
<td>Summary of experimental data for ripple migration velocities.</td>
<td>92</td>
</tr>
<tr>
<td>8.1</td>
<td>Configuration of vegetation at each bar for a specified experiment.</td>
<td>124</td>
</tr>
<tr>
<td>8.2</td>
<td>Resulting parameters for vegetation experiments.</td>
<td>127</td>
</tr>
<tr>
<td>8.3</td>
<td>Relative growth heights ratios computed at 27 hrs and final asymptotic height limit of fits.</td>
<td>133</td>
</tr>
<tr>
<td>D.1</td>
<td>Additional conditions for vegetation experiments.</td>
<td>240</td>
</tr>
<tr>
<td>D.2</td>
<td>Results of the first harmonic amplitudes (via WaveAR code) for the first nine 3-hr blocks of the experiments (e.g., up to 27 hrs). Refer to Chapter 5 for details of the code.</td>
<td>241</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

1.1 Typical beach profile diagram which highlights the presence of various coastal features and zones .................. 2  
1.2 One of the earliest documented laboratory experimental observations on the sand ripple and mounds (i.e., bar) formations 3  

2.1 Schematic of the water wave problem .......................... 9  
2.2 Depiction of water particle velocities under (a) progressive wave and (b) standing wave and absolute value of free surface displacement abs(\(\eta\)) for (c) progressive waves and (d) standing waves. ................................................................. 13  
2.3 Particle trajectories under waves of various reflection coefficients ................................................................. 15  
2.4 Resulting bathymetry profiles for sand beds composed of various sediment sizes .................................................. 17  
2.5 Schematic of regions within the water column under waves 18  
2.6 Diagram of mass transport velocities under standing waves ................................................................. 20  
2.7 Type of bed response as function of \(u_n/w\) ................................................................. 21  
2.8 Effect of the presence of a free second harmonic on the wave envelope of a laboratory experiment ................. 24  

3.1 Wave flume facility in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign 26  
3.2 Measured distribution of sediment size for sand used in the wave flume facility .................................................. 28  
3.3 Perspective views of wooden vertical wall used as beach to generate full reflection within the tank ......................... 30  
3.4 General Acoustics UltraLab® ULS system shown with only one attached ultrasound sensor ................................................. 31  
3.5 Wave signal acquisition system ................................................................. 32  
3.6 ADV schematic depicting the typical probe tip configuration of the transmitting and receiving emitters and resulting sampling volume .................................................. 34  
3.7 Photographs of the DSTS prototype ................................................................. 35  
3.8 Schematic of the wave and velocity synchronization system ................................................................. 36  
3.9 Illustration of the SeaTek system ................................................................. 38  
3.10 Photograph of the Keyence laser displacement system ................................................................. 39
3.11 Comparison of measured bathymetry data via two systems . . 40
3.12 Illustration of setup for side camera used to produce evolutionary-
bathymetric profiles of the sand bed . . . . . . . . . . . . . . . . 41
3.13 Typical image acquired from the Canon 20D DSLR camera . . 42
3.14 Sample images from the Logitech® cameras . . . . . . . . . 44

4.1 Graphical user interface of the custom MATLAB® pro-
gram (WaveAR) used to fit wave parameters . . . . . . . . . . . 51
4.2 Results of circular Hough transform from MATLAB® . . . . 54
4.3 Results of detailed evolution images . . . . . . . . . . . . . . . 55
4.4 Typical resulting panoramic image. . . . . . . . . . . . . . . . 58

5.1 Main user interface for the WaveAR program . . . . . . . . . 66
5.2 Dynamic graph associated with WaveAR . . . . . . . . . . . 67
5.3 An example of the program results for the recommended
sampling frequency to implement based on constraints as-
associated with (5.11) . . . . . . . . . . . . . . . . . . . . . . . 69
5.4 Graphical user interface for the Virtualizer companion pro-
gram, which generates analytical datasets for testing the
main WaveAR program. . . . . . . . . . . . . . . . . . . . . . . . 70
5.5 Example of typical wave profile measurements sampled at
specified times throughout the experiment (Landry, 2004). . . 71
5.6 Harmonic amplitude plot prior to free second harmonic
cancellation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 74
5.7 Harmonic amplitude plot after the free second harmonic
has been canceled . . . . . . . . . . . . . . . . . . . . . . . . . . 74

6.1 Illustration of computation of ripple geometric characteris-
tics in regards to a single ripple after filtering out the mean
bed elevation. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 80
6.2 Analysis of ripple geometries under high reflection (R =
0.88) experimental conditions. . . . . . . . . . . . . . . . . . . . . 86
6.3 Analysis of ripple geometries under low reflection (R =
0.24) experimental conditions. . . . . . . . . . . . . . . . . . . . 87

7.1 Flow diagram for processing ripple migration velocities. . . . 95
7.2 Representative wave and bed information for the entire
tank for experiment 324 acquired at a time near subse-
lected ripple camera times. . . . . . . . . . . . . . . . . . . . . . 97
7.3 Illustration of complete timestack for experiment 324. . . . . 99
7.4 Illustration of complete ripple velocity contour map for ex-
periment 324. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 100
7.5 Illustration of experiment 324 ripple velocity contour map
for selected subset (t = 2.49 to 2.91 hrs). . . . . . . . . . . . . 101
A.1 Latch circuit diagram for direction sensing triggering system, DSTS, (Page 1/2) ................................................. 149
A.2 Relay circuit diagram for direction sensing triggering system, DSTS, (Page 2/2) .................................................. 150

C.1 Experiment 123 composite wave and bed information plot ........................................ 155
C.2 Complete timestack for experiment 123 ......................................................... 156
C.3 Complete ripple velocity contour map for experiment 123 .................................. 157
C.4 Subset ripple velocity contour map for experiment 123 ..................................... 158
C.5 Ripple velocity distribution boxplot for experiment 123 ..................................... 159
C.6 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 123 subset ............................................ 160
C.7 Experiment 124 composite wave and bed information plot ................................ 161
C.8 Complete timestack for experiment 124 .......................................................... 162
C.9 Complete ripple velocity contour map for experiment 124 ................................ 163
C.10 Subset ripple velocity contour map for experiment 124 .................................... 164
C.11 Ripple velocity distribution boxplot for experiment 124 .................................. 165
C.12 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 124 subset ............................................ 166
C.13 Experiment 212 composite wave and bed information plot ................................ 167
C.14 Complete timestack for experiment 212 .......................................................... 168
C.15 Complete ripple velocity contour map for experiment 212 ................................ 169
C.16 Subset ripple velocity contour map for experiment 212 .................................... 170
C.17 Ripple velocity distribution boxplot for experiment 212 .................................. 171
C.18 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 212 subset ............................................ 172
C.19 Experiment 226 composite wave and bed information plot ................................ 173
C.20 Complete timestack for experiment 226 .......................................................... 174
C.21 Complete ripple velocity contour map for experiment 226 ................................ 175
C.22 Subset ripple velocity contour map for experiment 226 .................................... 176
C.23 Ripple velocity distribution boxplot for experiment 226 .................................. 177
C.24 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 226 subset ............................................ 178
C.25 Experiment 324 composite wave and bed information plot ................................ 179
C.26 Complete timestack for experiment 324 .......................................................... 180
C.27 Complete ripple velocity contour map for experiment 324 ................................ 181
C.28 Subset ripple velocity contour map for experiment 324 .................................... 182
C.29 Ripple velocity distribution boxplot for experiment 324 .................................. 183
C.30 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 324 subset ............................................ 184
C.31 Experiment 407 composite wave and bed information plot ................................ 185
C.32 Complete timestack for experiment 407 .......................................................... 186
C.33 Complete ripple velocity contour map for experiment 407 ................................ 187
C.34 Subset ripple velocity contour map for experiment 407 .................................... 188
C.72 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 519 subset . . . . . . . . . 226
C.73 Experiment 525 composite wave and bed information plot . 227
C.74 Complete timestack for experiment 525 . . . . . . . . . . . . . 228
C.75 Complete ripple velocity contour map for experiment 525 . . 229
C.76 Subset ripple velocity contour map for experiment 525 . . . . 230
C.77 Ripple velocity distribution boxplot for experiment 525 . . . 231
C.78 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 525 subset . . . . . . . . . 232
C.79 Experiment 527 composite wave and bed information plot . 233
C.80 Complete timestack for experiment 527 . . . . . . . . . . . . . 234
C.81 Complete ripple velocity contour map for experiment 527 . . 235
C.82 Subset ripple velocity contour map for experiment 527 . . . . 236
C.83 Ripple velocity distribution boxplot for experiment 527 . . . 237
C.84 Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 527 subset . . . . . . . . . 238

D.1 Plot of first harmonic incident amplitudes throughout each experiment . . . . . . . . . . . . . . . . . . . . . . . . . . . 242
D.2 Superposition of wave conditions for all experiments for block 01 (first 3 hrs) . . . . . . . . . . . . . . . . . . . . . . . . . . . 243
D.3 Superposition of wave conditions for all experiments for block 05 (15 hrs) . . . . . . . . . . . . . . . . . . . . . . . . . . . 244
D.4 Experiment 2009-07-15 timestack of bar profiles: base case of no vegetation on all bars . . . . . . . . . . . . . . . . . . . . . 246
D.5 Experiment 2009-09-08 timestack of bar profiles: 2x2S (bar 03) and 4x4S (bar05) . . . . . . . . . . . . . . . . . . . . . . . . . . . 247
D.6 Experiment 2009-12-10 timestack of bar profiles: 3x3S (bar 03) and Dx6 (bar 05) . . . . . . . . . . . . . . . . . . . . . . . . . . . 248
D.7 Experiment 2010-02-11 timestack of bar profiles: 2Dx12 (bar 03) and Dx12 (bar05) . . . . . . . . . . . . . . . . . . . . . . . . . . . 249
D.8 Experiment 2010-04-22 timestack of bar profiles: Dx6Full (bar 03) . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 250
D.9 Laser bathymetry scan with image texture map of 2x2S case . 252
D.10 Laser bathymetry scan with image texture map of 4x4S case . 253
D.11 Laser bathymetry scan of 2x2S case . . . . . . . . . . . . . . 254
D.12 Laser bathymetry scan of 4x4S case . . . . . . . . . . . . . . 255
D.13 Laser bathymetry scan of 3x3S case . . . . . . . . . . . . . . 256
D.14 Laser bathymetry scan of Dx6 case . . . . . . . . . . . . . . 257
D.15 Laser bathymetry scan of 2Dx12 case . . . . . . . . . . . . . . 258
D.16 Laser bathymetry scan of Dx12 case . . . . . . . . . . . . . . 259
D.17 Laser bathymetry scan of Dx6Full case . . . . . . . . . . . . 260

xiv
CHAPTER 1

INTRODUCTION AND MOTIVATION

1.1 General Overview and Impacts

Throughout the history of mankind coastal areas have played an integral role in establishing successful and thriving civilizations due to the vast resources that the coast provides. Primarily, coastal regions provide a stable food supply and allow for trade/transport of countless goods across the entire world. Focusing within the United States of America, specifically, on the state of Louisiana alone, the Congressional Research Service Report by Cieslak (2005), the Port of South Louisiana and two other Louisiana-based ports, Ports of New Orleans and Baton Rouge, accounts for roughly 13% of total trade by the United States of America to all world ports. Together, these three ports generate roughly $43 billion U.S. dollars in trade per year.

Besides these social and economical impacts, the coastal areas provide a natural habitat for various marine and terrestrial species. It is the coastal regions that are directly responsible for protecting inland regions from the full brunt of natural disasters such as tsunamis, hurricanes, and typhoons, saving billions of dollars in reparations, not to mention, countless, priceless lives. However, due to anthropogenic and/or natural conditions, these dynamic systems are altered, often resulting in the case of coastline recession. The encroachment of sea water permanently changes existing environments, potentially killing certain coastal species as well as destroying nearby coastal communities and shortening the attenuation distance of storm surges to other nearby communities. It is imperative to research various methods which can be implemented to aid in protecting the coastline. On this very note, the contributions herein will significantly aid in the further understanding of coastal processes, eventually leading to sustainable methods which contribute to mitigating the effects of coastal erosion.
1.2 Scientific Basis and Motivation

More specifically, this work focuses on bedform morphodynamics which occur primarily within the nearshore region of the coastal line, as illustrated in Figure 1.1. Within this region there are typically two predominant bedforms: sand ripples which are superimposed onto sand bars, as well as various submarine vegetation, all of which have great impacts on the dynamics of the region.

![Typical beach profile diagram](image)

Figure 1.1: Typical beach profile diagram which highlights the presence of various coastal features and zones, modified from Morang and Parson (2006).

Ripples:

Smaller scale sand ripples occur on an order of magnitude less than the bars, at roughly centimeter- to meter-scales and play a vital role in a variety of coastal engineering topics. Ripples present a natural roughness which vastly alters the properties of flow in the boundary layer leading to changes in the sediment transport rates, thereby affecting regions of erosion and deposition. In addition, flow moving over the ripple feels friction resulting directly in wave attenuation and further changes in sediment transport. Thus, it is no surprise that ripples have constantly held the attention of researchers, spawning numerous theoretical, numerical, and experimental works. One of the earliest
documented works on ripples can be found dating back to Darwin (1883), and subsequently by Ayrton (1910) in which she documented the presence of both bedforms features, sand ripples and mounds (i.e., bars) in her small scale laboratory experiments shown in Figure 1.2. Later years brought numerous additional contributions to the study of ripples and bar forms, though not usually presented together. Subsequent experimental investigations have been conducted exploring the mechanism(s) of ripple formation and equilibrium ripple characteristics under constant oscillatory flow conditions which have led to numerous equilibrium ripple predictors such as Nielsen (1981) and Wiberg and Harris (1994).

Figure 1.2: One of the earliest documented laboratory experimental observations on the sand ripple and mounds (i.e., bar) formations, based on Fig. 1 in Ayrton (1910).

Sand Bars:
Observations have been made by numerous researchers, such as Kindle (1936) and Dolan (1983) in Chesapeake Bay; Evans (1940) and Saylor and Hands (1970) in Lake Michigan; Lau and Travis (1973) in Escambia Bay; Sheppard (1950) on the Southern California coast; and Short (1975) in the Alaskan Arctic. Typically, multiple bars are usually reported for beaches having very mild slopes (slope < 0.005) upon which plunging breakers are frequently observed. The general bar wavelengths are on the order of 10 to 100 meters, increasing in length as water depth increases toward the offshore direction (Mei, 1985). One of the most plausible explanations for parallel longshore bars can be attributed to partially reflected waves formed from incident waves interacting with the reflecting waves from the beach (Allen, 1982).

Like ripples, sand bars play a crucial role in coastal processes. They alter
the mean water depth resulting in wave shoaling and plunging on the outward bar which reduces wave impact on the shoreline. Also, under proper conditions, Bragg resonance over the parallel bar patch can further shelter beaches (Yu and Mei, 2000a). Based on the importance of bar forms, various theoretical, numerical, and experimental works have been performed over the years. However, since the work carried out for this thesis is mainly experimental, we will focus on the laboratory experiments.

Past laboratory experiments, such as de Best et al. (1971) and Xie (1981), studied various wave and sediment conditions within small tanks. However, due to the tank size, scale effects were often present in which ripples scaled on the same order as bars. In some cases, undesirable wave conditions having high Ursell numbers (which fall outside of linear wave theory) were imposed to ensure the Shields parameter was above the critical value for the inception of particle motion to occur. More recently, experimental work has been done by Landry and Hancock (Landry, 2004; Hancock, 2005) and Cataño-Lopera (2005) in which bars with superimposed ripples were measured and characterized. Though Landry and Hancock covered a wide range of conditions (various reflection, different sediment sizes) and had controlled/detailed wave records, there were no velocity profile measurements, and standard wave theory (second order at most) was used to estimate water particle velocities. Conversely, Cataño reported measurements of the velocity (only the maximum excursions) and the sand bed, yet lacked wave envelope measurements along the tank. The combination of both detailed wave field and velocity profile measurements along with detailed bathymetric measurements is beneficial to truly understand the dynamics of the system.

However, despite all the experimental efforts, the majority of the work has been performed in small-scale tanks in which nonlinear and scaling effects become important (refer to Section 2.2.2). Data is still lacking for large-scale experiments under controlled laboratory conditions in which detailed bed evolution of both ripples and bars, wave fields, and velocity profiles are acquired as well as generalized empirical relations which characterize the evolution of both ripples and bars under a full range of wave reflections. This study seeks to apply prior knowledge of bed formations to understand the variability in ripple characteristics under partially progressive waves and the impact that plants can impart on the aforementioned bedforms within this coastal region.
Vegetation:

Over the years, much of the work with flow through aquatic vegetation is based on previous studies in terrestrial canopies which are essentially vertically unbounded flows (López and García, 2001). In the limit of water depth to aquatic canopy height becoming very large, $H_p/h_p >> 1$ (case of deeply submerged canopies), aquatic flows are shown to exhibit very similar behaviors to terrestrial flows. However, the aquatic environment adds an additional layer of complexity to the physics of terrestrial canopy flows due to the fact that submarine canopy flows found in nature occur in water bodies of finite depth. Thus, submarine canopy flows experience depth-limited conditions not felt by the terrestrial counterparts which experience virtually unbounded vertical flow conditions. Various researchers, e.g., Dunn et al. (1996), López and García (1998), Nepf (1999), and Wilson et al. (2008), have conducted research to understand and quantify the drag which the vegetation imposes on the flow as well as to understand the turbulent processes near the canopy shear layer and the penetration depth of the turbulence structures.

In the coastal scientific and engineering community, plants have been frequently studied as a method of sustainable, natural shoreline protection. The vegetation is used to directly attenuate the surface waves which reduces the bottom shear stress and therefore decreases sediment transport, as well as limits the wave energy from reaching shoreline. Recently, Danielsen et al. (2005) highlighted the role that mangrove forests played in attenuating the waves from the 2004 Indian Ocean tsunami. Also, the U.S. Army Corps of Engineers currently published a technical report (Koch et al., 2006) which reviews the impacts of seagrass on wave conditions and gives technical recommendations on the implementation of this natural ecosystem engineering method.

In this current work, plants of relatively short height are implemented to serve as a sediment armoring/trapping region rather than directly attenuating the waves so that cases with and without vegetation, having the same imposed wave conditions throughout, can be directly compared. The special case of fully reflected waves, further explained in Chapter 8, will be used to explore/quantify the impacts of the proposal vegetation which, to the present knowledge of the author, has not been studied before in a large scale laboratory setting. The ultimate goal of this present work intends to address
this issue by conducting detailed large scale laboratory experiments from
which empirical relations can be established and implemented in sustainable
coastal erosion protection along beaches, in addition to, regions near vertical
breakwaters where local scour can significantly undermine the stability of a
structure.

1.3 Objectives and Outline of Present Study

The ultimate objective of the study is to better elucidate bedform morpho-
dynamics in the littoral zone with special emphasis on vegetated conditions.
More specially, the present study is aimed at investigating the following as-
pects:

i proper characterization of wave conditions to understand variations in
bedforms characteristics

ii effect of ripple geometries and velocities when superimposed on larger-
scale bar formations

iii effect that partially reflected waves impose on ripple migration velocities

iv characterization near-deeply submerged vegetative conditions that result
in significant large-scale bathymetric deviations from non-vegetated con-
dition.

v effect of vegetation of small-scale ripples within the canopy region

1.3.1 Objectives of Present Study

The following chapters in this manuscript are summarized as follows:

Chapter 2: Theoretical background is presented, including equation of mo-
tions for linear wave dynamics for the general case of partially reflected
waves as well as equations for mass transport in the boundary bottom
layer. In addition, relationship for dominant bed response and resulting
bar forms are discussed.

Chapter 3: Experimental facility and instrumentation are presented.
Chapter 4: Experimental techniques are discussed.

Chapter 5: The developed wave parameterization software package, which was extensively used throughout this study to characterize wave conditions is presented.

Chapter 6: Analysis of large-scale experiments mild and high reflections are presented which highlights the need for proper wave measurements especially when studying bed features (e.g., ripples) that form over finite extents under the wave envelope. Also, the validity of existing ripple predictors in the presence of significant large-scale bedforms is examined.

Chapter 7: Further analysis of a former dataset (obtained by the writer) is presented to provide detailed information regarding spatial variation of ripple migration velocities under conditions of low and high wave reflection.

Chapter 8: Experimental results on the impact of near-deeply submerged vegetation on bathymetry evolution under standing waves are presented and discussed.

Chapter 9: A summary of the main contributions of this study and proposed future work are presented.
CHAPTER 2

THEORETICAL BACKGROUND

This chapter presents an overview of the basic background theory associated with some of the key coastal processes discussed within this manuscript for completeness and to offer some theoretical insight into explaining the occurrence of the physical phenomena. The majority of the theory presented can be seen throughout various coastal engineering/scientific texts such as Ippen (1966), Mei (1989), Dean and Dalrymple (1991), etc.

2.1 Summary of Linear Wave Theory

2.1.1 Case of Progressive Waves

The simplest wave theory is from the seminal work done by Airy (1845), often referred to as linear wave theory, which assumes that the water waves are periodic and sinusoidal in form and have small amplitudes, which the ratio of wave height $H$ to wavelength $L$ and ratio of $H$ to mean water depth $h$ is much less than one (i.e. $H/L << 1$ and $H/h << 1$). For completeness, the theory also assumes surface tension forces are negligible, fluid flow is homogeneous, incompressible, irrotational, impermeable/horizontal bottom boundary, and has constant surface pressure. Figure 2.1 illustrates a simplified schematic of the problem along with defining key parameters. From the aforementioned assumptions and the implementation of velocity potentials (i.e., $\mathbf{v} = \nabla \phi$), the governing Navier-Stokes equations can be reduced to the Laplace equation in terms of the velocity potential,

$$\nabla^2 \phi = 0 \quad -h \leq z \leq \eta, \quad (2.1)$$

and must satisfy the following boundary conditions:
Figure 2.1: Schematic of the water wave problem, where SWL denotes the still water level, \( h \) = mean water depth, \( H \) = wave height, \( a = H/2 \) = wave amplitude, \( L \) = wavelength, \( c \) = wave celerity, \( \eta \) free surface displacement from SWL, \( z \) is the upwards-positive vertical axis referenced from SWL, \( x \) is the horizontal axis, \( u \) and \( w \) at the horizontal and vertical water particle velocities, respectively, and \( \phi \) is the velocity potential.

- At the bottom, the horizontal bottom boundary condition (BBC) of no flux states
  \[
  w = \frac{\partial \phi}{\partial z} = 0 \quad \text{on} \quad z = -h. \tag{2.2}
  \]

- At the free surface, both the kinematic free surface boundary condition (KFSBC), stating that the water particles on the surface must remain there, expressed as
  \[
  -\frac{\partial \phi}{\partial z} = \frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} \quad \text{on} \quad z = \eta(x,t), \tag{2.3}
  \]
  where \( t \) is time, and for the dynamic free surface boundary condition (DFSBC),
  \[
  -\frac{\partial \phi}{\partial t} + \frac{1}{2} \left[ \left( \frac{\partial \phi}{\partial x} \right)^2 + \left( \frac{\partial \phi}{\partial z} \right)^2 \right] + g\eta = C(t) \quad \text{on} \quad z = \eta(x,t), \tag{2.4}
  \]
  which requires the pressure to be uniform along the waveform (uses unsteady Bernoulli equation), where \( C(t) \) is an arbitrary constant, and
$g$ is the gravitational acceleration.

Upon linearizing (2.1) (2.2), (2.3), and (2.8), respectively results in

\[ \nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0, \quad -h \leq z \leq \eta, \quad (2.5) \]

\[ \frac{\partial \phi}{\partial z} = 0 \quad \text{on} \quad z = -h, \quad (2.6) \]

\[ \frac{\partial \eta}{\partial t} = w = 0 \quad \text{on} \quad z = 0, \quad (2.7) \]

\[ \frac{\partial \phi}{\partial t} = -g \eta \quad \text{on} \quad z = 0. \quad (2.8) \]

Then, by using the method of separation of variables, assuming the solution of $\phi$ has the form of

\[ \phi(x, z, t) = F(z) \sin(kx - \omega t + \theta), \quad (2.9) \]

where $F(z)$ is a unknown function of $z$ only and $\theta$ is a phase shift. Applying the linearized BBC and DFSBC, the equation for the velocity potential $\phi$ and free surface displacement $\eta$ for progressive waves can be determined as

\[ \phi = \frac{Hg \cosh(k(h + z))}{2\omega \cosh(kh)} \sin(kx - \omega t), \quad (2.10) \]

\[ \eta = \frac{H}{2} \cos(kx - \omega t), \quad (2.11) \]

where $k = 2\pi/L$ is the wave number, and $\theta$ is taken to be zero. The remaining KFSBC, in conjunction with (2.10) and (2.11), is used to solve for the relationship between $\omega$ and $k$, known as the dispersion equation,

\[ \omega^2 = kg \tanh(kh). \quad (2.12) \]

Finally, using the definition of the potential, the general horizontal and vertical water particle velocities for progressive waves are

\[ u = \frac{a \omega \cosh(k(z + h))}{\sinh(kh)} \cos(kx - \omega t), \quad (2.13) \]

\[ w = \frac{a \omega \sinh(k(z + h))}{\sinh(kh)} \sin(kx - \omega t). \quad (2.14) \]
Refer to Figure 2.2 (a) for the water particle velocity diagram under a progressive wave. Also, the absolute value of the free surface displacement abs(\(\eta\)) for the progressive case is shown in Figure 2.2 (c).

2.1.2 Case of Standing Waves

The progressive wave theory can be extended to the case of full reflection by implementing the principle of superposition with both the free surface displacement and velocity potential, since the governing equations are linear in terms of the \(\eta\) and \(\phi\), respectively. By superimposing a second wave propagating in the opposite direction of the first (incident) wave, a condition which would result from a normally incident wave fully reflecting (100%) off a vertical wall, the free surface displacement for a standing wave can be represented as

\[
\eta_{\text{total}} = \frac{H_i}{2} \cos(kx - \omega t) + \frac{H_r}{2} \cos(kx + \omega t + \theta),
\]

(2.15)

where the subscripts \(i\), \(r\), and \(\text{total}\) respectively represent incident, reflected, and total combined wave heights, the term with \((kx - \omega t + \theta)\) denotes the reflected wave, and \(\theta\) is the relative phase angle between incident and reflected waves. By definition, the reflection coefficient is the ratio of the reflected wave amplitude \(a_r\) to the incident amplitude \(a_i\),

\[
R = \frac{a_r}{a_i} = \frac{H_r}{H_i},
\]

(2.16)

and for the case of full reflection \((R = 1)\), \(H_i\) and \(H_r\) are equal, i.e., \(H_i = H_r = H\), and \(\theta = 0\). Thus, (2.15) can be rewritten as

\[
\eta_s = H \cos(kx) \cos(\omega t) = \frac{H_s}{2} \cos(kx) \cos(\omega t),
\]

(2.17)

where the subscript \(s\) represents standing wave parameters, e.g., \(H_s\) is the total standing wave height. Clearly, it can be seen from (2.17) that \(H_s = 2H\), meaning that the total standing wave height is the sum of the incident and reflected waves.

Likewise, the total velocity potential can be expressed as the sum of the
potentials from incident and reflected waves,
\[ \phi_{\text{total}} = \frac{H_i g \cosh(k(h + z))}{2 \omega \cosh(kh)} \sin(kx - \omega t) + \frac{-H_r g \cosh(k(h + z))}{2 \omega \cosh(kh)} \sin(kx + \omega t + \theta). \]

Note that the last term (the reflected term) from (2.18) has a sign change due to change in direction of wave propagation. As previously imposed for \( \eta \) in (2.17), \( H_i = H_r = H \) and \( \theta = 0 \), reduces (2.18) to
\[ \phi_s = \frac{H g \cosh(k(h + z))}{2 \omega \cosh(kh)} (-2 \cos(kx) \sin(\omega t)) = \frac{-H_s g \cosh(k(h + z))}{2 \omega \cosh(kh)} \cos(kx) \sin(\omega t), \]

where \( H_s = 2H \) as before. The standing wave horizontal \( u_s \) and velocity \( w_s \) velocities can be determined from the potential as
\[ u_s = \frac{H_s g k \cosh(k(h + z))}{2 \omega \cosh(kh)} \sin(kx) \sin(\omega t), \]
\[ w_s = \frac{-H_s g k \sinh(k(h + z))}{2 \omega \cosh(kh)} \cos(kx) \sin(\omega t). \]

Refer to Figure 2.2 (b) for a diagram illustrating the water particle velocities distribution and Figure 2.2(d) for the absolute value of free surface displacement \( \text{abs}(\eta_s) \) under a standing wave. Notice when comparing the free surface displacements between the two cases, the progressive waves have a uniform displacement over the entire domain whereas the standing waves have significant spatial variation, ranging from zero (referred to as wave nodes) to a peak maximum value (antinodes).

### 2.1.3 Case of Partially Reflected Waves

The previous Sections 2.1.1 and 2.1.2 were special, extreme cases of wave reflection, i.e., zero reflection and 100\% reflection, respectively. A generalized, more complex set of equations can be written to account for all reflection conditions, \( 0 \leq R \leq 1 \). The general equations for \( \eta \) and \( \phi \) were stated (2.15) and (2.18). Thus, from the definition of the potential, the horizontal and vertical velocities can be determined just as presented in the previous sections.
Figure 2.2: Depiction of water particle velocities under (a) progressive wave and (b) standing wave and absolute value of free surface displacement $\text{abs}(\eta)$ for (c) progressive waves and (d) standing waves.

For the horizontal velocity,

$$u_{\text{total}} = \frac{\partial \phi_{\text{total}}}{\partial x} = \frac{kg \cosh(k(z + h))}{\omega} \left( a_i \cos(kx - \omega t) - a_r \cos(kx + \omega t + \theta) \right). \quad (2.22)$$

Multiplying (2.22) by $\frac{\omega \sinh(kh)}{\omega \sinh(kh)}$ and using (2.12), the dispersion relationship, results in

$$u_{\text{total}} = \frac{\omega \cosh(k(z + h))}{\sinh(kh)} \left( a_i \cos(kx - \omega t) - a_r \cos(kx + \omega t + \theta) \right). \quad (2.23)$$

Using the fact that $a_r = a_i R$, (2.23) can be rewritten as

$$u_{\text{total}} = \frac{a_i \omega \cosh(k(z + h))}{\sinh(kh)} \left( \cos(kx - \omega t) - R \cos(kx + \omega t + \theta) \right). \quad (2.24)$$
Similar for the vertical velocity,

\[ w_{\text{total}} = \frac{\partial \phi_{\text{total}}}{\partial z} = \frac{g k \sinh(k(h + z))}{\omega \cosh(kh)} (a_i \sin(kx - \omega t) - a_r \sin(kx + \omega t + \theta)). \quad (2.25) \]

Then, using the dispersion relation and definition of the reflection coefficient, results in

\[ w_{\text{total}} = \frac{a_i \omega \sinh(k(h + z))}{\sinh(kh)} (\sin(kx - \omega t) - R \sin(kx + \omega t + \theta)), \quad (2.26) \]

Refer to Figure 2.3 for images of particle trajectories under wave of various reflection coefficients ranging from 0 to 1. Derivation of a partially progressive wave envelope is presented in Chapter 5.
Figure 2.3: Particle trajectories under waves of various reflection coefficients $R$: (a) case of purely progressive waves, $R = 0$; (a) case of 25% reflection or $R = 0.25$; (c) $R = 0.38$; (d) $R = 0.53$; (e) $R = 0.71$; (f) $R = 0.85$; (g) case of pure standing waves $R = 1$ (after Van Dyke, 1982).
2.2 Background on Sand Bar Theory

Based on the standing wave inviscid velocity distribution shown in Figure 2.2(b), one can see there is a net flow away from each node toward the nearest antinode, in either direction of oscillation. Thus, it would be expected that a net sediment transport would result in the same directions (provided that conditions are above the critical Shields parameter to initiate motion). As illustrated in Figure 2.4(e), this transport (from nodes to antinodes) only occurs for fine sediment present in the bed and differs from the observed transport of coarse sediments seen in Figure 2.4(d). In the case of a mixed sediment bed, sediment sorting occurs which can be seen in 2.4(b) and 2.4(c). Thus, there must exist another phenomenon which is directly responsible for the antinode-to-node transport which the coarser sand grains undergo. The enigma can be explained by analysis of a region very near the sand bed, the bottom boundary layer.
Figure 2.4: Resulting bathymetry profiles for sand beds composed of various sediment sizes: (a) standing wave field; (b) bed profile for mixed sediment case ($d_{50} = 0.1$ and $0.2$ mm); (c) measured median sediment size along the bed for mixed sediment case; (d) bed profile for coarse sand case ($d_{50} = 0.2$ mm); and (e) bed profile for fine sand case ($d_{50} = 0.1$ mm); modified from Landry et al. (2007).
2.2.1 Bottom Boundary Layer

The bottom boundary layer (BBL) is a region near the bed where viscous effects are important (refer to Figure 2.5 for illustration). For short period waves, since the flow changes direction before BBL reaches the free surface, the BBL is confined to a very small layer close to the seabed. The magnitude of the wave BBL can be expressed as

\[ \delta_{\text{wave bbl}} \sim O\left(\frac{u_*}{\omega}\right), \]

where \( u_* \) is the shear velocity and \( \omega \) is the wave angular frequency.

Figure 2.5: Schematic of regions within the water column under waves, modified from Grant and Madsen (1986).

Based on the work of numerous researchers over the past two centuries, the Lagrangian drift, or more commonly referred to as the mass transport velocity, was discovered which explains the directional difference in sediment flux between fine and coarse grain sand. First discovered in acoustics when steady streaming was introduced by oscillating adjacent fluid near solid wall,
Eulerian streaming, was analyzed theoretically by Rayleigh (1883) in which he determined the presence of Eulerian streaming in the wave boundary layer. Half a century later, Longuet-Higgins (1953) noted that the Stokes drift should be included in addition to the Eulerian streaming to properly determine the Lagrangian mass transport velocity of the particles,

$$
\bar{u}_L = \frac{k \omega a_i^2}{4 \sinh^2(kh)} \left[ (1 - R^2) \left( -8e^{-\xi} \cos \xi + 3e^{-2\xi} + 5 \right) + 2R \sin(2kx + \theta) \left( 8e^{-\xi} \sin \xi + 3e^{-2\xi} - 3 \right) \right], \quad (2.28)
$$

where $h$ is the mean water depth, $a_i$ is the incident wave amplitude, $R$ is the reflection coefficient, $k$ is the wave number, $\theta$ is the phase shift, and $\xi = z/\delta$ is the dimensionless vertical distance in the BBL (i.e., $\xi = 0$ is at the bed and $\xi \gg 1$ is at the bottom of the inviscid core). Subsequently, formulas were deduced for the Eulerian streaming in 2-D waves and the Lagrangian drift at the outer edge of the boundary layer by Hunt and Johns (1963).

Furthermore, based on (2.28), the work by Carter et al. (1973) for partially progressive waves theoretically (accompanied by small-scale experiments) showed the existence of a critical reflection coefficient, $R = 0.414$, above which the flow in the bottom boundary layer reversed, resulting in the potential for sediment sorting. A diagram summarizing the circulation under standing waves ($R = 1$) can be seen in Figure 2.6. Notice that since the mass transport velocities just outside and within the BBL are out of phase, this results in a circulation pattern as seen in Figure 2.6 (d). Any sediment which remains in the bottom boundary layer is transported (predominantly via bedload) toward the wave node locations, and any sediment that suspends and escapes the BBL, drifts toward the antinodes (predominantly suspended load transport).
Figure 2.6: Diagram of mass transport velocities under standing waves (after Mei, 1982). Figure 2.6 (a) depicts the wave envelope in which $kx = \pi/2$, and $3\pi/2$ are nodal locations and $kx = 0, \pi$, and $2\pi$ are antinodes; Figure 2.6 (b) plots $u_L(\infty)$, the mass transport velocity evaluated at the outer edge of the boundary layer, $\xi = z/\delta = \infty$; Figure 2.6 (c) shows mass transport velocity evaluated within the boundary layer at elevation $\xi = z/\delta$, i.e. $\overline{u}_L(\xi)$; Figure 2.6 (d) illustrates the circulation mass transport patterns that occur due to the out of phase velocities inside and outside the BBL which are responsible for sediment sorting within the sand bed.
Later, experimentally deduced findings by O’Donoghue (2001), seen in Figure 2.7, showed that sediment transport was dominated by suspended load transport outside the BBL for the ratio of the near-bed nodal velocity $u_n$ to sediment fall velocity $w$ greater than 19. This type of transport, referred to as L-type, transports the sand toward the wave antinodes. Conversely, when $u_n/w < 14$, N-type sediment transport occurs (i.e., bedload transport within the bottom boundary layer) moving sediment toward the wave node. Mixed transport modes, in which both transport modes are dominant, result for $14 < u_n/w < 19$.

![Type of bed response as function of $u_n/w$, where N-type is bedload dominated, and L-type is suspended load dominated sediment transport (after O’Donoghue, 2001)](image)

**Figure 2.7**

2.2.2 Scaling Effects (importance of large wave facilities)

It is of great importance to conduct laboratory experiments in large scale wave flumes in order to mitigate the adverse effects inherent to smaller scale facilities. The still water depth condition for small wave facilities is typically less than 30 cm, resulting in steep, nonlinear waves required to achieve a turbulent boundary layer. In addition, the height of ripples superimposed
on the bar forms in small wave tanks occurs on the same order of the bar height which is atypical of field conditions, where ripples scale an order of magnitude less than the bar forms. Presented by Yu (1999), the scaling of ripples in the laboratory to those in nature are dynamically similar if

\[(A_b\omega)_{\text{lab}} = (A_b\omega)_{\text{field}}, \tag{2.29}\]

where \(A_b\) is the near bed orbital amplitude \((A_b = a_i(1 + R)/\sinh kh)\). This similarity is achieved in the laboratory and agrees with empirical ripple predictors such as Nielsen (1981), Wiberg and Harris (1994), etc. However, a problem occurs when scaling is applied for laboratory bars to that of nature.

It was shown by Yu (1999) and later by Hancock (2005) that by equating the model to prototype ratios of wave slope \(\zeta = kA_b\), sand bar time coefficient \(\alpha_1\), and Shields parameter that

\[(kd_{50})_p = (kd_{50})_m, \tag{2.30}\]

where \(d_{50}\) is the median grain size, \(k\) is the wave number, and subscripts \(p\) and \(m\) denote properties of the prototype and model, respectively. Based on (2.30), large laboratory experiments typically have a \(k_m/k_p \sim 10\), resulting in \((d_{50})_m / (d_{50})_p \sim 1/10\). Assuming that the field has coarse sand of \((d_{50})_p = 1\) mm, the model sand of \((d_{50})_m = 0.1\) mm should result. Yet, based on the laboratory experimental profiles presented in Figure 2.4, the results show that \((d_{50})_m = 0.1\) mm does not mimic that of the coarse field sand, but instead transports as fine grain sand. From this, it seems impossible to achieve similarity between laboratory and field bars, however, relaxing the condition of similar bar time coefficients in (2.30), which only impacts the growth rate and not shape, results in

\[(A_b\omega)_p = (A_b\omega)_m, \tag{2.31}\]

as shown in Hancock (2005). The new bar scaling (2.31) is the same as the ripple scaling in (2.29) which can be achieved in the laboratory as mentioned above.
2.2.3 Note on Free Second Harmonic

It is important to ensure that only the desired wave conditions are present in the experimental facility and there exists no pronounced second order effects. From theory, it can be shown that when the leading order wave forcing is monochromatic, any secondary effects (i.e, $O(\epsilon)$, where $\epsilon$ is a small parameter) contribute to the leading order of the bedload forcing which can significantly affect bar formation (Hancock, 2005). As discussed in Madsen (1971), the presence of a free second harmonic occurs in waves tanks as a result of the moving boundary condition (i.e., the wavemaker). The wavemaker is imposing the forcing of temporal frequency $\omega$; however, the generated wave has a naturally occurring nonlinear second harmonic which is bound to the first harmonic (i.e., Stokes waves). Since the system is being forced by only the primary harmonic, this introduces a free second harmonic $2\omega$ which satisfies the dispersion relationship, i.e., $(2\omega)^2 = kg \tanh kh$. Thus, one must impose a second harmonic in the motion of the wavemaker to cancel out this free second harmonic in the tank. A cancellation theory was presented by Madsen (1971) for waves traveling over a flat bottom. However, due to the bottom complexities usually found in laboratory experiments (e.g., wooden ramps, etc.), a trial and error method outlined in Landry (2004) and Hancock (2005) should be implemented to ensure correct cancellation. Figure 2.8 illustrates the difference between the cases with and without the presence of a free second harmonic. Notice in Figure 2.8(a) the large scale variation in the second harmonic wave amplitude along the tank, which is indicative of the presence of a free second harmonic. The effect of the harmonic cancellation is seen in Figure 2.8(b) where the second harmonic wave envelope lacks a significant long scale variation.
Figure 2.8: Effect of the presence of a free second harmonic on the wave envelope of a laboratory experiment: (a) case including the free second harmonic, and (b) case of canceled free second harmonic. First, second, and third harmonic amplitudes are denoted with 1st, 2nd, and 3rd, respectively.
This chapter provides details about the large wave flume located in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign. The flume is considered among the largest wave flumes in North America, having a total length of 49 m, width of 1.83 m, and depth of 1.2 m. The facility is ideal for studying wave-sediment interaction and bedform morphodynamics which occur in shallow to intermediate water depth within coastal regions due to its substantial size which mitigates the aforementioned scaling effects (refer to Section 2.2.2) associated with smaller flumes.

3.1 Wave Flume Facility

The large tilting wave flume located in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign is 49-m long x 1.83-m wide x 1.20-m high, see Figure 3.1. The tank’s skeleton is composed of steel members which provide the core structural integrity of the facility and allows for a total of 64 plexiglas sidewall panels (32 on each side) each of 4-ft long x 4-ft high x 1-in thick sections to allow for optical visualizations and measurements for experiments. Additional side panel sections, as well as, the ends and the floor of the tank are composed of 0.5-inch steel plating.

Roughly, 7.2 m from the front end of the flume is situated the paddle of the piston wavemaker which spans the width of the tank, extending 4 ft in height and resting just above a false floor which is 6 in from the true steel bottom of the tank.
Figure 3.1: Wave flume facility in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign: (a) panoramic photograph of the facility, and (b) facility schematic: 1. wave flume; 2. wavemaker paddle; 3. sand bed; 4. wooden ramp; 5. waves; 6. current inlet; 7. fibrous beach (beach option one); 8. removable vertical wooden wall (beach option two); 9. movable I-beam frame carriage; 10. wave sensors; 11. Velmex position system and secondary carriage; 12. velocity probe (ADV); 13. bathymetry sensors. (modified from Cataño-Lopera, 2005)
The wavemaker MTS hydraulic system (rated for working pressure of 3000 psi) is controlled via a MTS 458.20 MicroConsole™ from the MTS Systems Corporation which an installed function generator module (458.90 Fctn Gen) is used to specify the desired sinusoidal frequency over the range of 0.1 to 0.6 Hz. In addition, the console contains a 458.13 AC controller module and calibrated ±12 in load cell module which allowed for a maximum paddle displacement of ±12 in from the mean position of the paddle. The paddle excursion is controlled via the span control knob on the 458.13 module which ranges from 0 to 10 whereby this factor multiplied by 10 translates into the percentage of the total span to impose for the desired waves. Lastly, the system incorporates a real-time, dynamic feedback control that ensures proper motion of the paddle. The system constantly monitors the difference between the desired motion (i.e., frequency and span) input into the hydraulic system and the resulting physical motion undergone by the paddle as measured by the linear variable displacement transducer (LVDT). Based on the feedback, the system internally applies slight compensation to the controlling signal to minimize the error between the desired and produced motion. As a result, the desired paddle frequency and span entered on the modules is ensured as the resulting frequency and span of the physical paddle itself.

As previously mentioned, under the wavemaker paddle is the false floor which spans the width of the tank and is elevated 6 in from the true bottom. This floor is actually the top panel of a rectangular diffuser which was installed to allow for the possibility of superimposed wave and current experimental conditions. The diffuser is coupled to an 8-in diameter steel pipe to which an Allis-Chalmers centrifugal pump (model V.T., rated at 4000 G.P.M at 80 feet of head), powered by an U.S. Electrical Motors electrical hollow shaft pump motor (150 H.P. 460 Volt) which supplied the flow of water to the tank from the sump (concrete-lined reservoir) located directly under portions of the laboratory floor. The flow was controlled via an 8-in gate value in-line with diffuser pipeline. At maximum capacity, the system is capable of produce a mean current of approximately 0.2 m/s in a water depth of 0.6 m (i.e., flow discharge ≈ 0.22 m³/s).

Over the central 24 meters of the tank, a sand bed (approximately 0.30 m thick) composed of 0.25 mm median grain size diameter sand was located over the entire lateral span of the flume. Wooden ramps having a 1:6 slope flanked either end of the bed to provide a gradual transition to the top of
the elevated sand bed while aiding to retain the sand. The results of the grain size distribution test conducted here in the laboratory can be seen in Figure 3.2 which agreed well with the curve provided by U.S. Silica for their Silica Sand 60-80.

Figure 3.2: Measured distribution of sediment size for sand used in the wave flume facility. The medium diameter, $d_{50}$, is 0.25 mm

Based on the size distribution, the grain size was converted between $\varphi$ and mm units according to

$$
\varphi = -\log_2 d, \quad (3.1)
$$

$$
d = 2^{-\varphi}, \quad (3.2)
$$

respectively (King and Galvin, 2003). Additional sediment properties such as the mean grain size diameter $M_d$ in mm, phi standard deviation $\sigma_\varphi$, phi coefficient of skewness $\alpha_\varphi$, and phi coefficient of kurtosis $\beta_\varphi$ are computed to
be

\[ M_d = 2^{-\left(\frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3}\right)} = 0.257 \text{ mm}, \quad (3.3) \]

\[ \sigma_\phi = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_{5}}{6} = -0.336 \phi, \quad (3.4) \]

\[ \alpha_\phi = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2(\varphi_{84} - \varphi_{16})} + \frac{\varphi_{5} + \varphi_{95} - 2\varphi_{50}}{2(\varphi_{95} - \varphi_{5})} = 0.051, \quad (3.5) \]

\[ \beta_\phi = \frac{\varphi_{95} - \varphi_{5}}{2.44(\varphi_{75} - \varphi_{25})} = 0.796, \quad (3.6) \]

for which the sand can be classified as very well sorted, near-symmetrical, and platykurtic (King and Galvin, 2003).

At the end opposite the wavemaker lies the artificial beach. Over the course of the experiments, two distinct beaches were implemented depending on the resulting wave conditions desired, both of which can be seen in Figure 3.1(b).

The first beach was composed of fiberous matting (Wollastic™ Rubberized Bound Fibre) from F. P. Woll and Company purchased in 6-ft wide, 2-in thick, 50-ft rolls. The bundles were stretched out and cut into various lengths that enabled the formation of a 1:9 sloping beach when the various lengths were layered on top one another in order of descending length. The layers of matting were positioned on top of a false floor from which nine vertical threaded rods where attached and forced through each of the layers to anchor them in place. The elevated floor was 1.5 ft from the true floor in order to ensure the optional superimposed current would not be obstructed by the beach. After passing under the beach, the water would be allowed to overtop the circular tailgate and enter the receptor tank to be recirculated in the system (refer to Figure 3.1).

Based on wave measurement methodology presented later in Section 4.2, the beach greatly aided in minimizing the wave reflections for the various experiments conducted. Typically, reflections coefficients were only around \( R = 0.05 \) (i.e. only 5% reflection) allowing the generation of essentially purely progressive waves in the facility. The other beach was a vertical wooden wall (seen in Figures 3.1 and 3.3) which was positioned at 26.37 m from the mean position of the wavemaker. The base support was placed on the true steel floor of the tank and large concrete cylinders were fitted between the vertical braces along the lateral direction providing structural support to ensure the wall held its location under various wave forcings. Also, as an
added precaution, wooden beams which spanned the width of the flume were fixed to the tank rails flanking either side of the top of the vertical wall to provide added support points.

Figure 3.3: Perspective views of wooden vertical wall used as beach to generate full reflection within the tank: (a) front perspective view of the wall as seen from the direction of incident waves generated by the wavemaker, and (b) rear perspective view of the wall as seen from the end of the tank (i.e., direction in opposition to that of incident wave propagation)

Lastly, tubular railings located on the top of each sidewall, spanning the entire length of the tank, formed a parallel bar system upon which rode an 8-ft long aluminum I-beam frame carriage. Resting on this primary carriage is a smaller secondary carriage system which is capable of traversing 150 cm in the longitudinal direction (over the primary carriage) via a gear-and-threaded rod control system. The secondary carriage can also undergo slight lateral displacement up to approximately ±8 cm. The combination of the primary and secondary carriages provides the rigid movable framework to which the majority of all the experimental equipment discussed in the in next section is attached. (Refer to Figure 3.8, presented later, for illustration of the carriage system.)
3.2 Experimental Equipment

In order to help understand and quantify the coastal sediment transport processes and bedform morphodynamics that are observed during experiments in the facility, the implementation of numerous equipment is required. Instrumentation ranging from acoustic to optical sensors will be discussed in detail throughout the remainder of this chapter.

3.2.1 Water Surface Displacement System

Displacement of the water/air interface was measured via a General Acoustics UltraLab® ULS system with four attached USS2001300 ultrasonic sensors. (Refer to Figure 3.4 for an image of the system.) The instrumentation is capable of measuring a range of 200 to 1300 mm from the sensor. Thus, the sensor measures over a net range of 1.1 m using a 200 kHz signal having a 14 Hz output response time with a technical resolution of 0.18 mm and ± 2.00 mm reproducibility (i.e., accuracy). Sensors were attached to the supporting beams of the primary carriage spaced 0.5 m on center in the longitudinal direction. However, since all four sensors simultaneously measured the surface, a 0.5 m staggered lateral offset between adjacent sensors was imposed to eliminate signal interference from nearby sensors (i.e., crosstalk). (Refer to Figure 3.8 for positioning diagram.) The output analog voltage signals from the UltraLab® ULS were feed via BNC cables to an in-house developed breakout box which changes the cables to 22-gauge wires to easily interface the National instruments data acquisition device, discussed in the next subsection.

Figure 3.4: General Acoustics UltraLab® ULS system shown with only one attached ultrasound sensor (after General Acoustics, 2011)
3.2.2 National Instruments Data Acquisition Device

In order to sample the analog data generated from General Acoustic system, a National Instruments data acquisition device (NI USB-6009) connected to a PC via USB was utilized. The USB-6009 device, as seen in Figure 3.5(a), allowed for sampling of four differential signals at 48 kS/s with a 14-bit resolution. This equates in $2^{14} = 16384$ incremental levels to resolve maximum net range of the wave gages (i.e., 1100 mm) which results in a physical resolution of

$$\frac{1100 \text{ mm}}{16383 \text{ divisions}} \approx 0.0671 \text{ mm/division.} \quad (3.7)$$

Since the USB-6009 capabilities surpass that of the wave sensors, the acquired measurements are limited by the wave sensors. Thus, the sampling frequency of the NI USB-6009 was set to 14 Hz to achieve the maximum temporal resolution available and the resolution expected was taken as 0.18 mm with $\pm 2.00$ mm reproducibility. In order to expedite the measurement process and minimize user error while maintaining accurate measurements, custom MATLAB® scripts and functions where encapsulated within graphical users interfaces (GUIs) to allow for full feature controls in a very manageable/organized environment. Refer to Figure 3.5(b) for the main GUI window for interfacing the wave acquisition system.

Figure 3.5: Wave signal acquisition system: (a) photograph of the NI USB-6009 device (after National Instruments, 2011) and (b) MATLAB® custom in-house GUI.
3.2.3 Acoustic Doppler Velocimeter (ADV)

In addition to wave gages, a Sontek 16-MHz micro field acoustic doppler velocimeter (ADV) was used to measure 3-dimensional velocity components at multiple point-wise locations and produce phase-averaged velocity profiles when incorporating the simultaneous wave measurements. For completeness, the basic fundamental principles of the ADV will be explained here, however for greater details the reader is directed to SonTek/YSI (2001), Kraus et al. (1994), Voulgaris and Trowbridge (1998), Nikora and Goring (1998), and McLelland and Nicholas (2000). The ADV unit is composed of one transmitting transducer and three receiving transducers each positioned around the central emitter extending outwards at 120° azimuth angles, each forming a 30° angle with emitter, as illustrated in Figure 3.6. Short acoustic pulses are generated by the emitter and are then scattered by fine particles (i.e., seeding particles, suspended sediment, micro bubbles, etc.) in the cylindrical measuring volume of 0.07 cm³ (height and diameter = 4.5 mm) and picked up by the receiving transducers ≈ 5 cm above the sampling volume. These returning scattered signals (i.e., echoes) have an inherent change in frequency, known as the Doppler effect/shift, from which it is able to determine the motion of the fine particle in the project along each of the three receiving beams. The projection of the velocity components to the standard Cartesian coordinate system can be performed with a priori knowledge of the physical, geometric configuration between the transducers. The system results in a resolution of 0.01 cm/s with an accuracy of nearly ±0.25 cm/s. Finally, the ADV unit is controlled via Horizon software and allows to start sampling on signal or only sample on signal, the former of which is instrumental to the ability of phase averaging, discussed in the next subsection. Note: for additional examples of ADV implementation, the reader should refer to Carter (2002), Cataño-Lopera (2005), and García et al. (2005).

3.2.4 Direction Sensing Triggering System (DSTS)

In order to utilize the wave and velocity sensor to their full potential, a method was required to synchronize sampling of the sensors. However, the wave flume facility presented a unique problem: only triggering the wave and velocities sensors to start sampling at the same instant allowed for
a phase-averaged velocity profile at that singular $x$-location in which the multiple vertical velocity point were measured. This triggering did not easily allow for spatial phase-averaged velocity across multiple velocity profiles over additional $x$-locations. To ensure this capability with considerable ease, a system was needed that triggered the sampling in relation to a global absolute motion, i.e., the motion of the wavemaker. Thus, a custom-designed, simple, direction sensing triggering system (DSTS) was developed using a few integrated-circuits (ICs), magnetic switches, and common electric components, such as resistors, light-emitting-diode (LED), and connectors/switches. The DSTS was composed of two primary modules: 1) latching circuit module and 2) the relay module, both shown in Figure 3.7(a). A brief explanation of the system follows, but for a more detailed overview, the reader can refer directly to the circuit diagrams in Figures A.1 and A.2 in the Appendix.

The latching circuit module incorporated a latch integrated-circuit (CD 4043 BE) and two buffer ICs (SN74LS04N). The magnetic switches were positioned on the fixed support of the wavemaker along the same lateral line with switch 2 located closer to the beach than switch 1 (refer to Figure 3.8). The switches were wired to the latch IC so that switch 1 was on the reset pin and switch 2 was on the set pin, resulting in a 5 V signal only when the paddle
moved forward after crossing switch 2, otherwise a 0 V signal was present. The output triggering signal was then passed to buffer ICs which ensured that the triggered signal had enough current at 5 V to trigger the added loads (i.e., NI USB-6009 and ADV).

Prior to activating the sensors, the signal had to be disconnected from the latch circuit module due to the internal design of the NI USB-6009 (a pull-up resistor that enabled a 5 V high signal on the NI USB-6009 trigger pin). The separation was enabled by the solid state relay switch, located in module 2, which, in turn, simultaneously triggered both the wave and velocity sampling. On a side note, since both the wave and velocity systems required different durations to arm each device to accept a triggering signal, an enable output rocker switch was used in conjunction with an LED which served as a visual indicator to allow the user to know when the enable output switch should be activated. Thus, prior to arming either system, the enable output switch was set to off and both systems were armed. Then, since the LED was not effected by the rocker switch, the LED would light up when a 5 V signal was present in the trigger, i.e., when the paddle was undergoing a forward motion after passing switch 2. After the LED would turn off, the enable output rocker switch would be turned on, allowing for the subsequent 5 V signal pulse to trigger the acquisition systems at a consistent temporal
point in the wave period regardless of the spatial location of the wave and velocity sensors, so long as the wave sensor was measuring free surface at the same longitudinal location the velocity was acquired.

Figure 3.8: Schematic of the wave and velocity synchronization system
3.2.5 Velmex BiSlide® System

The ADV and other equipment was accurately positioned via a dual-axis Velmex stepper motor system having the capability of moving 0.0050 mm/step. The system was attached on top of the secondary carriage and positioned so that one axis allowed for vertical motion and the other enabled lateral motion (shown in Figure 3.8). Due to the physical constraints of the carriage system, the lateral motion was slightly limited to 73 cm; however, the vertical motion was unrestricted and maintained full motion over the entire depth of the tank. The system allowed for the user to manually jog each axis for immediate control or programmed motion (axis direction and displacement) which allowed for precise motion control. MS-DOS® batch files were created to execute multiple, predefined motions by interfacing the Velmex system through one of its optional interface programming languages, MS-QBASIC®. Since the system was quite versatile, a second Slo-Syn® M092 motor was connected to the gear system that controlled the secondary carriage movement over the primary carriage. Using a 4:1 gear reduction, the system was able to drive the carriage at a modest pace of 1 cm per 6 sec which was ideal for bathymetry measurements from the SeaTek array or Keyence sensor discussed in the next section.

3.2.6 Bathymetric Measurements

Due to large the spatial scale of the tank in combination with short and long time scales for bedform evolution (i.e., ripples and bars, respectively) numerous techniques were employed to capture various aspects of the bathymetry, depending on the desired spatial and temporal resolutions required for bed measurements. (Note: not all methods may have been conducted at one time for a given experiment.)

Direct Measurement Systems

(i) SeaTek Acoustic System: The SeaTek acoustic system is composed of 32 individual ultrasound sensors spaced 4 cm on center from each other with the entire array spanning the central 128 cm of the lateral dimension of the tank, as illustrated in Figures 3.8 and 3.9. The supports were mounted to the
secondary carriage and the array was positioned \( \approx 30 \) cm above the initial flat sand bed and resulted in a resolution of \( \approx 2 \) mm in the vertical. (For a more comprehensive analysis of the capabilities of the system, refer to Jetté and Hanes (1997).) Since the system was attached to the secondary carriage, the entire array was allowed to translate 150 cm in the \( x \)-direction at a constant velocity of 1 cm per 6 sec via the Velmex motor controller and gear reduction system acquiring a lateral line of 32 points spaced 4 cm apart every 1 cm in the \( x \)-direction. If so desired, the secondary carriage could be offset laterally 2 cm and the SeaTek could scan over the same region resulting in a combined spatial resolution of up to 2 cm in the lateral direction. The procedure could be repeated at these 150-cm intervals along the tank which equated to the quickest method to resolve the fully thee-dimensional structure of the entire sand bed. Despite the relatively quick nature for detailed data the SeaTek provides, one pass over a 150 cm region (i.e., 4 cm lateral resolution) requires \( \approx 15 \) minutes which is too slow for capturing detailed ripple migrations which can be on the order of 10 cm/hr. Furthermore, although the SeaTek is able to measure under wave conditions, the increase in suspended sediment alters the true acoustic backscatter, and combined with ambient signal noise from other operational electronics, presents a very difficult environment to obtain accurate results.

(ii) Keyence Laser Displacement Sensor: In special cases in which the sharp gradients and/or smaller secondary bedform features occur in the
bathymetry and extremely fine scale measurements are required to resolve the region, a Keyence laser displacement system (head sensor model LB-300 and controller model LB-1201) is utilized as long as measurement duration is not a factor. The laser sensor requires an offset of 30 cm and can measure within the range of \( \pm 10 \text{ cm} \) from this offset with a vertical resolution of 0.5 \( \mu \text{m} \) over a spot diameter of roughly 1.2 x 2.5 mm (Keyence Corporation, 1992). The manufacturer supplied calibration curve for normal (air) conditions, verified in the laboratory, is given by the relation

\[
\Delta = 0.3 + 0.05V, \quad (3.8)
\]

where \( \Delta \) is the distance in meters from the sensor to the boundary, and \( V \) is the analog output voltage of the Keyence sensor. However, despite this superb resolution, this sensor is a point measurement and requires movement in both the lateral and longitudinal directions requiring considerably more time than the SeaTek to sample the similar regional domain (i.e., on the order of 20x increase). After slowly draining the tank to avoid disturbance of the bedforms, the laser system was attached to the ADV support rod, and the Velmex systems moved the laser system at 0.5 cm/s over the central 73 cm lateral span from which the analog signal was sampled at 1 Hz (i.e., 0.5 cm lateral resolution) via an additional NI USB-6009 device. After a lateral pass, the system was advanced 1 cm in the x-direction and a new lateral scan was conducted. The process was repeated until all of the desired region was sampled. Sample results from the two bathymetric sensors can be seen in Figure 3.11.
Figure 3.11: Comparison of measured bathymetry data via two systems (not from same experiment): (a) Seatek data acquired at $dx = 1$ cm and $dy = 4$ cm (b) Laser data acquired at $dx = 1$ cm and $dy = 0.5$ cm. Note: the laser is able to resolve the small features and sharp gradient details better than the SeaTek.
Indirect Measurement via Image Analysis

While the both the SeaTek and Keyence laser capture the bathymetry quite nicely, both still require an excessive amount time to capture the entire bed in a timely manner (i.e., during an experiment). Thus, the implementation of camera systems provided for a rapid temporal evolution of a specified region or the entire bed. Refer to Figure 3.12 for diagram.

![Diagram of camera setup](image)

Figure 3.12: Illustration of setup for side camera used to produce evolutionary-bathymetric profiles of the sand bed

(iii) Canon 20D DSLR Camera: A Canon 20D digital single-lens reflex (DSLR) camera was used to capture the profile of the bed as seen through the plexiglas side windows. The camera was mounted to the primary carriage on an over-hanging support which positioned the camera at the mean sediment-water interface, ≈1.5 ft from the sidewall; refer to Figure 3.12 for a diagram. The camera allowed for full manual control over the image settings (zoom, focus, aperture, & shutter speed) which resulted in consistence quality of acquired images. Also, the camera’s captured image size was set to 1728 x 1152 pixels, in conjunction with the zoom, equated to a resolution
of $\approx 0.32$ mm/pixel. Figure 3.13 shows a typical image acquired from the camera. Details of the implementation procedure will be discussed in the upcoming Section 4.3.2.

![Figure 3.13: Typical image acquired from the Canon 20D DSLR camera. Annotations for scale, sediment-water interface, and incident wave propagation direction were added to the figure for clarity.](image)

(iv) Logitech® 2 Megapixel and 1.3 Megapixel Cameras: Rapid evolution over a selected region of the experimental sand bed was captured via two Logitech® cameras, QuickCam® Pro for Notebooks (2 Megapixel) and QuickCam® Ultra Vision (1.3 Megapixel). The cameras were placed normal to and 3.5 ft away from one of the 4-ft section plexiglas sidewalls, as seen in Figure 3.12, where the higher resolution camera (Pro) was positioned in-plane with the initial level of the sand bed (referred to as the sideward camera). The Ultra camera was $\approx 2$ ft above the Pro camera angled at roughly $30^\circ$ downward from the horizontal plane to view the sand near the sidewall as well as the majority of sand in the depth-wise lateral direction of that 4-ft section (referred to as the angled camera). This angled camera allowed for the visualization of the bedform(s) dimensionality and ensured that what was viewed/measured from the sideward camera was
indicative of the conditions in the middle of the tank (i.e., no sidewall effects). At maximum native camera resolutions, 1600 x 1200 pixels (Pro) and 1280 x 960 pixels (Ultra), resulted in resolutions of ≈0.71 mm/pixel (i.e., 14 pixels/cm) and ≈1.11 mm/pixel (i.e., 9 pixels/cm), respectively. However, since the Ultra camera was elevated and angled, it was used more for depth-wise visualization purposes rather than for digitalization and measurements of bedforms. Both cameras were connected to a computer which ran two instances of Yawcam 0.3.0 software, a freely available Java based image acquisition program (Lundvall, 2007), which were initialized together. Images were captured at 30-second intervals throughout the duration of the experiment with each image file name containing its capture time. Sample images resulting from the Logitech® cameras can be seen in Figure 3.14. Based on the images acquired from the sideward camera, bathymetric evolution profiles and ripple trajectory diagrams can be obtained by implementing the procedures described in Section 4.3.1.
Figure 3.14: Sample images from the Logitech® cameras: (a) sideward facing QuickCam® Pro for Notebooks (2 Megapixel) camera and (b) angled QuickCam® Ultra Vision (1.3 Megapixel) camera
CHAPTER 4

GENERAL EXPERIMENTAL METHODOLOGY

4.1 Signal Sampling Considerations

In dealing with periodic signals, it becomes imperative to be conscious of the periodicity of the phenomena one is measuring in addition to the sampling rate used to resolve the signal. It is commonly known from signal analysis that the highest frequency waveform that can be theoretically resolved for a given sampling frequency $f_s$ is referred to as the Nyquist frequency $N_f$ in which

$$N_f = \frac{f_s}{2} = \frac{1}{2\Delta t_s}, \quad (4.1)$$

where $\Delta t_s$ is the time interval between samples, refer to Bendat and Piersol (2000). Thus, (4.1) theoretically dictates that for a given water wave of frequency $f$, one must sample at $2f$ in order to resolve signal and avoid signal aliasing, that is,

$$f_s = 2N_f = 2f, \quad (4.2)$$

assuming the primary water wave frequency $f$ is equal to the Nyquist frequency (i.e., $f = N_f$). However, since the generated waves are often Stokian in form, it is required to resolve the higher secondary frequency $f_2$ which is $2f$, requiring the Nyquist frequency in (4.2) to be equated to $f_2$, resulting in a sampling frequency of $4f$. Generalizing (4.2) in order to resolve up to the $n^{th}$ harmonic, results in

$$f_s = 2N_f = 2(nf) = 2nf, \quad (4.3)$$

where $N_f = nf$ in which $n$ denotes the $n^{th}$ harmonic of the water wave. Conservatively, if the highest wave frequency the wavemaker is capable of generating is 1 Hz and the wave sensors are resampled at 8 Hz (roughly half
of the sensors’ maximum frequency), (4.3) results in $n = 4$, resolving up to the 4th harmonic, double that of the predominant two harmonics in the case of Stokes waves.

It is common practice with electrical signal processing (when signal noise is a problem) to sample at 10 to 100 times the maximum signal frequency in order to ensure an accurate representation of the true signal (Makela, 2007). However, due to the relatively low frequency (as compared to electronic signals) of the Stokes water waves generated in the laboratory experiments and lack of complex wave spectra of high frequencies, sampling at roughly one order of magnitude, around 14 Hz, of the highest desired frequency proved more than adequate to resolve the waveforms. With the frequency resolution criteria met, additional sampling constraints discussed in the following paragraphs were implemented in order to get accurate measurements of harmonic amplitudes.

Since the majority of the resulting information derived from the signal is a direct result of fast Fourier transforms (FFTs), one needs to be clever on the sampling interval and frequency in order to ensure the optimal sampling conditions. To avoid a discontinuity when representing the measured data as a repeated signal in the FFT sequence (i.e., matching points between the end of series and beginning of the next repeated), the duration of the total sample must be constrained so that an integer number of waves are captured. This can simply be achieved by equating the total time required for a specified integer number of waves to that of the total sampling duration,

$$N_w T = \frac{n_{pts}}{f_s},$$  \hspace{1cm} (4.4)

where $N_w$ is an integer number of waves, $T$ is the primary wave period [sec], $n_{pts}$ is the number of data points to sample (equal to $2^\alpha$ points), and $f_s$ is the sampling frequency [Hz]. Note that $n_{pts}$ are constrained by forcing the number of points sampled to be two raised to some integer power $\alpha$ since the FFT is more efficient with $2^\alpha$ samples. Lastly, a constrain must be imposed so that one results in an integer number equal to $2^\beta$ (were $\beta$ is a user specified integer) of equal time divisions within a single period, in addition to the aforementioned integer number of waves. This guarantees that the signal is continuous and sampled at the same discretely spaced points when the signal is repeated in a series during FFT process. This results in mitigating spec-
tral leakage which provides for accurate peak measurements of the harmonic amplitudes while concurrently aiding in the computations of phase averaging of synchronized velocities. Since the measurements always have the same integer number and positions within periods, one can easily ensemble average based on a number of points which defines a complete period, rather than using zero up-crossings or down-crossings to determine individual periods. As a result, these sampling considerations were implemented in all instrumental measurements conducted throughout this study.

4.2 Wave Measurements

4.2.1 Measurement Types

Numerous previous studies have been conducted exploring various methodologies to estimate wave reflections. These can often be generalized in one of three gaging methods (despite the way the measurements are analyzed): 1) synchronous spatially-separated wave gages, 2) synchronous co-located gages, or 3) asynchronous (and/or synchronous) spanwise repositioned gages (SRG).

The first method, synchronous spatially-separated wave gages, discussed by Goda and Suzuki (1976), based on the earlier work of Kajima (1969) and Thornton and Calhoun (1972), used two wave gages separated by a specified distance and positioned in-line with the direction of wave propagation to estimate the incident and reflected amplitude and phase components of the wave field via fast Fourier transforms. However, as stated by the authors, the method fails when the spacing between the two gages $\Delta_{gage}$ is equal to an integer number of half wavelengths, i.e., one should take care that

$$\Delta_{gage} \neq n_i \frac{\lambda}{2} \quad \text{for all } n_i=0,1,2,3,...,$$

(4.5)

where $n_i$ is an integer number, and $\lambda$ is the water wavelength. While this problem can be avoided, provided the generated wavelength is known \textit{a priori}, but in the case when it is not possible to have prior knowledge or when there are multiple frequencies are present, i.e., wave spectrum, it poses an issue. On further extension of the method, this failure can be avoided by
utilizing an extra gage, for a total of three gages, in which the two spacings are different. Despite this limitation and the fact that this Goda method uses linear wave theory assuming long-crested waves propagating over a flat bottom are normally incident to the reflective structure, it is commonly used in laboratory facilities to estimate wave reflection.

The second method involves two sensors (typically, a pressure sensor and current probe) positioned along the same vertical line, hence the term co-located gages. This method is commonly applied in the field as seen from such studies by Guza et al. (1984), Tatavarti et al. (1988), and Walton (1992). Further work by Hughes (1993) focused on laboratory experiments in which temporal records of a single point’s vertical and horizontal water velocities components or synchronous time series of co-located wave gage and horizontal velocity at a specified depth were used to estimate the incident and reflected waves.

Despite the wide acceptance of these two methods, the final method of asynchronous (and/or synchronous) spanwise repositioned gages was the one that was implemented in the studies presented herein as well as the basis for the WaveAR program discussed in Chapter 5. This method requires more than two spatial measurements along the tank, on the order of 0.5 m spacing and results in spanwise estimates of wave field properties such as the spanwise incident and reflected amplitudes. Although the additional sample locations prolong the temporal sampling extent of the measurements, the wave field over the entire span (or tank, provided points spanned the entire tank) is captured which is of the utmost importance when conducting studies within an environment where there exists spatial variability along the wave envelope. Even if one expects negligible variability (i.e., as in the case of purely progressive waves), this method should still be used to verify the conditions present. Furthermore, the acquired data can be reprocessed according to spatially-separated wave gage method assuming that the sensor pair used was sampled synchronously, resulting in multiple local estimates of reflection coefficients in addition to those based on the entire domain. The spanwise repositioned gage (SRG) method, as it is referred to herein, can be seen utilized in studies by Mathisen (1989), Rosengaus (1987), Carter (2002), and Landry (2004), to list a few. The procedure for the SRG method measurements conducted for the experiments presented herein is summarized in following section.
4.2.2 Procedure for Spanwise Repositioned Gages (SRG)

Since the wavemaker was capable of sustaining the input frequency for a range of excursion amplitudes, the input frequency could be prescribed independently of the span amplitude, without having to be concerned that a new span setting would alter the paddle frequency. Thus, for a desired water wave frequency \( f \), the empirical relationship

\[
    f = 0.9774f_{wm} + 0.0487,
\]

from Cataño-Lopera (2005), where \( f_{wm} \) is input frequency of the wavemaker, was used to estimate the input setting. The waves were sampled using the UltraLab\textsuperscript{®} ULS system, and from FFT methods, a primary wave frequency was computed. Based on this computation, slight corrections were made to the wavemaker input frequency (if needed) and the wave frequency was recomputed. This process was iterated until the desired wave frequency was achieved. Then, adjustment to the wave amplitude was performed by changing the span knob on the wavemaker. Adjusting the span as a secondary parameter allowed for the correct sampling parameters (i.e., sampling considerations discussed in Section 4.1) to be configured which resulted in an accurate estimation of the water wave amplitude. It should be noted that for the case of standing waves with the wall positioned at 26.37 m from the paddle (i.e., \( \approx 22.0 \) m from the start of the sand bed) only a select number of wave conditions are possible to achieve a stable wave field.

Once both the frequency and amplitude parameters were configured, the primary carriage was positioned at 400 to 600 cm from the beginning of the sand bed. Sampling via all four sensors (spaced 0.5 m apart) was conducted based on the consideration previously discussed in Section 4.1, and measurement results were saved to data files. The primary carriage was then moved further along the sand bed at a distance determined by the desired spatial resolution of the wave field. Typically, sensor measurements every 0.5 m are adequate (carriage moved at 2 m intervals due to the 4-sensor array); however, for greater details, sometimes a 0.25 m measurement spacing was employed (moved in repeated interval combination of 0.25 m then 1.5 m). This process of acquiring the temporal surface displacement records along the desired span of the tank will be denoted as a wave run for ease of fu-
ture referencing. Then, the resulting measurements of the wave run were processed using a custom developed MATLAB® code and graphical user interface (GUI) entitled WaveAR discussed in greater detail in Chapter 5.


In Figure 4.1, the reader can see the two components of the MATLAB® GUI wave code which includes the parameter configuration panel and the real-time comparison plot of measurements and fitted theoretical equations. Figure 4.1(a) depicts the GUI with only the measured data and no fitting parameters selected. The solid black line with circle markers and dashed line denote the first and second harmonic amplitudes, respectively. The appearance of a strong spatial variation in the wave envelope which is representative of a standing wave field can be seen. As mentioned in Section 2.1.2, the locations of zero vertical free surface displacements are wave nodes whereas places of maximum vertical excursions are considered wave antinodes. In Figure 4.1(b), the results of the parameter fitting based on the plotted experimental data can be seen. The solid blue line depicts the fitting results for the first harmonic amplitude whereas the solid red line represents the fit for the second harmonic. From this example figure, it can be seen that the fit agrees well to the measured data; however, there is a slight long-scale variation in the second harmonic which is indicative of the minor presence of the aforementioned free second harmonic within the tank (refer back to Section 2.2.3).
Figure 4.1: Graphical user interface of the custom MATLAB® code (WaveAR) to fit wave parameters: (a) measured data shown only (solid black line with ○ markers and black dashed line denote first and second harmonic amplitudes, respectively, and (b) includes fitting (solid blue line and red lines represent fits for first and second harmonics, respectively.
4.3 Bathymetric Measurements

4.3.1 Detailed Evolution Images

In addition to the wave measurements, the detailed records of a specified sand bed region were captured using the Logitech® cameras presented in Section 3.2.6. Primary data was computed from the Logitech® camera located on plane with the mean sand bed and normal to the window, at position (a), as illustrated in Figure 3.12. Prior to acquiring the images over the experiments, a calibration image was taken. A white sheet of paper having circular shaped targets spaced in a square grid 2 cm apart was affixed to the side of the plexiglas panel of the tank. Then, the camera parameters (exposure, gain, contrast, white balance, etc.) were adjusted to achieve a well defined image of the black targets on the white sheet. The resulting image was captured as the calibration image. Based on knowing the physical distance of one of the circular targets in relation to the global tank coordinate system (i.e., distance from the start of the sand bed $x$ and vertical elevation from initial sand bed) the calibration grid could be referenced to the global coordinates.

The resulting image was then processed in a custom created MATLAB® script which utilized MATLAB®’s Hough transform function and example code by Peng (2005) in order to automatically identify the centroids of each of the circular targets. Refer to Shoelson (2008) for more information on the circular Hough transform method. Figure 4.2(a) shows the 3-D matrix of the output of the Hough algorithm where each peak represents the computed centroid of a target, and Figure 4.2(b) shows the computed raw target locations imposed on the calibration image grid. The raw results were filtered to acquire only the true target positions and used in the MATLAB® function `cp2tform` to create a polynomial image transform to account for lens distortion and later used to convert to scaled physical units.

With the calibration mapping complete, the subsequent images taken at 30-second intervals were passed through a second custom MATLAB® script which performed a black and white image thresholding and determined the sand-water interface for each image. The resulting profiles for each time were compiled together to generate ripple time stacks (or ripple trajectory plots) which allowed one to easily view the temporal evolution of ripples (and bars) over the course of the experiment, of which the initial 3 hrs is especially
important for ripple growth and migration due to the rapid changes that occur. Figure 4.3(a) illustrates one of these 3-dimensional ripple trajectory plots, and Figure 4.3(b) shows the mean ripple velocities associated with the ripples in Figure 4.3(a). Notice how the strong variation in ripple velocities along the x-direction are resolved, in addition to the full growth evolution of each ripple.
Figure 4.2: Results of circular Hough transform from MATLAB®: (a) accumulation matrix of the Hough transform where each peak is a detected circular target (b) depicts the unfiltered detected targets (blue circles with magenta * makers) superimposed on top of the calibration image grid.
Figure 4.3: Results of detailed evolution images: (a) sample ripple trajectory plot (b) mean ripple velocities associated with the above ripple trajectory plot.
4.3.2 Processing Panoramic Images

While the detailed evolution image method provided detailed results, it was limited to roughly a 4-ft section along the sand bed. Thus, the Canon 20D DSLR camera affixed to carriage camera support, as depicted in Figure 3.12 and mentioned in Section 3.2.6, was utilized. An aluminum I-shaped bracket (used as a momentary spacer between the camera and the plexiglas wall) and tri-axis bubble level mounted in the hot shoe of the camera were used to establish that the camera was on a level plane and located normal to the sidewall. Furthermore, the camera settings (zoom, focus, etc.) were adjusted and set to manual mode prior to acquiring images which focused the settings to be static. The primary carriage was positioned at the end of the desired span and the carriage was moved at approximately 0.6-ft intervals taking an image at each location.

In order to minimize lens distortions, a commercial software package, *PTLens 7.6.1*, was used to automatically correct for the distortions. Also, to mitigate optical diffraction by viewing through the plexiglas, the camera was moved at small longitudinal increments which allowed for roughly 50% overlap among images, so that only the center portion of each image was used, and the individual images were stitched together on/near the sediment-water interface for composite image profile of the entire sand bed. The composite profile (i.e., panoramic image of the bed) was performed via another commercial software, *PanaVue ImageAssembler 3*, which allowed for precise manual control of stitching flag points between images. For example, a resulting panoramic image can be seen in Figure 4.4. Refer to Niemann (2004) and PanaVue (2006) for technical documentation regarding PTLens and Image-Assembler softwares, respectively.

Once the panoramic was created, the image was imported into an open source image editing program, *GIMP 2.4*, and regional based black and white thresholding was performed since the lighting along the entire tank was nonuniform despite using a halogen light bulb as a local light source. After the thresholding, the image was edited to ensure a sharp interface and the only transition from the white pixels (water) to black pixels (sand) occurred only at the water sand interface. Though this required a considerable amount of time, it assured clean results from the subsequently applied MATLAB® script which scanned the entire image column-wise for the pixel
transition from white to black and later re-scaled the pixel values to physical coordinates along the tank, resulting in a complete bed profile associated with that “shot” sequence of acquired images. (Refer to Appendix B for detailed directions for process bar images.)
Figure 4.4: Typical resulting panoramic image composed from ImageAssembler 3. (Note: the image is vertically exaggerated to enhance finer details for presentation.)
CHAPTER 5

WAVEAR: AN EASY TO USE TOOL TO RESOLVE INCIDENT AND REFLECTED WATER WAVES

5.1 Abstract

WaveAR is a program that was developed to aid in the analysis of water waves generated in laboratory flumes. The program accounts for effects due to reflection, attenuation, Stokes second order waves, and free second harmonics, in order for the end-user to easily obtain the dynamics that are occurring over an entire wave tank. While the fundamental wave theory underlying this problem is well-known, there exists no publicly available program that researchers can readily utilize and compare against other standardized measurements. The work presented herein addresses the aforementioned issues by implementation of the established wave theories and sampling methods in a way that allows the end-user to apply this software to their data with relative ease. The program allows the user to resolve the dynamics along the entire tank and establish a common reference for which other similar wave experiments among various researchers and facilities can be compared. The MATLAB® based source code has been compiled for Windows®, Mac®, and Linux® operating systems to allow for ease of use and deployment. An additional companion program, Virtualizer, is included to allow the user to generate virtual wave measurements and explore the fitting results with WaveAR. Furthermore, this companion program serves as an excellent teaching tool to understand both water wave and data sampling theories.

5.2 Introduction

The necessity to measure surface waves is of great importance to a wide variety of littoral processes, such as wave attenuation and transformations,
sediment transport, and bed morphodynamics. Particularly under the controlled conditions of laboratory experiments, the ability to accurately resolve the water wave forcing is fundamental to ensure proper experimental conditions for a study or to explore the wave response to a specific test condition. Despite the growing use of more complex wave spectra (due to advances in wavemaker controls), many experimental studies still require the generation of monochromatic or Stokian type waves, for example, mine burial studies (Cataño-Lopera and García, 2005, 2007), wave friction factor estimates (Carter, 2002), and bedform evolution (Cataño-Lopera and García, 2006a,b; Landry and García, 2007).

In the case of wave tank studies, researchers generally need to resolve and quantify the incident wave amplitude and reflection coefficient, among other key parameters, and often use methods based on two wave gages (Thornton and Calhoun, 1972; Goda and Suzuki, 1976), or three gages (Mansard and Funke, 1980; Isaacson, 1991). These methods are well-established and quickly estimate the wave parameters within the facility rather than using the average of maximum and minimum wave heights obtained from measuring the wave envelope which is regarded as time-consuming and subject to human error (Nallayarasu et al., 1995). However, it has been shown in the special case of bedform geometries (Landry et al., 2009) that simply knowing the wave parameters (i.e., amplitude and reflection) without complete knowledge of the wave envelope (or wave profile) does not give a complete understanding of the dynamics associated with bedform characteristics.

Thus, in order to expedite and reduce human error due to the aforementioned wave envelope method, a new user-friendly program, WaveAR, is presented herein. This program relies on classical second order Stokes wave theory to construct a relation for the wave envelope and fit the theory to the measured data via minimization of least-squared error to quickly and accurately resolve a complete view of the wave forcing. While resolving the entire envelope is still more time consuming than the two and three gage methods, the program results of WaveAR are indispensable for a complete understanding of the wave dynamics along the tank. For more time-sensitive experiments about a small localized region, if the number of gages is limited, it is recommended that at least one set of measurements (i.e., prior to, during, or after the experiment) be processed with the WaveAR program, which then can be used in conjunction with the more rapid methods.
previously mentioned. However, for cases that require resolving the physics within finite distances (e.g., bedform morphodyanmics), it becomes essential to acquire multiple wave surface profiles to adequately capture the interaction between the wave forcing and the evolving sediment bed. It has been shown that for the case of parallel bar formation, intervals of approximately 3 hours or longer, depending on the stage of the bed evolution, are sufficient to capture the sand bar and surface wave interaction (Landry, 2004; Hancock, 2005).

5.2.1 Development history of the software

The conceptualization of this code grew out of requirements during combined experimental and numerical efforts to observe, measure, and predict the evolution of large scale sand bars in response to various imposed water wave forcing conditions in the Ralph M. Parsons Laboratory at Massachusetts Institute of Technology (Landry, 2004; Hancock, 2005). The key problem was resolving the wave profile along the entire tank multiple times over the course of each experiment and translating those measured results into wave parameters (e.g., incident wave amplitude, reflection coefficient, phase shift, free second harmonic amplitude, and wave attenuation). The resulting parameters would be pertinent inputs for numerical model verification and prediction.

Though numerous methods and codes were available to decompose the wave field as mentioned in Section 7.2, only the wave envelope approach was most relevant. Based on the previously developed reference measuring method (RMM) by Rosengaus (1987) for conditions of small wave reflections, the theory underlying WaveAR was generalized for both low and high reflections, developed into a numerical code, and encapsulated in a dynamic user-friendly interface (Hancock, 2005). In subsequent related experimental work on bedform evolution at the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign, the core functionality was revised and expanded by the author for use in a generic wave tank facility as well as for virtual data generated by a companion program, Virtualizer. Throughout the development, WaveAR has been continuously improved and validated against numerous experimental conditions (both physical and virtual) and has remained a vital tool in analyzing wave characteristics (Landry,
5.3 Brief Theoretical Background

The purpose of the work explained herein is to describe the computational characteristics, implementation, and applicability of the software rather than focusing on the well-established theory on which the code is based. However, to better elucidate the importance of this model, a brief overview of the supporting theory is presented below.

The software assumes that the water waves to be measured can be adequately described by second order Stokes wave theory which can be found in standard wave mechanics texts (Mei, 1989; Dean and Dalrymple, 1991). As Madsen (1971) theoretically explained, a piston wave maker with a sinusoidal monochromatic forcing will generate a wave at the primary frequency and a secondary bound wave (associated with Stokes theory). In addition, a free second harmonic (which is not bound to the first harmonic $k_{2f} \neq 2k_1$) is also generated due to the wavemaker motion not perfectly matching the fluid particle orbital displacements. This free second harmonic moves slightly slower than the primary wave resulting in a modulation of the second harmonic wave components along the wave tank. Utilizing this theory, we assume that there exists both incident and reflected waves associated with each of the following harmonics: first, bound second, and free second. The following subscripts: $1, 2b, 2f, i, \text{ and } r$ denote the first harmonic, bound second harmonic, free second harmonics, incident wave, and reflected wave, respectively. The first harmonic incident wave can be expressed as

$$
\eta_{1i} = a_{1i} \cos (\omega_1 t - k_1 x),
$$

(5.1)

where $a_{1i}$ is the incident wave amplitude, $\omega_1$ is the angular frequency, $t$ is time, $k_1$ is the wave number, and $x$ is the longitudinal spatial position (positive in the direction of the incident wave). Likewise, the reflected wave associated with the incident first harmonic can be written as

$$
\eta_{1r} = a_{1r} \cos (\omega_1 t + k_1 x + \epsilon_1),
$$

(5.2)

where the reflected wave amplitude, $a_{1r} = a_{1i} R_1$, in which $R_1$ is the reflection
coefficient for the first harmonic, and $\epsilon_1$ is the relative phase shift between the incident and reflected first harmonic waves. From second order Stokes wave theory, the bound second harmonic incident ($\eta_{2bi}$) and reflected waves ($\eta_{2br}$) can be expressed as

$$\eta_{2bi} = \left[ \frac{(a_{i1})^2 k_1 \cosh(k_1 h)}{4 \sinh^3(k_1 h)} \left( 2 + \cosh(2k_1 h) \right) \right] \times \cos (2k_1 x - 2\omega_1 t),$$

(5.3)

and

$$\eta_{2br} = \left[ \frac{(a_{r1})^2 k_1 \cosh(k_1 h)}{4 \sinh^3(k_1 h)} \left( 2 + \cosh(2k_1 h) \right) \right] \times \cos (2k_1 x + 2\omega_1 t + 2\epsilon_1).$$

(5.4)

The total wave form is a superposition of the incident and reflected waves,

$$\eta = \eta_{1i} + \eta_{1r} + \eta_{2bi} + \eta_{2br} + \eta_{2fi} + \eta_{2fr}$$

(5.5)

with the inclusion of free second harmonic incident and reflected waves, $\eta_{2fi}$ and $\eta_{2fr}$, respectively. The free second harmonic components are similar to (5.1) and (5.2) with the “1” subscript replaced with “2f”. After some manipulation, the first harmonic amplitude surface variation along the tank can be written as

$$\eta_{1\text{max}} = (a_{i1} e^{-Lk_1 x}) \sqrt{1 + R_1^2 + 2R_1 \cos(2k_1 x - \epsilon_1)}.$$  

(5.6)

Similarly, for each of the second harmonics, the max amplitude of bound second harmonic can be expressed in complex form as

$$\eta_{2b\text{max}} = \left[ k_1 (1 + 2\cosh^2(k_1 h)) \frac{\cosh(k_1 h)}{4\sinh^3(k_1 h)} (a_{i1} e^{-Lk_1 x})^2 \right] \times \left[ e^{2ik_1 x} + R_2^2 e^{2i\theta} e^{2ik_1 x} e^{\ast} \right],$$

(5.7)

where $\theta$ denotes the phase for a wave as specified by its subscript and the superscript “*$" denotes the complex conjugate of the term, and the envelope
of the free second harmonic can be written as

\[ \eta_{2fi \text{ max}} = A_2e^{i\theta_2} \left[ e^{ik_2f_2x} + R_2e^{i\theta R_2} \left( e^{ik_2f_2x} \right)^* \right]. \]  

(5.8)

In order to get the total maximum envelope of the second harmonics, \( \eta_{2 \text{ max}} \), (5.7) and (5.8) are combined,

\[ \eta_{2 \text{ max}} = \eta_{2b \text{ max}} + \eta_{2fi \text{ max}}. \]  

(5.9)

The WaveAR program applies (5.6) and (5.9) to temporal experimental records of the water surface at numerous \( x \)-locations along the wave tank, i.e., SGR method discussed in Section 4.2. The code uses Fourier analysis to resolve the water wave lengths, periods, and individual harmonic amplitudes associated with each measurement location. A nonlinear curve-fitting routine using the least-squares approach is implemented to achieve the best fit for the theoretical relations, resulting in all the wave parameters, e.g., \( a, R, L, k, T, \theta \).

From the theory above, the procedure for generating a virtual wave field is straightforward. The Virtualizer program implements numerical probes at specified positions along the virtual tank to capture a time series of the total water surface according to (5.5). The results from these numerical probes serve as artificial measurements which can be resolved into various wave component parameters using the WaveAR software to allow the user to understand the methodology.

5.4 Software Description

As stated, the software has been developed in MATLAB®; however, to facilitate ease of use and deployment, compiled versions for Windows®, Mac®, and Linux® are freely available to download at the following website: http://vtchl.illinois.edu/software/. Two programs are included in the software package: the main program WaveAR (short for wave amplitude and reflection graphical user interface and pronounced Wave-A-R-) allows for graphical fitting of wave parameters to measured data; a companion program Virtualizer generates artificial measurements at specified numerical probe locations. The purpose of the Virtualizer is to facilitate understanding of how
the main WaveAR works and to serve as a teaching tool for students to explore wave theory and data sampling techniques.

5.4.1 Main program: WaveAR

The graphical user interface of WaveAR version 1.0 (shown in Figure 5.1) incorporates numerous dynamic interface controls (e.g., sliders, check boxes, edit boxes, and push buttons) to facilitate ease of user interaction. After opening the program, the user can select the directory of the profile data set to process via the “getdata” push button. Typically, the data format is such that all probe files are within a “run” directory of a particular experiment. Each probe text file is entitled with the location (expressed in centimeters) of the probe and contains a two column ASCII (American Standard Code for Information Interchange) format of time and water surface elevation, respectively.

Once the data directory is selected, the program resolves the wavelengths, wave periods, and harmonic amplitude displacements of the surface for each wave component and plots the results as seen in Figure 5.2. The user can then adjust each of the wave parameter values via the slider controls immediately adjacent to the corresponding parameter label. The numerical value next to the parameter label on the user interface, as well as the theoretical fit lines (solid blue line for first harmonic and red line for second harmonic) on the plot (e.g., Figure 5.2), are updated in real-time. In addition, the absolute relative error is computed as

\[
\text{error} = \frac{\sqrt{\sum (a_{\text{fit}} - a_{\text{measured}})^2}}{\sum (a_{\text{measured}})^2},
\]

where \(a_{\text{measured}}\) are the measured surface harmonic amplitudes at measured \(x\)-positions along the tanks, and \(a_{\text{fit}}\) are associated fit results for surface harmonic amplitudes at the same measured \(x\)-positions. The error values associated with the user-selected fitting parameters are displayed in the upper right corner of the main interface (Figure 5.1), as indicated by “error1” and “error2”. The “AutoFit” button allows for parameter fitting to be assisted by minimizing the error associated with each harmonic as computed from (5.10). The final results can be exported to a standard text file via the
“Print results” button. Also, the check boxes along the left side of Figure 5.1 enable the parameter to become static in the auto-fitting process for added end-user control. Additional controls (i.e., “View Spectrum” and “Check Sampling Rate” buttons) allow the user to view the single-sided FFT spectra at each of the sampled $x$-locations to explore the full spectra and ensure the Fourier analysis is providing accurate results. For instance, if the data is not sampled properly, a well known spectral leakage problem (attributed to the discontinuities in the series of replicated signals during FFT analysis) becomes clear in spectrum, indicated as broadening of the peaks.

While a variety of windowing methods exist to mitigate leakage, these more complex methods can be avoided in the simple case of second order water waves, provided that the harmonic frequencies of the waves are known a priori (Bendat and Piersol, 2000). By selecting the “Check Sampling Rate” button, the user can determine the best sampling parameters to minimize leakage and accurately resolve the waves during Fast Fourier Transform (FFT) analysis as shown in Figure 5.3. To achieve this, the program implements the simple relation,

$$\frac{N_{\text{pts}}}{f_s} = TN_{\text{waves}},$$

(5.11)

where $N_{\text{pts}}$ is the integer number of $2^n$ sample points in the times series, $N_{\text{waves}}$ denotes the integer number of $2^m$ waves to sample, and $n$ and $m$ are user specified integers. The desired sampling frequency is $f_s$, and $T$ is the wave period. Additional constraints on the desired sampling frequency must be imposed. The frequency is limited by the maximum possible sampling
frequency of the device (i.e., $f_s \leq f_{s\text{max}}$) and should satisfy the Nyquist frequency in conjugation with the associated harmonic to resolve, $f_s \geq f_{\text{Nyquist}}$, where $f_{\text{Nyquist}}$ is the Nyquist frequency which is twice the frequency of the harmonic to be resolved. In the case of resolving up to the $n_{\text{harm}}$-th bound harmonic, the prior expression can be stated as $f_s \geq 2n_{\text{harm}}f_1$, in which $f_1$ is the first harmonic frequency. (Note: the reader should refer to the help documentation included with the software package for specific details regarding the required file structure, program parameters, and step-by-step instructions for using the code.)

Figure 5.2: Dynamic graph associated with WaveAR. Black solid line with open circle markers denote measured first harmonic amplitudes. Dashed black line represents measured second harmonic amplitudes. The solid blue and red lines signify the theoretical fit lines for first harmonic and second harmonic, respectively. (Note: fit lines are intentionally not optimized for clear depiction).
5.4.2 Companion program: Virtualizer

While the WaveAR program was primarily designed to analyze laboratory measurements, the software can also be used to analyze virtual datasets, which is especially useful for educational settings that may not have the laboratory resources at their disposal. The graphical interface for the artificial dataset creator, Virtualizer, can be seen in Figure 5.4 with key input parameters grouped into various panels. The user can control first and free second harmonic wave characteristics (i.e., amplitude, reflection, period, phase, etc.) and the inclusion of a bound second harmonic (i.e., Stokes waves). Furthermore, parameters such as spatial and temporal ranges enable full control of the domain and duration of the simulation visualization, and the “data sampling parameters” enables the simulated data to be sampled at specified intervals in space and time (independent of the simulation visualization parameters).

Once a set of user-inputs is selected, the program generates an animation of the wave interaction and saves the sampled data to text files (provided that the saving option was enabled) which are ready to be processed by WaveAR. Finally, a useful feature incorporated into the “?” button near the sampling frequency on the interface enables users to quickly determine the best sampling rate for a given wave period and number of samples. This ensures accuracy in resolving the waves during Fast Fourier Transform (FFT) analysis, avoiding the aforementioned spectral leakage issues.
Max Sensor limit = 25 Hz (user input)
Number of harmonic to resolve = 3 (user input)
Entered wave period = 2.6300 sec
Min sampling for 3 harmonics is 4.563 Hz

----------- Complete List (#points2sample = 2048) -----------
">" = GOOD values, between 4.56274 Hz and 25 Hz

<table>
<thead>
<tr>
<th># of Waves</th>
<th>Sampling Frequency[Hz]</th>
<th>Time2sample[min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>389.35361</td>
<td>0.09</td>
</tr>
<tr>
<td>4</td>
<td>194.67681</td>
<td>0.18</td>
</tr>
<tr>
<td>8</td>
<td>97.33840</td>
<td>0.35</td>
</tr>
<tr>
<td>16</td>
<td>48.66920</td>
<td>0.70</td>
</tr>
<tr>
<td>&gt;</td>
<td>32</td>
<td>&gt; 24.33460</td>
</tr>
<tr>
<td>&gt;</td>
<td>64</td>
<td>&gt; 12.16730</td>
</tr>
<tr>
<td>&gt;</td>
<td>128</td>
<td>&gt; 6.08365</td>
</tr>
<tr>
<td>256</td>
<td>3.04183</td>
<td>11.22</td>
</tr>
<tr>
<td>512</td>
<td>1.52091</td>
<td>22.44</td>
</tr>
<tr>
<td>1024</td>
<td>0.76046</td>
<td>44.89</td>
</tr>
<tr>
<td>2048</td>
<td>0.38023</td>
<td>89.77</td>
</tr>
<tr>
<td>4096</td>
<td>0.19011</td>
<td>179.54</td>
</tr>
<tr>
<td>8192</td>
<td>0.09506</td>
<td>359.08</td>
</tr>
<tr>
<td>16384</td>
<td>0.04753</td>
<td>718.17</td>
</tr>
<tr>
<td>32768</td>
<td>0.02376</td>
<td>1436.33</td>
</tr>
<tr>
<td>65536</td>
<td>0.01188</td>
<td>2872.66</td>
</tr>
<tr>
<td>131072</td>
<td>0.00594</td>
<td>5745.32</td>
</tr>
<tr>
<td>262144</td>
<td>0.00297</td>
<td>11490.65</td>
</tr>
<tr>
<td>524288</td>
<td>0.00149</td>
<td>22981.29</td>
</tr>
<tr>
<td>1048576</td>
<td>0.00074</td>
<td>45962.58</td>
</tr>
</tbody>
</table>

Recommended Sample Frequency = 24.3346 Hz
Using number of sample points = 2048

Figure 5.3: An example of the program results for the recommended sampling frequency to implement based on constraints associated with (5.11). For this example the user specified a 2048 number of samples and wave period of 2.63 sec which resulted in “good” sampling rates of 24.3346, 12.16730, and 6.08365 Hz, indicated by the “>” symbol to the left of the values. From this subset, the program recommends the highest available “good” sampling rate which in this example is 24.3346 Hz.
Figure 5.4: Graphical user interface for the Virtualizer companion program, which generates analytical datasets for testing the main WaveAR program.
5.5 Applications

5.5.1 Resolution of wave parameters

As mentioned, WaveAR was created in response to a crucial need to rapidly resolve multiple entire-tank wave field measurements during bedform evolution studies (Landry, 2004; Hancock, 2005; Landry et al., 2009). Throughout numerous multi-day experiments, complete sets of wave runs were conducted at specified time intervals during each experiment as shown in Figure 5.5. Table 5.1 provides the corresponding wave parameter results via WaveAR analysis for one such experiment. A detailed outline for a typical measurement procedure is presented next.

Figure 5.5: Example of typical wave profile measurements sampled at specified times throughout the experiment (Landry, 2004).
Table 5.1: Fitting results from WaveAR for wave measurements displayed in Figure 5.5

**Detailed example outline of using WaveAR to measure a wave surface profile:**

This section details the methodology of acquiring surface wave profiles for the case of experiments presented in Landry (2004). For this study, an array of three wave gages were spaced at 0.5-m intervals (along the direction of wave propagation, i.e., $x$-direction) on a carriage that was capable of translating along the entire 16.5-m test section.

1. Once the wave field has stabilized from the onset of the wave generation (roughly 5 to 10 minutes), the wave gage carriage is positioned around an antinode or quasi-antinode, and wave measurements are taken at a sufficient sampling rate to resolve the wave period, i.e., above the Nyquist frequency. (Note: since this step serves to resolve the primary period, the additional sampling criteria stated in (5.11) are not required at this point.)

2. The wave measurement files are imported into the WaveAR program (using the “Get Data” button), and the data can be probed. Checking the spectrum and refining the sampling rate (to minimize leakage) are conducted via “View Spectrum” and “Check Sampling Rate” buttons, respectively.

3. Once the new sampling rate is estimated (via the results of “Check Sampling Rate” button) the user can re-measure the surface waves at that sampling rate or sample at a higher rate and then down sample to that rate prior to processing with WaveAR. This sampling rate is
used to acquire measurements at additional $x$-locations via translation of the carriage along the tank. For these experiments it was found that the initial measurement profile at 0.25-m spacing and subsequent measurements at 0.5-m spacing along the $x$-directions were adequate to resolve the waves and mitigate any experimental variation.

4. After all the $x$-location measurements for a wave profile are obtained, the user can import all the files into WaveAR and obtain the data fitting plot shown in Figure 5.2. The various user interface controls on the main window (Figure 5.1) can be used to easily and quickly fit the theoretical fit lines to the data and resolve all the necessary wave parameters. Results can be displayed to the screen and saved to a fitting file for later use.

5. This procedure is then repeated for each additional wave profile set or wave measurement run.

5.5.2 Second harmonic correction

The presence of a pronounced free second harmonic can significantly alter the surface wave envelope and impact the bedform development. Madsen (1971) first derived a theory for canceling the free second harmonic within a facility. However, the theory was limited to flat bottom and zero beach reflection and, unfortunately, becomes inapplicable in cases where tanks have bottom transitions or other complex geometries (e.g., small ramp to transition the bed to sediment test section). In these more complex cases, the only way to properly cancel the free second harmonic is by an iterative trial-and-error procedure (Hancock, 2005). The WaveAR tool allows the user to measure the phase and amplitude of the free second harmonic and aids in estimating the necessary second-order correction to the wave maker controller for each iteration of the procedure. Figure 5.6 and Figure 5.7 illustrate the resulting harmonic amplitude plots before and after the free second harmonic cancellation procedure, respectively.
Figure 5.6: Harmonic amplitude plot prior to free second harmonic cancellation. Presence of the free harmonic can be seen in the slow modulation of the measured second harmonic amplitude (black dashed line).

Figure 5.7: Harmonic amplitude plot after the free second harmonic has been canceled. The slow modulation is no longer present in the measured second harmonic amplitude (black dashed line).
5.6 Discussion

The main WaveAR program can be easily implemented for data files and quickly allows the user to understand the wave dynamics throughout the entire tank. Speed of implementation is limited by the number of individual wave probes used to measure the wave forcing. While more time demanding than the other methods for a small number of gages, it is recommended that the profiling method be conducted in conjunction with other faster methods to ensure that a complete view of the wave dynamics is achieved. For instance the presence of the free second harmonic spatial variation would be overlooked if the wave profile was not acquired. As typical with data collection, care must be taken to ensure the proper sampling rates to avoid spectral leakage during the FFT analysis. As discussed in Section 5.5.1, improper rates can results in a reduced harmonic amplitude associated with dominant harmonic frequencies. Although the fitting algorithm is limited to second order Stokes waves (with a free harmonic), the program can still be used to view and quantify first and second harmonic components of more complex wave fields, for example, Cnoidal waves, JONSWAP spectra, etc.

5.7 Conclusion

WaveAR is a user-friendly program for Windows®, Mac®, and Linux® operating systems which allows the user to readily process wave surface elevation data to achieve a clear understanding of the wave dynamics within a wave tank facility and allows for a unified benchmark (based on well-understood wave theory) for researchers to make comparisons between datasets. Although often more time consuming than the two and three gage wave methods, profiling the tank and using WaveAR resolves additional key wave parameters which otherwise would be omitted. In addition, the program provides detailed information regarding any spatial variability in the wave field which the quicker methods are unable to capture. Furthermore, the additional Virtualizer program allows the exploration of WaveAR results and serves as an excellent teaching tool to explore water wave and data sampling theories.
CHAPTER 6

EFFECT OF SPATIAL VARIATION OF A WAVE FIELD ON THE RESULTING RIPPLE CHARACTERISTICS AND COMPARISON TO PRESENT RIPPLE PREDICTORS

6.1 Abstract

Laboratory experiments analyzed herein focus on the validity of ripple predictors under spatially variable wave envelopes. Present-day ripple predictors commonly derived from laboratory data (for smaller wave periods of about 1 to 4 s) within which only small regions of the facilities were used to observe and measure the sand ripple geometric characteristics of the nearly progressive waves measured overhead. When extended to large sediment test sections, our results show that the predictors are still valid along the tank under wave conditions which have significant wave envelope spatial variation (e.g., standing waves), provided that ripple predictors use the wave measurements directly above the respective locations within the computations. Results indicate that even under the case of mild reflection, noticeable variation in ripple characteristics can be seen along the sediment test section; compelling the necessity of measuring the wave field along the entire sediment section to achieve accurate results.

6.2 Introduction

Sand ripples have long held the attention of the coastal research/engineering community. The presence of which dramatically alter and control the near-bed hydrodynamics and sediment transport. Ripples can even affect the forcing of the system by attenuating the surface waves. It is for these very reasons that numerous previous laboratory studies have been conducted to

---

1 This chapter has been previously published as part of the OMAE 2009 conference proceedings (Landry et al., 2009). Reprinted with permission of the American Society of Mechanical Engineers (ASME).
investigate sand ripple characteristic for a given wave condition in order to extract empirical relations and aid in the enhancement of mathematical and numerical models to better reproduce the physical processes (Nielsen, 1981; Wiberg and Harris, 1994). In proceeding to establish ripple predictors, laboratory experiments have been conducted with controlled nearly-progressive monochromatic waves. In such experiments wave forcing and resulting ripple geometry (i.e., ripple wavelength, height, and steepness) were measured directly underneath only at a small region of the entire facility (Karim, 1999; Faraci and Foti, 2002), with the exception of Kennedy and Falcon (1965) who measured over the entire sediment section. Since laboratory conditions are typically limited in water depth, wave period, and amplitude, field studies have also been conducted (Nielsen, 1981). In many of the field investigations ripples were measured directly underneath fairly progressive waves and uniform grain size distributions. While these nearly uniform conditions are ideal to aid in the establishment of ripple predictors, real wave conditions often have considerable reflection creating a noticeable spatial variation in the water wave envelope as well as a spectrum of water wave periods, amplitudes, and directions. It is with this condition in mind that analysis of the large scale laboratory experiments presented herein focus on the validity of the ripple predictors under noticeable spatial variability of the wave envelope along the entire sediment test section.

6.3 Experimental Dataset

6.3.1 Original Dataset Overview

Data analyzed herein was obtained from a previously large scale laboratory study conducted in the Ralph M. Parsons Laboratory at MIT in which controlled and detailed measurements of wave forcing and bathymetry (ripple and bars) evolution were recorded throughout the duration of all 16 experimental conditions. Experimental runs included cases of various wave amplitudes and wavelengths, high and low reflection coefficients, and sand beds of predominately coarse or fine grained sands. An experiment was also conducted with a bi-modal mixture of the two sediment types (Landry et al., 2007). The full experimental dataset and details regarding measurement pro-
6.3.2 Selected Data Subsets

Though the original dataset contains 16 experiments, only two experiments were selected from the dataset to exemplify the methodology presented in this chapter. The first case was a high reflection case (R = 0.88) where the wave period was 2.53 sec, the incident first harmonic amplitude was 2.8 cm, and the second harmonic incident amplitude was 0.19 cm. The second case considered a low reflection coefficient (R = 0.24) with wave period of 2.63 s, and had incident first and second harmonic wave amplitudes of 5.7 cm and 0.17 cm, respectively. Both experiments had a mean water depth of 60 cm and 0.2 mm median sand grain size diameter $d_{50}$. For the selected experiments, the dataset contained measures of both the water wave envelope and sediment bed profile along the entire sediment section at various temporal intervals over the course of the experiment. In order to explore the effects in which pronounced bar formation impacts the superimposed ripples, only the initial bathymetry (i.e., onset of bar growth) and final bathymetry (i.e., equilibrium bar formation), as well as the corresponding wave forcing, are analyzed.

6.4 Dataset Analysis

6.4.1 Wave Computations

Based on the reported first harmonic amplitudes along the wave tank, a surface envelope relation from standard linear wave theory for partially reflected waves can be stated as

$$
\eta = \sqrt{(a_i^2 + a_i^2 R^2 + 2a_i^2 R \cos(2kx + \theta))},
$$

(6.1)
where $\eta$ is the free water surface amplitude variation, $a_i$ is the incident first harmonic amplitude, $R$ is the reflection coefficient (mentioned previously), $k$ is the water wave number ($k = 2\pi/L$, where $L$ is the water wavelength), $x$ is the longitudinal distance in the direction for incident wave propagation measured from an user defined datum, i.e., start of sediment bed, and $\theta$ is the relative phase shift between incident and reflected waves (Dean and Dalrymple, 1991). Similarly, Airy theory for partially progressive waves was used to compute the maximum near-bed horizontal velocity $u_{bm}$. From the generalized form of linear waves having a specified reflection $R$, the horizontal water velocity $u$ is

$$u = \frac{a_i \omega \cosh k(z + h)}{\sinh kh} (\cos(kx - \omega t) - R \cos(kx + \omega t + \theta)),$$  \hspace{1cm} (6.2)

where $\omega$ is the angular velocity ($\omega = 2\pi/T$, where $T$ is the wave period), $t$ is time, $h$ is mean water depth, and $z$ is the vertical distance above the still water level. The bottom horizontal velocity $u_b$ can be determined by replacing $z = -h$ in (6.2) resulting in

$$u(z = -h) = u_b = \frac{a_i \omega}{\sinh kh} (\cos(kx - \omega t) - R \cos(kx + \omega t + \theta)),$$  \hspace{1cm} (6.3)

and the bottom horizontal velocity envelope can be deduced by taking the derivative of (6.3) with respect to time and setting it equal to zero. Solving the resulting relation for $t$ which corresponds to the time of maximum for a specified $x$ and replacing this solution for $t$ in (6.3) results in an expression for the bottom orbital maximum horizontal velocity $u_{bm}$ at each $x$-location, stated as

$$u_{bm} = \frac{\omega a_i}{\sinh kh} \sqrt{1 + R^2 - 2R \cos(2kx - \theta)}.$$  \hspace{1cm} (6.4)

Finally, using the relationship between the bottom orbital diameter $d_o$ and the bottom maximum horizontal velocity, $u_{bm} = \pi d_o / T$, a relationship for $d_o$ (which is often a key parameter in various commonly accepted geometric ripple predictor relations) can be expressed in terms of the wave parameters as

$$d_o = \frac{2a_i}{\sinh kh} \sqrt{1 + R^2 - 2R \cos(2kx - \theta)},$$  \hspace{1cm} (6.5)

allowing for evaluation at any $x$-location along the tank.
Figure 6.1: Illustration of computation of ripple geometric characteristics in regards to a single ripple after filtering out the mean bed elevation.

6.5 Measured Ripple Geometric Characteristics

Using the available bathymetry profile data, ripple geometric characteristics (i.e., ripple wavelength, and height) were computed centered on each ripple crest along the entire bed profile. Prior to ripple analysis, the mean bed elevations (i.e., sand bars) were subtracted from the original bed profiles to ensure clearer visualization and more accurate estimation of the ripple properties. Since ripples are comprised of a finite length over which the surface wave envelope responsible for their development exhibits variation, three different metrics were used to estimate the ripple properties and variability associated with each individual ripple. The height of each ripple was taken as the mean ripple height $\eta_m$ which is the average of the measured ripple stoss-height $\eta_s$ and the ripple lee-height $\eta_l$ (stoss and lee in reference to the direction of incident wave propagation). Ripple amplitudes ($a_m$, $a_l$, and $a_s$) are taken as half of the corresponding ripple heights (where subscripts maintain the same notation as with ripple heights). The reader is referred to Figure 6.1 below for a depiction of the computed ripple characteristics.

Regarding the ripple wavelength measurements, the mean wavelength was measured as the sum of the lee-length $\lambda_l/2$ and stoss-length $\lambda_s/2$ around the corresponding ripple crest. In addition, stossward and leeward based ripple
wavelengths were computed by doubling the corresponding measured stoss-length and lee-length, respectively. These leeward and stossward measured estimates were used to establish upper and lower bound error bars around the mean values to help quantify the variable associated with each mean ripple measurement. These error bars can be seen in Figure 6.2 and Figure 6.3, subplots (d) for ripple amplitudes and subplots (e) in relation to ripple wavelengths, which are subsequently discussed in Section 6.5.2.

6.5.1 Computed Ripple Geometric Characteristics Via Ripple Predictor

Based on wave measurements, a commonly accepted geometric ripple predictor presented by Wiberg and Harris (1994) was used to predict ripple wavelengths and amplitudes at 1-mm intervals along the entire measured sediment test section. Since the empirical predictor lacks a condition for the critical threshold for the initiation of sediment motion, the relation estimates ripples in sediment regions even where these small bedforms are nonexistent. Thus, the friction model by Grant and Madsen (1979) was utilized to compute the Shields parameter associated with every $x$-location along the sediment bed. Only regions in which the Shields parameter was greater or equal to the critical shear stress were considered as valid regions where the empirical ripple predictors were applied.

6.5.2 Results

Figure 6.2 shows results for the first case of high reflection ($R = 0.88$). Both the initial and final temporal measurements are reported with the earlier results (12-hrs) as unfilled or lighter shades than the darker latter measurements at 96-hrs. Subplot (a) depicts the measured first and second harmonic wave amplitudes along the entire sediment section with large and small markers, respectively. The corresponding wave envelope fit for the first harmonic from (6.1) is plotted as a black line. Based on the first harmonic envelope fitting relation, the near bottom horizontal amplitude stated in (6.4) is displayed in subplot (b). The corresponding bathymetric data for the complete sediment section is presented in subplot (c) as the solid black lines (having
the presence of high frequency fluctuations, i.e., sand ripples) and with a smoother solid black line which denotes the mean bed elevation (bar elevation only with the ripples filtered out). Subplots (d) and (e) illustrate the measured experimental ripple amplitude and wavelength, respectively, based on the methodology previously mentioned in Section 6.5. Circular markers denote the mean measured values, while the corresponding error bars encapsulate the values for the stossward and leeward estimated values. In addition, the geometric ripple predictor is shown as a thin solid line and the predictor corrected for critical stress criteria is denoted as the thicker solid line in both subplots. Note that the corrected predictor has regions of discontinuities which are indicative of regions below the critical Shields parameter (i.e., no ripples can theoretically form in these areas). Likewise for the case of low reflection, similar plots of the results are shown in Figure 6.3. For this case, the unfilled or lighter shades denote the initial time of 3-hrs (limited bar growth) and the final time of 12-hrs (pronounced bars present) is represented by the darker shades. Subplots (a) through (e) in Figure 6.3 are consistent with the aforementioned descriptions associated with the corresponding subplots presented in Figure 6.2.

6.5.3 Discussion

From Figures 6.2(a) and 6.3(a) it can be seen that the initial and final time wave measurements for each reflection case are essentially the same, indicating a stable wave field throughout either experiment. Due to this stability, the corrected ripple predictors computed from the waves were virtually the same for each case’s temporal measurements. Likewise, similar results for the measured ripple characteristics after having removed the mean bed elevation for each profile are achieved between the initial and final measurements. Thus, it seems that the presences of the large scale bedforms (i.e., sand bars) do not significantly alter the resulting ripples geometric characteristics which are superimposed upon the bars.

From the measured wave field amplitude harmonics presented in subplots (a) of Figures 6.2 and 6.3 measured along the entire sediment section, detailed insight into the wave forcing imposed to the sediment bed can be observed. According to the second harmonic amplitude wave field presented
in Figures 6.2(a) and 6.3(a), the second harmonic is void of a long scale spatial variation which is indicative of absence/cancellation of a free second harmonic within the wave flume. Madsen (1971) noticed that the free second harmonic is inherent to the boundary condition imposed by the wavemaker and presented a cancellation procedure for this free second harmonic under progressive waves over a uniformly flat bed. However, due to the complexities of tank bathymetry and high reflections, the experiments used herein employed a systematic experimental “trial and error” procedure to cancel the free second harmonic and eliminate any undesirable wave forcing which could significantly impact bedform morphodynamics (Landry, 2004; Hancock, 2005).

Furthermore, the measured first harmonic amplitude wave field along the entire tank for the low reflection case, shown in Figure 6.3(a), depicts a mild attenuation in the harmonic amplitude which is apparent in the linear decay of the envelope of the first harmonic amplitude. For simplicity, the fitted relation for the first harmonic amplitude (6.1) neglected the decay term. However, the fit agrees well with measured wave data especially in the case of high reflection, seen in Figure 6.2(a), and slightly overestimates the low reflection case measurements, Figure 6.3(a), by approximately 5% and 12% in the region near the beach ($x = 14$ m to 19 m) for the initial and final fits, respectively.

As one may surmise, the increase in wave reflection and spatial variability in the first harmonic amplitude envelope increased variation in both measured and predicted ripple lengths and amplitudes. Predicted ripple characteristics agreed well with the measured ripple properties. Notice there is a small overestimate in the predicted ripple geometric characteristics for the low reflection case which can be attributed to the wave fit slightly over predicting the wave forcing. Based on the predictors, percent differences as much as 85% for ripple amplitudes and 84% for ripple wavelengths over half a wave beat length ($L/4$) occurred for the high reflection case. [Note: Percent difference is computed as $(\text{fit}_{\text{max}} - \text{fit}_{\text{min}})/\text{data}_{\text{mean}} \times 100$, where fit values account for critical Shields parameter criterion.] Less apparent is how sensitive the bedform geometry is to minor spatial variation. Even under the case of mild reflection, noticeable percent differences in ripple characteristics of 56% in ripple amplitudes and wavelengths are present.
6.5.4 Conclusions and Implications

As expected, the case of higher reflection (i.e., case of greater spatial variability in the wave envelope) had the most impact on the percent difference in ripple characteristics resulting in 85% and 84% differences in ripple amplitudes and wavelengths, respectively. However, it was unexpected that even the case of low reflection (less spatial variation) would have a significant variation in resulting ripple characteristics of as much as 56% difference for both ripple amplitude and wavelength. Thus, the imperativeness of accounting for the spatial variability in the wave field by conducting detailed wave envelope records above the entire sediment region is clearly evident based on the results and discussions presented herein.

While rapid methods exist to estimate the amount of reflection (a major component of wave envelope spatial variability) such as the 2-gage method by Goda and Suzuki (1976) and 3-gage method (Gaillard et al., 1980), these methods lack the sufficient detail to truly quantify the complete “image” of the wave forcing present in the experimental facility. Only by taking multiple point measurements along the entire tank can one identify and measure the presence of long scale variation in the second harmonic amplitude (i.e., a free second harmonic) as well as measuring the wave attenuation which reading over a considerable distance. Roughly, measurements over two or more water wavelengths at small enough spatial intervals (less than a fourth of the water wavelength) to resolve the beats in the wave envelope are required. Even if these parameters are undesired, it should be considered good experimental practice to perform wave envelope measurements to ensure the conditions present within the tank. Detailed wave envelope information becomes invaluable for associated mathematical and numerical models to verify the wave forcing conditions along the domain of the model.

6.5.5 Future Work

While findings show distinct tendencies and provide a strong argument for the necessity of accounting for wave envelope spatial variability when studying bedform morphodynamics under various wave conditions, further research is required to accurately quantify the degree of variation in ripple characteristics for a specified range of wave conditions. Thus, such an understanding
would allow one to predict the range of expected ripple characteristic values (ripple wavelengths and amplitudes) for a given wave condition and aid in estimating a criteria for the wave envelope in which the spatial variation can be neglected in terms of the resulting ripple characteristics below. In addition, the experimental dataset used in the present manuscript was limited to Stokian waves. Great potential exists in exploring the effect of pronounced second harmonic amplitudes and/or wave spectrum on the resulting ripple characteristics along the entire sediment section. Furthermore, the extension of this study to field applications, in order to predict bed morphology from wave field data, is very promising.
Figure 6.2: Analysis of ripple geometries under high reflection ($R = 0.88$) experimental conditions. Note all subfigures include two temporal measurements (time = 12-hr and 96-hr) with the former time measurements illustrated with unfilled and/or lighter shades throughout the plots. Subplot (a): depicts the measured first and second harmonic amplitudes along the entire sediment section represented with larger and smaller markers, respectively. The resulting measurements fits based on (6.1) are denoted with solid lines. Subplot (b): plots the computed maximum near-bed horizontal velocity from (6.4) based on fitting the wave measurements. Subplot (c): shows the complete sand bed profile (ripples and bars) with the smoother lines indicating the filtered “bar only” profiles. Subplot (d) and (e): illustrate the results for ripple amplitudes and wavelengths, respectively. The circle markers represent the mean measured ripple amplitude/wavelengths with error bars indicated the upper and lower corresponding estimates. The thin solid lines denote the geometric ripple predictor relations of Wiberg and Harris (1994), while the thick solid lines highlight the applicable regions of the ripple predictors accounting for necessary Shields stress conditions.
Figure 6.3: Analysis of ripple geometries under high reflection ($R = 0.24$) experimental conditions. Note all subfigures include two temporal measurements (time = 3-hr and 12-hr) with the former time measurements illustrated with unfilled and/or lighter shades throughout the plots. Subplot (a): depicts the measured first and second harmonic amplitudes along the entire sediment section represented with larger and smaller markers, respectively. The resulting measurements fits based on (6.1) are denoted with solid lines. Subplot (b): plots the computed maximum near-bed horizontal velocity from (6.4) based on fitting the wave measurements. Subplot (c): shows the complete sand bed profile (ripples and bars) with the smoother lines indicating the filtered "bar only" profiles. Subplot (d) and (e): illustrate the results for ripple amplitudes and wavelengths, respectively. The circle markers represent the mean measured ripple amplitude/wavelengths with error bars indicated the upper and lower corresponding estimates. The thin solid lines denote the geometric ripple predictor relations of Wiberg and Harris (1994), while the thick solid lines highlight the applicable regions of the ripple predictors accounting for necessary Shields stress conditions.
CHAPTER 7

EFFECT OF WATER WAVE ENVELOPE VARIATION ON SAND RIPPLE MIGRATIONS

7.1 Abstract

Ripple morphodynamics is an integral aspect of a variety of coastal processes which include boundary layer development, friction factors, and sediment transport. Laboratory experiments analyzed herein focus on elucidating ripple migration dynamics under spatially variable water wave envelopes. Numerous previous studies have provided detailed information regarding ripple geometric characteristics, which has led to the formulation of many popular, present-day geometric ripple predictors. However, due to the scarcity of detailed data for ripple migration, fewer migration relations exist, and these predictors have only been applied assuming the case of purely progressive waves. This study provides crucial and detailed experimental data regarding ripple migrations measured over a large spatial extent under spatially varying water wave envelopes attributed to the more general condition of partially progressive waves (both low and high cases of reflection). The work herein shows significant variations in ripple velocities along the spatial extent of the wave field under cases of low reflection. Conversely, in cases of high reflection, ripple migrations are substantially reduced, having defined regions of positive and negative migrations. Results show that local Lagrangian mass transport velocities imposed via the surface wave envelope can be used to predict the variation in ripple migration velocities under mild to high wave reflections.
7.2 Introduction

The presence of sand ripples plays a significant role in a variety of littoral dynamics such as bottom boundary layer development, wave attenuation, and sediment transport. Since the early detailed observational studies on ripple evolution under oscillatory flows (Hunt, 1882; Darwin, 1883; Ayrton, 1910; Bagnold, 1946), ripple dynamics has remained a persistent topic of research. The first detailed field observations by Forel (1895) of ripple morphodynamics provided key insights. However, it was not until nearly half a century later that the first comprehensive field measurements of wave induced ripples by Inman (1957) were obtained, where ripple geometric characteristics (heights and wavelengths) were measured in situ as well as the water wave period and height from the boat above the ripple field.

Additional laboratory work (both in wave tanks and oscillatory tunnels) as well as field work (Kennedy and Falcon, 1965; Komar, 1974; Lofquist, 1978; Traykovski et al., 1999; Rousseaux et al., 2004a) led to numerous diagrams and formulations relating the oscillatory flow properties to ripple geometric characteristics. Ripple wavelengths, amplitudes, and steepnesses were often related to the Shields parameter, mobility number, or orbital diameter (which can also be expressed as maximum near bed horizontal velocity) based on linear wave theory (Airy, 1845). Gradually, numerous popular geometric ripple predictors (Nielsen, 1981; Grant and Madsen, 1982; Wiberg and Harris, 1994) began to emerge as well as a recent advancement resolution of the flow structure around ripples (Rousseaux et al., 2004b; Admiraal et al., 2006) and prediction of 2D- to 3D-ripple transitions (Pedocchi and García, 2009a,b).

However, while great effort has been placed on prediction of ripple geometric characteristics, considerably less experimental data (both in the lab and field) is available for ripple migration velocities. Based on limited data, it was shown in laboratory experiments (Inman and Bowen, 1963) that the bottom wave-drift current could reproduce an onshore ripple migration. Subsequent field work presented a relationship between near bed drift and ripple migration velocities; however, caution was stressed that this relation was not well understood and additional work was needed (Dingler, 1974; Dingler and Inman, 1976). Similarly, in subsequent work, researchers have managed to develop many popular ripple migration trends and relations despite the limited data (Kennedy and Falcon, 1965; Dingler and Inman, 1976; Blondeaux
et al., 2000; Faraci and Foti, 2002; Cataño-Lopera and García, 2006b). The majority of these predictors assume fully progressive waves, while others try to take into account wave skewness; yet, all are unable to account for the common occurrence of partially progressive waves, whereby spatial variability is introduced in the water surface envelope.

Similar to variation in ripple geometries (Chapter 6), ripple migration velocities have also been observed to be influenced by spatial variation in the wave field. Experimental studies with mild wave reflection and predominate bedload transport have documented that ripple migrations tend to be faster under the wave quasi-node and slower under the quasi-antinode (Landry, 2004; Cataño-Lopera and García, 2006b). However, as mentioned in recent work (Cataño-Lopera and García, 2006b), ripple migration is not well understood and still requires much work, reaffirming a consistent problem from earlier literature (Inman and Bowen, 1963; Dingler and Inman, 1976).

The principal purpose of this chapter is to present highly resolved ripple migration data from large-scale laboratory experiments and report key findings to provide further insight into migration velocities. Specifically, the study focuses on how the ripple migration velocities are affected by variations in the surface wave envelope, which is unprecedented due to lack of available detailed data. The work presented herein is a further examination of a newly available detailed laboratory dataset (which will otherwise be referred to as the DS) by Landry (2004). This chapter is organized into three subsequent sections. The first section describes the DS used for the analysis and explains the uniqueness of the data. The second section examines the applicability of the existing ripple migration formulations using the DS in which spatial variation in the wave envelope is apparent. The third section examines additional trends obtained from the DS.

### 7.3 Experimental Dataset

As mentioned in the introduction, significant progress has been made on ripple geometry characteristics; however, the general consensus is that detailed information regarding ripple migration is lacking and could substantially benefit from additional effort in this area. With this in mind, we returned to the only set of data currently available (to the author’s knowledge) that incorpo-
rates large-scale controlled laboratory experiments involving detailed measurements of the water wave surface envelope in conjunction with detailed measurements of the underlying evolving sediment bed. For completeness, a highlight of the details of the experimental data are utilized herein; however, for more in-depth and comprehensive information regarding the experimental setup and methodology the reader should refer to Landry (2004).

The dataset was obtained from large-scale experiments conducted in a large wave tank located in the Parsons Laboratory at Massachusetts Institute of Technology. The facility measures 36.5-m long by 76-cm wide, having a central 16.5-m sand bed test section. For the majority of experiments, the test section was filled 30-cm deep with well-sorted silica sand having a 0.21-mm median grain size diameter. However, additional experiments were conducted in which a finer, median grain size of 0.11 mm was utilized. The DS also included a final special experiment comprised of a bimodal mixture (equal parts by weight) of the two grain sizes where only the coarse sediment was colored red in order to visually explore natural sediment sorting (Landry et al., 2007). For both sediment bed cases, various wave conditions of high and low reflection were conducted. Based on custom wave measurement software discussed in Chapter 5, the key wave parameters (i.e., incident wave amplitude, reflection coefficient) were obtained from water wave envelope measurements along the entire tank at 0.25-m or 0.5-m intervals at specified time intervals (e.g., 3, 6, 12, and 24-hr intervals). Directly after each wave measurement run, a panoramic profile of the underlying bathymetry was obtained along the entire tank. Key sediment, wave, and velocity parameters of each experiment in the DS that will be used for the analysis presented herein can be seen in Table 7.1.

While a primary focus of the original set of experiments was to collect detailed, large-scale bed morphodynamics, e.g., growth rates of sand bars, to verify numerical bar models (Hancock et al., 2008), additional equipment was used to resolve the evolutionary behavior of smaller scale features (e.g., sand ripples) at increased temporal resolutions (as indicated in the final columns of Table 7.1). Unique bed evolution records via two monochromatic, progressive scan, CCD cameras (Pulnix TM-9701) allowed for rapid temporal bed resolution (60-sec intervals), spanning a broad range along the tank (in relation to envelope variation) of approximately 5 ft or 1.524 m (i.e., approximately one fourth of water wavelength or one half of a bar wavelength). The
Table 7.1: Experiment summary for ripple migration data. B-load and S-load denote the dominant modes of sediment transport as bedload (N-type) and suspended load (L-type), respectively. High R and Low R denote high and low reflection conditions, respectively. Exp ID denotes experiment identification. Median grain size is represented by $d_{50}$. Wave parameters (based on fitting results of WaveAR program to first wave reading): $R_1$ is the first harmonic reflection coefficient; $a_{1i}$ is the first harmonic incident wave amplitude; $T$ is the wave period; $a_{2i}/a_{1i}$ is the ratio of second to first harmonic incident amplitudes (\(^*\)) denotes presence of a free second harmonic); $U_{bm[n]}$ and $U_{bm[a]}$ are horizontal near bed node and antinode velocities, respectively, based on linear wave theory. Under the “Time” column, values under cam 01 and cam 02 denote the recordings for camera 01 and camera 02, respectively, for the experiment. “-” denotes that the camera data was unavailable. (Refer to Appendix C for wave profiles and full timestack plots.)
cameras were faced normal to the glass sidewalls and offset 1.75-m away from the wall. This span provided the necessary distance over which to acquire ripple trajectories, without losing resolution of ripple height. From the captured images, the water/sediment interfaces on each image were extracted similarly to the profiling technique discussed in Section 4.3.1 to track bed evolution.

Though extensive duration of ripple evolution data (indicated in Table 7.1) was collected as part of the former experimental effort, the previous study was concerned with ripple dynamics prior to formation of large scale variations in the mean bed elevation (i.e., sand bars). As a result, the study reported timestacks and other collected ripple evolutionary data prior to 3 hours for each experiment and the full ripple timestacks acquired as part of the original dataset were never published or analyzed in the prior work (Landry, 2004). (The reader can refer to Figure 7.3 as an example of a timestack plot. Note that a timestack contains full information of the bed evolution displayed in a compact form. Often timestacks are viewed in the $x$-$y$ plane with $z$ values color-coded by value, where the $x$-axis is distance along the bed; $y$-axis is time; $z$-axis is elevation.)

In this present analysis, the primary focus is on ripple migrations, especially the spatial variability in relation to the surface wave envelope above. As a result, long temporal records are ideal to ensure that ripples have achieved quasi-equilibrium migration velocities. While significant bar growth is present in the DS for longer time scales, we hypothesize that the bar presence on ripple velocities will be negligible. Based on prior findings that ripple geometries still follow ripple predictors even when bars are present (Chapter 6), it is suspected that a similar behavior will be valid for ripple migration velocities. As a preliminary, the analysis effort herein seeks to determine the validity of the hypothesis, and if true, the analysis will not be limited to locating ripple velocities within the initial 3-hrs.

Provided that bar effects on ripple velocities are negligible, the probability of identifying a temporal region with quasi-equilibrium ripples velocities along the captured spatial extent is greatly improved. Thus, ripple velocities within the subset should not exhibit local variability often attributed to bifurcations and mergers between nearby ripples which otherwise add considerable biases to the migration results.
7.3.1 Resolution of the Dataset

For completeness, the resolution of the DS is presented. (Refer to Landry (2004) for additional details.) Based on the CCD camera resolution of 720 [or 640] pixels capturing a 5-ft (1.5-m) longitudinal span, there is an inherent resolution of 0.083 inches/pixel (2.117 mm/pixel) [or 0.0938 inches/pixel (2.381 mm/pixel) for the 640 pixel case]. In addition, a variability of ± 1 pixel (2.117 mm or 2.381 mm) occurred due to edge detection from converted gray scale image to a 1-bit image (i.e, black and white image). For measuring ripple wavelength, which are on the order of 10 cm, the resulting 2 mm/pixel resolution with variation due to 1-bit conversion proved to be adequate. On the other hand, the ripple amplitudes (on the order of 2 cm) had reduced accuracy; although, the resolution of the ripple crest was sufficient to capture clear ripple trajectories associated with the crest of each ripple.

7.4 Data Analysis of the Dataset

As seen in Figure C.2 (ripples 107 and 106 around 2 hrs), the ripple migration trajectories can be significantly influenced by the local phenomena of ripple merging and bifurcating. At these local events, ripple velocities noticeably deviate from the mean velocity trend, often increasing in speed to merge with a ripple to the shoreward side or decreasing in speed, possibly even reversing direction (e.g., onshore becomes offshore migration) due to a bifurcation and possibly merging with a ripple to its seaward side. Thus, special care must be taken to avoid these temporal regions of local instability. Furthermore, studying the spatial variation of ripple velocity due to partially progressive waves (of various reflection coefficients) introduces an additional level of complexity to the analysis.

In order to overcome the difficulties, an analysis procedure was developed as illustrated in Figure 7.1. First, the full experiment timestack data from camera(s) (one or two, depending on record) was processed. Then, the full ripple timestack was visually inspected to determine if the general ripple migration trend was representative throughout the timestack. Though visual inspection proved useful, a quantitative metric was implemented to achieve more consistent and reliable results.

The metric utilized the ripple crest trajectories that were processed via a
hybrid (manual/automatic) algorithm which enabled each ripple crest to be tracked backward in time despite local complex interactions that may have occurred (step 3 in Figure 7.1). For each ripple, the user specified bounding lines that were positioned to flank either side of the ripple crest being processed. Then, the algorithm automatically scanned for the maximum elevation (e.g., ripple crest) within the bounds for that time and was repeated for all prior times for that ripple. The process was likewise conducted for other ripple crests in the full timestack. While this hybrid process is rather demanding, requiring substantial time and effort to conduct, versus more automated methods, the hybrid approach allowed for full control over the crest capturing. The user had detailed control over the detection of ripple migration and could easily circumvent tracking issues arising from discontinuities in the trajectories.

Based on the newly extracted ripple crest trajectories throughout the entire timestack, smooth cubic splines were fit to each ripple crest trajectory (step 4). After verifying the accuracy of the fits, the gradient at 1-min intervals along each ripple trajectory was determined. The resulting time, space, and velocity data for each ripple crest was aggregated and a velocity contour map associated to the timestack was generated (step 5). This contour map enables a clear view of regions which either were or were not affected by local variations. Based on the contour map, a band of time was selected in which all (or the majority) of the ripples along the entire measured spatial extent were unaffected by the aforementioned local phenomena (step 6). All the information (time, position, and velocity) associated with the ripple crest
within this temporal subrange without local effects was extracted from the
timestack dataset to form a data subset for further analysis.

Following the data filtering, a boxplot (step 7b) was constructed from the
data subset for the ripple velocities versus longitudinal ripple positions. The
ripple positions were binned at 5-cm intervals over the spatial extent of the
data and associated ripple velocities were grouped accordingly and used to
construct the boxplot statistics (e.g., quartiles and outliers). A more detailed
discussion of key image results at points in the process will be presented in
the following section.

7.5 Results

Based on the analysis procedure described above, numerous resulting plots
were created for each experiment. In order to help orient the reader, a
detailed description of each plot for a selected experiment will be discussed
in this section. The reader is directed to Appendix C for full page plots of
all resulting plots including those used as examples in this section.

Composite wave and bed information plot:

The first resulting plot for each experiment is a composite plot which subplots
the wave information over bed information (if available) for the entire tank
at a close associated time to the sub-selected ripple camera data as shown
in Figure 7.2. This plot provides insight as to the global dynamics within
which the ripples domain was captured, e.g., bar size, location of bar crest
to wave node, and relative region which the cameras captured. The top
subplot illustrates the surface wave form at different time phases which are
superimposed upon one another. The second subplot denotes the harmonic
amplitudes along the tank. Black “o” markers and “.” markers with dotted
line denote the measured first and second harmonic amplitudes, respectively.
The solid blue line indicates the fitted first harmonic envelope via WaveAR
program. Filled circular markers represent key points in the wave envelope:
quasi-antinode (blue), quasi-node (blue), and mid-point between (green).
The third subplot presents the horizontal bottom velocities computed from
the fitted wave envelope based on linear wave theory, refer to (2.24). The
bottom subplot depicts the complete bed profile as a black line and mean bed (ripples filtered out) with a red line. Bold black points highlight the domain which the ripple cameras measured. Vertical dashed red lines indicate nodal locations of the surface wave for reference. In cases where the bed profile was not available, a wave beat phase was plotted instead, in which phase was zero starting at an antinode, increasing to $\pi$ at the node and approaching $2\pi$ for the next antinode. This cycle was continued for each wave beat along the tank.

Figure 7.2: Representative wave and bed information for the entire tank for experiment 324 acquired at a time near subselected ripple camera times.
Complete timestack plot:

The second resulting image for each experiment is the complete timestack record (step 1), as seen in Figure 7.3. The abscissa is the longitudinal direction along the tank from the wavemaker, and the ordinate is time of the profile. The colorbar denotes bed elevation in centimeters. The information for both cameras (if available) is combined into a single image to achieve a complete temporal view of the entire spatial domain. Due to vertical supports on the tank, certain regions may be void of information throughout the entire duration of the experiment (e.g., white region between 650 and 700 cm in Figure 7.3), or a camera may have been turned off for a portion of the experiment (e.g., greater than 9 hrs, between 500 and 670 cm in Figure 7.3). The thin black lines over each ripple crest are the results from the hybrid tracking algorithm (step 3). Ripple labels appear at the temporal end of each trace, where the first digit is the camera number and the remaining digits are the ripple number. For example, a ripple label of 111 would denote it is the 11th ripple that was traced in the camera 1 domain. The darker black points overlaid at portions along ripple traces indicate the subsampled ripple information (step 6) that will be used to generate ripple distributions. The temporal subsample interval is also indicated in the heading of the figure.

Complete ripple migration velocity contour plot (for inspection only):

Based on the results of step 4, an example of a complete velocity contour map is shown in Figure 7.4. The abscissa is the longitudinal direction along the tank from the wavemaker in centimeters, the ordinate is the corresponding time in hours, and the colorbar represents ripple migration velocities in cm/hr. For reference, the original ripple trajectories are superimposed on top denoted as black dotted lines; e.g., the inverse of the trajectory slopes should correspond to contour values. Although this contour appears noisy, primarily due to large regions without information, it allows a comprehensive overview of how velocities change both in space and time, and aids in subset selection.
Figure 7.3: Illustration of complete timestack for experiment 324.

Subset ripple migration velocity contour plot:

Based on timeband subsampling (step 6), subregion ripple migration velocity contour plots were produced, as seen in Figure 7.5. Similarly to the complete time contours, the abscissa is the longitudinal direction along the tank from the wavemaker in centimeters, the ordinate is the corresponding time in hours, and the color map represents ripple migration velocities in cm/hr. Also, superimposed black dotted lines denote the original ripple trajectories. Notice how a distinct trend can now be observed by removing regions which had local effects (e.g., merging, diverging, or not well developed).

Subset ripple migration velocity distribution plot:

Based on the selected ripples in the subset, the black dots were binned at 5-cm intervals along the longitudinal, and associated velocities within each band were used to generated quartile statistics for the respective bin (step 7b). An example resulting ripple migration velocity distribution for the subset can be seen in Figure 7.6. The $x$-axis is the distance along the tank in centimeters and the $y$-axis is the ripple migration velocity in centimeters per hour. The
Figure 7.4: Illustration of complete ripple velocity contour map for experiment 324. Colorbar indicates ripple velocities in cm/hr.

The red line in the middle of each box denotes the median (second quartile, Q2). The bottom and top of each box represent the 25th and 75th percentiles (or Q1 and Q3), respectively. Whiskers extend to the most extreme point that are not classified as outliers. Outliers, denoted as small red “+” markers, are taken as any point that is larger than $Q3 + w(Q3 - Q1)$ or smaller than $Q1 - w(Q3 - Q1)$, where $w$ is taken to be 1.5 which corresponds to 99.3% coverage (or ±2.7σ, where σ is the standard deviation), for normally distributed data.

**Subset normalized composite of Lagrangian mass transport velocities and ripple migration velocities:**

Figure 7.7 shows the final resulting plot type for each experiment which is a composite plot that superimposes the prior results for Lagrangian mass transport velocities and ripple migration velocities onto one single plot with dual vertical axes. On the $y$-axis on the left side is the ripple velocity normalized by maximum ripple velocity in the range; and right side $y$-axis is the Lagrangian mass transport velocity normalized by maximum Lagrangian
mass transport velocity within the domain for each respective $\xi$ elevation. The $y$-axes are color-coded to the corresponding line type, black lines with “o” markers denote ripple velocities; whereas, the solid, dotted, and dashed blue lines denote Lagrangian mass transport velocities evaluated at $\xi = 0.25$, 0.5, and 6, respectively. Note that $u_l(\xi = 6)$ is indicative of Lagrangian mass transport velocities near the bottom of the inviscid core region, e.g, $u_l(\xi = \infty)$. Water wavelength and beat length are denoted by $\lambda$ and $\lambda_{\text{beat}}$, respectively, and value of the beat length is indicated on the $x$-axis label. Values for maximum ripple velocity and maximum Lagrangian mass transport velocities can be seen on the top of the figure. As a caveat, this type of plot amplifies the perception of the spatial variability, the overall magnitude is lost, and only the relative behavior is captured. For instance, experiment 525 shown in Figure C.78, which has the lowest reflection of all experiments, appears to still have large variation in drift velocities until the $y$-axis on the right side is read. As long as care is taken, this plot type is beneficial, since it allows for general trends in spatial variability to be observed readily.
Figure 7.6: Illustration of experiment 324 ripple velocity distribution boxplot statistics for selected subset (t = 2.49 to 2.91 hrs).

Figure 7.7: Normalized plot of ripple velocities and Lagrangian mass transport velocities for experiment 324 subset (t = 2.49 to 2.91 hrs).
7.6 Discussion

7.6.1 Spatial versus temporal variation in ripple migration velocities

Based on the results of the velocity contours throughout all experiments, it can be seen that the ripple velocities appear to remain fairly constant in time for specified spatial bands even in cases of pronounced bar growth. Furthermore, when compared to spatial variability, any slight temporal variation becomes trivial and can clearly be neglected. Thus, these results confirm the aforementioned hypothesis and the subsequent analysis should not be dependent on the timeband at which the ripple subset is selected. This increases the likelihood of a selected band exhibiting little to no local effects.

7.6.2 Comparison to prior relations

Although previous ripple velocity relations were not formulated for partially progressive waves, this section explores how the existing velocity predictors agree with the data collected in this study.

Relation to theoretical near bed inviscid core drift:

The theoretical bottom drift current near the bottom of the inviscid core has been shown to have a positive relation with the ripple migrations (Dingler and Inman, 1976). This outer drift can be express as

\[ u_\theta = \frac{5}{4} \frac{U_{bm}^2 T}{L}, \]  

(7.1)

where \( U_{bm} \) is the near bottom maximum horizontal velocity, \( T \) is the wave period, and \( L \) is the wavelength. \( U_{bm} \) can be expressed as \( U_{bm} = a_o \omega = \pi d_o / T = \omega a_i / \sinh(kh) \), where \( a_o \) is the bottom orbital amplitude, \( d_o = 2a_o \) is the bottom orbital diameter, \( h \) is still water depth, \( k \) is the wavenumber, and \( \omega \) is the angular frequency.

As an aside, it can be shown that (7.1) can be determined from (2.28) for
progressive waves. Taking $\xi \to \infty$, the exponential terms vanish,

\[
\bar{u}_L = \frac{k\omega a_i^2}{4 \sinh^2(kh)} \left[ (1 - R^2) \left( -8e^{-\xi} \cos \xi + 3e^{-2\xi} + 5 \right) + 2R \sin(2kx) \left( 8e^{-\xi} \sin \xi + 3e^{-2\xi} - 3 \right) \right],
\]

and introducing the case of purely progressive waves ($R = 0$),

\[
\bar{u}_L = \frac{k\omega a_i^2}{4 \sinh^2(kh)} (5(1-R^2) - 6R \sin(2kx)) = \frac{5k\omega a_i^2}{4 \sinh^2(kh)} = \frac{5 U_{bm}^2 T}{4 L},
\]

which is the same as (7.1). (Note that $\bar{u}_L$ and $u_l$ both denote Lagrangian mass transport velocities in the BBL.)

The field measurements from Dingler and Inman (1976) are plotted in Figure 7.8 along with all the median ripple migration velocities reported in the boxplots for each experiment from this study. Based on Figure 7.8, it is evident that laboratory conditions are considerably less energetic than those reported in the field. However, lower range of the field data between drift velocities of 0 to 3 cm/sec agree well with the upper envelope of the present results. This indicates that although ripples are experiencing velocity variability, a general ripple velocity estimate can be inferred based on the lowest drift value for the spatial range of interest. However, note that the majority of experiments cascade down from this upper bound, exhibiting elliptical distributions (similar to hysteresis effects) which cannot be captured with this relationship. As the drift velocities increase for a given experiment, the associated ripple velocities gradually tend to decrease until reaching maximum drift velocity. Then, following decreasing drift velocities along the lower portion of the ellipse, ripple migration velocities are considerably lower for the same drift velocities. It is worth noting that since this relationship is based on drift velocities outside the boundary layer, inherent problems will occur at reflections greater than 40% due to reversal in the bottom boundary layer (Carter et al., 1973).

Comparison with additional laboratory datasets:

Measured ripple velocity data from previous wave studies of Faraci and Foti (2002) and Cataño-Lopera and García (2006b) are plotted for comparison in
Figure 7.8: Ripple velocity versus theoretical bottom drift (bottom of inviscid core). Lagrangian mass transport velocities at bottom of the inviscid core appear on the $x$-axis and ripple velocities on the $y$-axis. For the current study, all median ripple velocities reported at various spatial location are plotted. Field data of Dingler and Inman (1976) is denoted with the black dashed line with solid black circular markers.

Figure 7.9 using two commonly used dimensionless parameters: the mobility number (left subplot) and Shields parameter (right subplot). The mobility number is the ratio of the disturbing wave force to the stabilizing force of gravity and is defined as $\psi = \frac{U_{bm}^2 (s-1) gd_{50}}{g}$, where $U_{bm}$ is near bed horizontal velocity, $s$ is the relative density of sediment, $g$ is acceleration of gravity, and $d_{50}$ is the median grain size diameter (Nielsen, 1992). The Shields parameter is similar in formulation but uses the shear stress as the disturbing force which can be expressed in terms of wave friction factor, $f_w$, defined by Jonsson (1966), resulting in $\theta = \frac{f_w U_{bm}^2}{2(s-1)gd_{50}}$, and the Grant and Madsen (1986) formulation was used to determine the friction factor (Madsen and Wood, 2002). Overall, it can be seen that the present data is lining up with previous results. However, this formulation does not represent the ripple variability.
Even when looking at additional plots for the mobility number and Shields parameter of for a subset of experiments as shown in Figure 7.10, a trend can be seen, but ripple variation within each experiment is not well defined.

7.6.3 New insights

While the relations tend to provide good estimates for mean behavior of the ripple migration velocities, none of these relations can predict the ripple migration velocity variations within a wave beat (taken from antinode to node). Resulting from (2.28) for the case of purely progressive waves, the Lagrangian mass transport velocities are constant along the direction of wave propagation; all have the same sign direction and only vary in magnitude based on vertical offset from the bed. Thus, the outer boundary layer drift velocity is indicative of the drift direction in the bottom layer and can be used to correlate with ripple velocities, as shown from aforementioned field measurements by Dingler and Inman (1976). However, in cases of increased
Figure 7.10: Plots of mobility number (left) and Shields parameter (right) for selected subset of current experiments under low reflection and bedload dominated conditions. Ripple velocities, $v_{\text{rip}}$, are nondimensionalized with near bed velocities, $U_{\text{bm}}$, on $y$-axis.

wave reflection, spatial variability is introduced into the mass transport velocities and the outer boundary layer velocities become out of phase with mass transport close to the bottom within the bottom boundary layer. As a result, lower values of outer boundary layer drift velocities will be associated with increased ripple velocities, resulting in plots of measured ripple velocities being bounded by the dashed red line, as seen in Figure 7.8.

This change in outer layer drift can be more clearly illustrated in Figure 7.11 for experiment 324 of bedload dominant transport and mild reflection. As depicted, the change in the mass transport near the outer layer (i.e., at $\xi = 6$) is out of phase with the transport velocities within the lower boundary layer, and more importantly, out of phase with the change in ripple velocities. It should become evident to the reader that the transport velocities within the lower boundary layer agree well with the behavior of the changes in ripple velocities. Note the spatial shift between the maximum ripple velocities and
maximum mass transport velocities. Based on (2.28), maximum values in drift occur at the inflection point between the node and antinode locations, at 0.25 of a wave beat, which is in-line with the onset of maximum ripple velocities. However, thereafter the ripple velocities maintain maximum velocities for roughly 1/5 of the beat before starting to decay in speed. The midpoint of the ripple velocity peak coincides well with the position of the bar crest for bedload dominated conditions at 0.4 of the wave beat.

Figure 7.11: Bedload dominated transport under low reflection (experiment 324)

The shift in the bar conditions for low reflection to the seaward side of the wave quasi-nodes indicate the presence of a slight return flow which has been neglected in the computations herein. Thus, it is suspected that the increased elevation of the bar crest (exposing the ripples to higher velocities) in conjunction with the return flow (opposing the increase in velocities) maintain more uniform ripple velocities over the bar crest occurring near the wave node. On a side note, it should be stated that bar heights tend to decay in the shoreward direction (especially for low reflection cases) which is attributed to energy transfer from the incident wave to the reflected wave, thus the reflection coefficient Bragg scattering (Yu and Mei, 2000b; Hancock,
In conditions of high wave reflection, the relation between ripple migration velocities and local near bed mass transport velocities is still valid for bedload dominated conditions. As discussed in Section 2.2, the near bed Lagrangian mass transport velocities are reversed (from the outer boundary layer) and sediment on the shoreward side of the wave node migrates slowly to the wave node as evident from the negative velocities in the upper half of the wave beat range in Figure 7.12. The drift velocities near the outer layer are out of phase with the inner boundary layer velocities. While the locally computed outer layer drift velocities could be used as an indicator for ripple migration velocities, it would be counterintuitive to use these velocities since they are opposite the direction of the ripple migration velocities. However, a simple sign change could resolve the issue if the outer layer drifts are used.

Figure 7.12: Bedload dominated transport under high reflection (experiment 416)

It should be further clarified that basing ripple migrations on near bed drift assumes that ripples are primarily transported by bedload and not suspended load. When applying the local near bed drift concept to cases of suspended dominant transport, results were less reliable since ripple migrations were not...
as coherent (e.g., refer to timestacks for experiments 519 and 525, Figure C.68 and Figure C.74, respectively.) compared to the cases of bedload dominated transport. In a representative case of low reflection and dominant suspended load as shown in Figure 7.13, there appears to be a better relation to \( u_l(\xi = 6) \) instead of \( u_l(\xi = 0.25) \) as in the previous case of bedload. However, the small range in normalized Lagrangian mass transport velocities makes it difficult to account for the larger variability seen in the ripple velocities.

![Figure 7.13: Suspended load dominated transport under low reflection (experiment 525)](image)

In Figure 7.14, the case for high reflection and suspended load dominant, there is a stronger relation to \( u_l(\xi = 0.25) \) instead of \( u_l(\xi = 6) \), especially in the fractional wave beat ranging from 0 to 0.35 and 0.65 to 0.9. Looking at the timestack for this case (Figure C.68), it can be seen that the ripples in the fraction of wave beat between 0.35 and 0.65 are not as well-formed as those on the shoreward or seaward sides. This poor agreement in the central fraction of the wave beat can be explained by revisiting the diagram presented in Figure 2.7. Using the local near bed velocities, \( U_{bm}(x) \), rather than the near bed nodal velocity, \( u_n \), helps to establish the valid conditions where bedload dominant conditions are present (i.e., \( U_{bm}(x)/w_s < 14 \)). The
central fraction of the wave beat has values of $U_{bm}(x)/w_s > 14$, well out of the N-type regime; however, the fractional wave beat ranging from 0 to 0.35 and 0.65 to 0.9 have values of $U_{bm}(x)/w_s$ below 14 and are well within N-type condition. Thus, the ripple velocities within the fractional wave beat ranging from 0 to 0.35 and 0.65 to 0.9 agree well with $u_l(\xi = 0.25)$ due to dominate bedload conditions in this region.

![Figure 7.14: Suspended load dominated transport under high reflection (experiment 519)](image)

Plotting only the low reflection cases together in Figure 7.15, the pronounced elliptical variation is evident. The magenta squares indicate points near the wave node, and light gray shaded points are values associated with the shoreward side of the bar. The suspended dominated cases do not collapse with experiments 324, 407, and 508 which is to be expected due to the change in dominant mode of sediment transport. A plot of all the bedload dominated cases (both low and high reflection) on a single plot with the fraction of wave beat on the abscissa and ripple velocity divided by maximum ripple velocity within the wave beat for the specified experiment on the ordinate can be seen in Figure 7.16. The legend denotes the data points for each associated experiment. The blue and red color markers denote low ($R \approx 0.2$)
Figure 7.15: Nondimensional ripple relation for low reflections including fine and course grains. Lagrangian mass transport velocities at evaluated at $\xi = 0.25$ normalized by the max transport values in the region appear on the $x$-axis and similar the $y$-axis normalizes the measured ripple velocities. and high ($R \approx 0.9$) reflection cases, respectively. The solid horizontal black line at $v_{\text{rip}}/\max(v_{\text{rip}}) = 1$ represents the idealized ripple velocities associated with purely progressive waves. As the reflection increases, so does variability in the ripple migration velocities (i.e., changing from the solid black line to the curved blue line). Further increasing the reflection to nearly full reflection results in ripple velocities approaching the linear trend line where ripple velocities in the range of $f_{\text{beat}} > 0.6$ become negative. Thus, knowing the maximum ripple velocity within a wave beat, all the ripple velocities across the entire wave beat can be predicted. Furthermore, the bounding line from Figure 7.8 could potentially be used to get a rough estimate of the maximum ripple velocity, if measure the maximum ripple velocity in situ is unable to be obtained. While results are promising, additional experiments are required, especially in the intermediate reflection conditions, to unify the velocity formulation depicted in Figure 7.16.
Figure 7.16: Ripple velocity distribution for bedload dominated cases. Black line denotes ideal case of ripple velocities under purely progressive waves ($R = 0$). Blue line is a sketched trend line for low reflection cases ($R \approx 0.2$). Red line is linear trend line for cases of high reflection ($R \approx 0.9$). Equation for linear trend written below $R \approx 0.9$ which has an R-squared value of 0.932 (after filtering the outliers). For reference, the gray dashed line denotes line of zero velocity.

7.7 Conclusion

The experimental findings help to elucidate the behavior of ripple migration under spatial variation in the wave envelope. Based on analysis of recently available detailed bathymetry data for mild to high reflections, the study found that the connection between drift and ripple velocities, reported by Dingler and Inman (1976) for progressive waves, can be extended to higher reflection if local values of the drift velocities were used as an indicator of associated ripple velocities. While drift velocities in the outer boundary layer can be used (provided a sign correction is implemented), it was found more beneficial to use near bed mass transport velocities in the boundary layer (i.e., ($\xi = 0.25$ or 0.5) since the sign of drift is indicative of ripple
migration direction. Furthermore, this concept is still adequate for explaining ripple migrations for high reflections when reversal occurs in the boundary layer Lagrangian mass transports. However, additional experimental data is required to further quantify the results in case of intermediate reflection, e.g., R=0.5.
CHAPTER 8

EFFECTS OF VEGETATION ON SAND BAR FORMATION

8.1 Abstract

Littoral processes such as sediment transport, wave attenuation, and boundary layer development are governed by the presence of bathymetric features, which include large-scale sand bars upon which smaller-scale sand ripples are superimposed, as well as the presence of submarine vegetation. Numerous studies on sand ripples and bars have aided to elucidate the dynamics in oscillatory flows. However, the effect of vegetation on the morphodynamics is less understood. Recent laboratory studies have focused on quantifying wave attenuation by emergent vegetation as a natural method to mitigate storm surges. The emergent vegetation, providing substantial coastal protection, alters sediment transport rates directly by the physical presence of the plants near the bed and indirectly from reduction in near-bed shear stresses due to attenuated wave energy.

The experimental work herein focuses on the marine environment near the deeply submerged vegetated canopy limit (current work has a ratio of mean still water depth to plant height, \( H_p/h_p \) of 7.9) to minimize the effect on the surface waves and discern the direct impact that vegetation has on sand bed morphodynamics. Experiments were conducted in the large wave tank (49-m long by 1.83-m wide by 1.22-m deep) in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign. High reflection wave forcing was used over a uniform sand bed with a 0.25-mm median sediment diameter in which staggered and uniform arrangements of idealized vegetation (6.35-mm diameter rigid wooden cylinders) were positioned along the bed (at predetermined sand bar troughs and over an entire sand bar).

The resulting bathymetric evolution from the vegetated case experiments were compared to the base case of no vegetation using two optical methods:
a high-resolution laser displacement sensor for three-dimensional surveys and digitized profiles via high-definition panoramic images of the entire test section. The experimental findings illustrate the profound effect that vegetation can impart on bedform evolution whereby the rate of development can be significantly mitigated or even completely redirected. These findings suggest that bottom roughness can be controlled with the help of vegetation thus providing a means to reduce wave energy and prevent sediment erosion.

8.2 Introduction

Typically, within the nearshore region of the coastline, there are two predominant bedform types: sand bars and sand ripples, the latter being superimposed on the former. The bedforms and submarine vegetation have important effects on the morphology of the coastline. While numerous studies have been conducted to examine the dynamics of bedforms and vegetation independently, presently, no detailed laboratory studies have explored the complex interaction of all three factors simultaneously (i.e., sand bars, ripples and vegetation). Our main goal is to understand and quantify the effect of vegetation on global sediment transport (through bed profile responses) under oscillatory flow of shallow to intermediate depths while having sufficient reflection to allow for sand bar formation with superimposed ripples. The long-term objective is to assess the role of interaction of sand bars, ripples and vegetation on the morphodynamics of coastlines, in particular inlets, bays and river mouths.

In terms of the smaller scale sand ripples which have dimensions an order of magnitude less than the bars, roughly centimeter- to meter-scales, numerous previous studies (laboratory and field-based) have been conducted (Blondeaux, 2001). Ripples present a natural roughness which vastly alters the properties of flow in the boundary layer, leading to changes in the sediment transport rates, and affecting regions of erosion and deposition. In addition, flow moving over the ripple “feels” friction which results in wave attenuation and further changes in sediment transport. One of the earliest documented works on ripples dates back to Darwin (1883); subsequently Ayrton (1910) documented the presence of both bedform features, sand ripples and mounds (i.e., bars), in small-scale laboratory experiments. The follow-
ing years brought numerous additional contributions to the study of ripples and bar forms, though not usually presented together. Subsequent experimental investigations were conducted exploring the mechanism(s) of ripple formation and equilibrium ripple characteristics under constant oscillatory flow conditions, leading to several ripple predictors such as Nielsen (1981) and Wiberg and Harris (1994). A recent review of ripple predictors can be found in Pedocchi and García (2009a,b).

Larger scale long-shore bar forms, upon which ripples are superimposed, often occur in inlets, bays or on open coasts. Observations have been made by numerous researchers, such as Kindle (1936) and Dolan (1983) in Chesapeake Bay; Evans (1940) and Saylor and Hands (1970) in Lake Michigan; Lau and Travis (1973) in Escambia Bay; Sheppard (1950) on the Southern California coast; and Short (1975) in the Alaskan Arctic. Typically, multiple bars are usually reported for beaches having very mild slopes (slope < 0.005) upon which plunging breakers are frequently observed. The general bar wavelengths are on the order of 10 to 100 meters, increasing in length as water depth increases toward the offshore direction (Mei, 1985).

One of the most plausible explanations for parallel long-shore bars can be attributed to partially reflected waves formed from incident waves interacting with the reflecting waves from the beach (Allen, 1982). Like ripples, sand bars play a crucial role in coastal processes. They alter the mean water depth resulting in wave shoaling and plunging on the outward bar which reduces the wave impact on the shoreline. Also, under proper conditions, Bragg resonance over the parallel bar patch can further shelter beaches (Yu and Mei, 2000a). Based on the importance of bar forms, various theoretical, numerical, and experimental works have been performed over the years. However, we will focus on prior laboratory experiments due to the experimental nature of this study.

Past laboratory bar experiments, such as de Best et al. (1971) and Xie (1981), studied various wave and sediment conditions within small tanks. However, due to the small tank size, scale effects were often present where ripples scaled on the same order as bars (Mei et al., 2001). Furthermore, in some cases, undesirable wave conditions having high Ursell numbers (which fall outside of linear wave theory) were imposed to ensure that the Shields parameter was above the critical value for the inception of particle motion. As mentioned, many of the studies focused on either ripples or bars, usually with
sparse measurements of the experimental conditions. Rarely do researchers make detailed measurements of all three physical features (waves, velocities, and bedforms) over a larger spatial region. Only fairly recently have large scale experimental studies on both ripples and bars been documented by Landry (2004), Hancock (2005), Cataño-Lopera and García (2005, 2006a,b), and Cataño-Lopera et al. (2009). It has been shown that the exact location of the bed features in relation to the wave envelope is critical in defining ripple geometric characteristics Landry et al. (2009). The observational data suggests that ripple location under the wave field might be the key to understanding the variability in ripple migration speed often reported by other researchers (Landry, 2004; Admiraal et al., 2006; Cataño-Lopera and García, 2006b).

The work herein intends to better understand the impact that plants can impart on bedforms within this coastal region. More specifically, this experimental study provides a rich dataset from which diagrams/relationships can be obtained to predict the bedform behavior as well as provide valuable information which can be used to calibrate and verify numerical models (i.e. roughness characteristics, friction coefficients). Over the years, much of the work with flow through aquatic vegetation has been based on previous studies in terrestrial canopies which are essentially vertically unbounded flows (López and García, 2001). In the limit of water depth to aquatic canopy height becoming very large, $H_p/h_p >> 1$ (case of deeply submerged canopies), aquatic flows are shown to exhibit very similar behaviors to terrestrial flows. However, the aquatic environment adds an additional layer of complexity to the physics of terrestrial canopy flows due to the fact that submarine canopy flows found in nature occur in water bodies of finite depth. Thus, submarine canopy flows experience depth-limited conditions not felt by the terrestrial counterparts which experience virtually unbounded vertical flow conditions. Various researchers, e.g., Dunn et al. (1996), López and García (1998), Nepf (1999), and Wilson et al. (2008), have conducted research to quantify the drag which the vegetation imposes on the flow as well as to understand the turbulent processes near the canopy shear layer and the penetration depth of the turbulence structures.

In the coastal scientific and engineering community, plants have been frequently studied as a method of sustainable, natural shoreline protection. The vegetation is used to directly attenuate the surface waves which reduces the
bottom shear stress and therefore decreases sediment transport, as well as limits the wave energy from reaching shoreline. Danielsen et al. (2005) highlighted the role that mangrove forests played in attenuating the waves from the 2004 Indian Ocean tsunami. Also, the U.S. Army Corps of Engineers recently published a technical report (Koch et al., 2006) which reviews the impacts of seagrass on wave conditions and gives technical recommendations on the implementation of this natural ecosystem engineering method. Recent studies (Lowe et al., 2005; Luhar et al., 2010) have focused on the comparison of intra-canopy velocities between cases of unidirectional and oscillatory flows with similar velocities at the top of the canopy and found enhanced intra-canopy velocities in oscillatory flow cases. However, no large-scale laboratory experiments have heretofore been conducted to examine the sediment armoring due to vegetation and the impact on the developing aforementioned bedforms.

8.3 Experimental Details

This section provides an overview of the experimental facility including all the instrumentation. Additionally, the experimental procedure is outlined. For further details regarding the facility, equipment, or background methodology, the reader should refer to Chapter 3.

8.3.1 Experimental Facility

The experiments were conducted in the large scale wave-current flume (LWCF) facility located in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign (refer to Figure 8.1). The flume is 49-m long, 1.83-m wide, and 1.20-m high with plexiglas sidewalls, a hydraulic piston wavemaker at one end, and a temporarily placed vertical wall at the opposite end. While the facility is capable of superimposing a unidirectional current, experiments discussed herein are for the case of waves only. The mobile bed is composed of a 30-cm depth layer of very well sorted silica sand with a median grain size of 0.25 mm. (For more details regarding the sediment refer to Chapter 3.)

A primary 2.4-m (8-ft) long movable carriage, spanning the lateral width of
the tank, was able to traverse the entire longitudinal span of the test section to acquire measurements of surface waves, fluid velocities, and bathymetry. The main carriage supported a secondary internal platform system which was capable of transversing 150 cm in the longitudinal and 73 cm in the lateral within the domain of the primary carriage at fine intervals (<1 mm) via a gear-and-threaded rod system driven by a Syo-Syn® M092 stepper motor. Affixed to the main carriage were four General Acoustic sensors (model number USS2001300) controlled via an UltraLab® ULS system which allowed for surface wave displacement measurements at a sampling rate of 14 Hz. The sensors have a dynamic measuring range of 200 to 1300 mm from the sensor face and have a technical resolution of 0.18 mm with ±2.00 mm reproducibility. To avoid crosstalk between the sensors, the sensors were positioned at 0.5-m intervals on the main carriage with a 0.5-m alternating lateral offset from the centerline.

The secondary carriage held a dual-axis Velmex BiSlide® system capable of moving at 0.0050 mm/step in the vertical and lateral directions. The lateral motion of travel was limited to ±36.5 cm from the lateral centerline, due to the interior supports of the main carriage. Attached to the Velmex BiSlide® was a Sontek 16-MHz micro field acoustic Doppler velocimeter (ADV) which allowed for 0.01 cm/s resolution of the water velocities at various locations in the water column at a sampling rate up to 50 Hz. In order to achieve phase-averaged velocity measurements, a custom direction sensing triggering system (DSTS) was constructed to synchronize the wave measurements with the velocity profile measurements taken at the same longitudinal position under the wave sensor.

Lastly, detailed bathymetry records were obtained through the use of two methods. The first method is an optical approach (as discussed in Sections 3.2.6 and 4.3.2) in which a Canon 20D DSLR affixed to the primary carriage was used to obtain a panoramic profile of the bed. As noted, though this method is limited to near wall measurements, it is quite rapid, capable of sub-millimeter resolution, and usually represents the centerline bathymetry accurately due to the two-dimensionality of the sediment bed under the imposed conditions. The second method was a direct measurement of the final equilibrium sand bed using a Keyence laser displacement sensor (sensor head model: LB-301 and controller model: LB-1201W) which was temporarily attached to the Velmex after the tank was drained. The laser sensor vertical
displacement has a resolution of 50 µm. The motion control systems on the secondary carriage allowed a 1 mm x 1 mm grid resolution for longitudinal and lateral spans of 150 cm and 73 cm, respectively. Refer to Appendix D.3 for bathymetry results from the Keyence laser system. While the facility has an additional sensor, a SeaTek system (see item 13b in Figure 8.1), it was not used due to the high spatial resolution required for this study.

Figure 8.1: Schematic of large wave-current flume (LWCF) facility in the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana-Champaign: 1. wave flume; 2. wavemaker paddle; 3. sand bed; 4. wooden ramp; 5. waves; 6. current inlet; 7. fibrous beach (beach option one); 8. removable vertical wooden wall (beach option two); 9. movable I-beam frame carriage; 10. wave sensors; 11. Velmex position system and secondary carriage; 12. velocity probe (ADV); 13. bathymetry sensors: a) Keyence laser system; b) SeaTek system. Image modified from Cataño-Lopera (2005).

8.3.2 Experimental Methodology

In order to examine the effects of vegetation, plants of relatively short height are implemented to serve as a sediment armoring/trapping region rather than directly attenuating the waves so that cases with and without vegetation, having the same imposed wave conditions throughout, can be directly compared. The special case of fully reflected waves is used to explore and quantify the impacts of the vegetation on bedform evolution and sediment transport, which has not been studied before in a large scale laboratory setting.

This case of standing water waves is ideal for studying this phenomenon in the laboratory due to the formation of bars at known fixed locations of one-half the wave wavelength. Furthermore, the regions between each wave antinode (intervals of half the water wavelength) can be viewed as closed sys-
tems since essentially there is no horizontal flux of sediment across antinode regions. This enables each bar region to be an independent sub-experiment, provided the vegetation does not significantly alter the wave field. Each experiment altered the density and/or the positioning of idealized plants (i.e., wooden dowel rods) over each evolving sand bar to provide qualitative and quantitative records of vegetation impact as compared to that of the base case of no vegetation.

Experiments were each conducted in 3-hr blocks for at least 36 hrs (typically up to 51 hrs). Prior to the onset of the experiment, the initial bed profile (named shot 0) was captured via the Canon 20D DSLR. Roughly 1 hr into the first 3-hr block of the experiment, a surface wave displacement profile was measured along the entire test section at 0.25 or 0.5-m intervals. After the first 3-hr block was completed, the waves were stopped to verify the correct water level was maintained, and another bed profile (shot 1) was captured. The bed measurements were repeated at the end of subsequent 3-hr blocks throughout the rest of the experiment. Typically, wave profiles were performed for each block; however, after 8 blocks (e.g., 24 hrs of experimental run time), wave measurements were limited longitudinally in range due to the introduction of synchronized water velocity profile measurements which will be discussed in a future manuscript. Column number two in Table 8.1 indicates the 3-hr block number for which bed profiles are available (e.g., shot 12 is at the end of the 12th 3-hr block which is after 36 hrs).

Throughout all experiments, the same wave forcing was applied. Wave profile measurements for each block were processed using the numerical code discussed in Chapter 5. Over the course of the study, the waves (on average) had an incident wave amplitude, $a_i$, of 4.1 cm; wave period, $T$, of 2.6 sec; water wavelength, $\lambda$, equal to 6.0 m; reflection coefficient of 1; and maximum near bed horizontal nodal velocities of around 26 cm/s (via linear wave theory). The ratio of nodal velocity to sediment fall velocity (0.33 m/s by Jiménez and Madsen (2003) formulation via García (2008)) for the experiments is 7.8. This value is well inside the range of bedload dominated transport according to Figure 2.7 from Section 2.2 based on work by O’Donoghue (2001). Thus, sand bed profiles with bar crest occurring near the wave nodes are expected, as shown in Figure 2.4, subplot (d). Although, as one may expect, the waves were not perfectly consistent within and across experiments due to slight variations in the initial bed level, wavemaker hydraulic pres-
sure, minor water seepage from the tank, and dynamic interaction between the growing bars and surface waves. However, as seen in Figures D.1, D.2, and D.3, the low level of inconsistency can be considered negligible for the purpose of this study. A detailed table of the fitted wave parameters can be seen in Table D.2.

The eight various bed conditions were implemented over the course of the five conducted experiments, which can be seen in Table 8.1. The tank geometry and applied constant wave forcing allowed for six complete sand bars to form. The bars are numbered sequentially from the start of the seaward side of the sediment bed. For illustration, from subsequent Figure 8.4, the crest of bar 01 is located around 6 m from the start of the sand bed. Note, only central bars (i.e., bar 03 and bar 05) were used for vegetation in order to minimize any potential edge effects. Also, bar 04 was always void of vegetation to serve as both a buffer between the two vegetated conditions and a control across the five experiments.

All experiments used birch wooden dowel rods with a diameter of 0.635 cm (0.25 in) and a length of 15.24 cm (6 in) placed individually into an initially leveled sediment bed at a depth of half the plant height, 7.62 cm (3 in). For a given experimental run, not more than two bars were covered with different vegetation configurations. The vegetation configuration for each of the six bars for each experiment can be seen in columns 3 to 8 of Table 8.1. Bars denoted with “-” have no vegetation. An illustration of the spacing configurations and placements can be seen in Figures 8.2 and 8.3. $D$ represents the diameter of the plant, $S_y$ is the lateral on-center spacing, and $S_x$ is the longitudinal on-center spacing. Spacing notations shown in Table 8.1 are in the form of $S_y$ by $S_x$ and are all assumed to be non-staggered and only over the trough region of the sand bar, unless noted otherwise. Appended “S” or “Full” denotes staggered arrangement or vegetation over full bar, respectively. As an example, experiment ID 2010-04-22 has non-staggered vegetation only on bar 3 which is spaced one plant diameter (e.g., 0.635 cm) on-center in the lateral, 6 cm on-center in the longitudinal, each placed 7.62 cm depth, and covers the bar fully.
Table 8.1: Configuration of vegetation at each bar for a specified experiment. Column one is the experiment identification name. Column two lists the captured 3-hr block bed profile shots. Columns 3 to 8 denote vegetation configuration for each of the six bars within the tank for that experiment ID. Bar 01 is nearest to the wavemaker and bar 06 is nearest to the vertical wall. Note: no vegetation on a bar is denoted with single dash (-). Spacing notations are all in centimeters and denoted as $S_y$ by $S_x$ as seen in Figure 8.2. Assumed non-staggered arrangement and placed only over the trough of the sand bar. An “S” denotes staggered arrangement, and “Full” indicates vegetation is over the full bar. $D$ indicates spacing was the diameter of the simulated vegetation. (Refer to Table D.1 for more experimental conditions.)

### 8.3.3 Data Analysis Methods

In order to determine effects of vegetation on bar development, the processed panoramic shot images at 3-hr block intervals were the primary measurement method. The profile data was filtered using a moving average smoothing algorithm base on a lowpass filter to clearly resolve large scale bar profiles and mitigate any undesired variation due to superimposed ripples. The bottom graph in Figure 8.4 illustrates the result of the filtered bed elevation (red line) versus total bed elevation (black line). Based on the WaveAR fitting from the wave profile measurements, wave node and antinode locations were determined to aid in establishing domain bounds for each of the six bars. For each bar crest, the overhead wave node was determined and the antinodes on either side of the node were taken as the maximum domain extent for the associated bar. Within each bar domain, bar heights were estimated as the difference between highest and lowest elevations within the region.

Based on the temporal bar height record for a given bar, a moving average was computed and superimposed to understand the general trend of the evolution. As a result of the observed asymptotic behavior of the measured bar growths, a purely mathematical formulation,

$$H(t) = H_f(1 - \exp(-\alpha t)),$$  

(8.1)
Figure 8.2: Plan view of two types of vegetation grids used in the experiments: a) non-staggered array; b) staggered grid. $S_x$ and $S_y$ denote the on-center spacing between cylindrical plants of diameter $D$ in the longitudinal and lateral directions, respectively. The dashed box indicates the influenced plan area, $A_T$.

was fit to the evolutionary maximum bar height for each of the vegetation conditions. The relation was fitted to the complete height time history for each bar condition, with the exception of case Dx6 which included an additional fit based on a limited subset of data points (i.e., $t \leq 27$ hrs), which will be discussed in Section 8.5. Inherently, the relation provides an estimate for the final asymptotic bar height limit at infinite time, $H_f$, as well as the temporal decay coefficient, $\alpha$.

In order to compare different bars to those in the same or other experiments, the growth height computed at each time was normalized by the associated growth height of that same bar in the base case scenario with no vegetation, $H(t)/H_{\text{base}}(t)$. Thus, a value of less than one denotes a decrease in bar growth due to the vegetation and conversely values greater than one indicate increased bar elevations (e.g., increased scour in the bar troughs) resulting from the vegetation. While seemingly trivial, this normalization is a crucial step to establish a common datum for comparison. Fundamentally, as waves propagate over a hydraulically rough bed, energy is attenuated due to friction losses associated with the bottom, thus resulting in a slight lon-
Figure 8.3: Plan (top) and profile (bottom) schematics of vegetation placement for experiments. Shaded red areas denote the regions of plants. a) only bar troughs; b) full bar.

The density of vegetation was characterized using the dimensionless frontal area, $\lambda_f$, and plan area, $\lambda_p$, parameters (Britter and Hanna, 2003), computed by the following relations:

\[
\lambda_f = \frac{A_f}{A_T} = \frac{Dh_{wp}}{S_x S_y}; \quad (8.2)
\]

\[
\lambda_p = \frac{A_p}{A_T} = \frac{\pi(D/2)^2}{S_x S_y}, \quad (8.3)
\]

where $A_T = S_x S_y$ is the projected planar area of influence of the vegetation (see dashed boxes in Figure 8.2) in which $S_x$ and $S_y$ are the longitudinal and lateral on-center spacings between vegetation. $A_f = Dh_{wp}$ is the wetted frontal area of the vegetation, a product of the wetted plant height, $h_{wp}$, and plant diameter, $D$. The projected planar area of the plants, $A_p$, equals the area for a circle, i.e., $\pi(D/2)^2$. Resulting values for each vegetation configuration can be seen in Table 5.1. For comparison, an additional dimensional parameterization of plant density is provided. Dunn et al. (1996) denoted the parameter $a$ as the ratio of projected frontal area of the plant to the influenced volume,

\[
a = \frac{A_f}{V_i} = \frac{Dh_{wp}}{S_x S_y h_{wp}} = \frac{D}{S_x S_y} = \frac{\lambda_f}{h_{wp}}. \quad (8.4)
\]
Table 8.2 presents all the parameters for each of the experimental conditions. Note that in the base case which is void of vegetation, the parameters become undefined due to division by zero. To mitigate the problem, it was assumed (as denoted with “*”) that the base case was equivalent to the limit of the plant spacing taken to be the entire 182.88-cm (6-ft) lateral width of the tank, and the entire bar length of 300cm. Thus, \( a << 1 \) and \( A_t >> 1 \), and results in \( \lambda_f \) and \( \lambda_p \) becoming zero.

<table>
<thead>
<tr>
<th>Case</th>
<th>( S_x ) [cm]</th>
<th>( S_y ) [cm]</th>
<th>( a ) [cm(^{-1})]</th>
<th>( A_t ) [cm(^2)]</th>
<th>( A_f ) [cm(^2)]</th>
<th>( A_p ) [cm(^2)]</th>
<th>( \lambda_f )</th>
<th>( \lambda_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>300*</td>
<td>182.88*</td>
<td>1.16E-05</td>
<td>54864</td>
<td>4.84</td>
<td>0.317</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4x4S</td>
<td>4</td>
<td>4</td>
<td>3.97E-02</td>
<td>16</td>
<td>4.84</td>
<td>0.317</td>
<td>0.302</td>
<td>0.020</td>
</tr>
<tr>
<td>2Dx12</td>
<td>1.27</td>
<td>12</td>
<td>4.17E-02</td>
<td>15.24</td>
<td>4.84</td>
<td>0.317</td>
<td>0.318</td>
<td>0.021</td>
</tr>
<tr>
<td>3x3S</td>
<td>3</td>
<td>3</td>
<td>7.06E-02</td>
<td>9</td>
<td>4.84</td>
<td>0.317</td>
<td>0.538</td>
<td>0.035</td>
</tr>
<tr>
<td>Dx12</td>
<td>0.635</td>
<td>12</td>
<td>8.33E-02</td>
<td>7.62</td>
<td>4.84</td>
<td>0.317</td>
<td>0.635</td>
<td>0.042</td>
</tr>
<tr>
<td>2x2 S</td>
<td>2</td>
<td>2</td>
<td>1.59E-01</td>
<td>4</td>
<td>4.84</td>
<td>0.317</td>
<td>1.210</td>
<td>0.079</td>
</tr>
<tr>
<td>Dx6</td>
<td>0.635</td>
<td>6</td>
<td>1.67E-01</td>
<td>3.81</td>
<td>4.84</td>
<td>0.317</td>
<td>1.270</td>
<td>0.083</td>
</tr>
<tr>
<td>Dx6Full</td>
<td>0.635</td>
<td>6</td>
<td>1.67E-01</td>
<td>3.81</td>
<td>4.84</td>
<td>0.317</td>
<td>1.270</td>
<td>0.083</td>
</tr>
</tbody>
</table>

Table 8.2: Resulting parameters for vegetation experiments. Note: since vegetation is not present in the base case, “*” denotes artificial values of 300 cm and 182.88 cm for \( S_x \) and \( S_y \), respectively, based on total bar length and width. (Refer to Table D.1 for more experimental conditions.)

### 8.4 Results

A complete overview of the bed evolution is provided through timestacks of the bar profiles for each of the experiments. An example timestack is shown in Figure 8.5. (Refer to Appendix D for timestacks of the all the experiments.) The abscissa is reversed for the plot to appear analogous to the tank schematic (Figure 8.1), with the wall at 22 m on the left side of the diagram and the beginning of the test section on the right side. The initial profile at 00 hrs (shot 00) was established as the reference datum and each successive profile was plotted with vertical offset of 10 cm to allow for a clear visualization of the entire evolution record. For each time profile in the stack, both the complete bed profile (blue line) and the smoothed profile (red line) are provided to illustrate the variability attributed to the small-scale bedforms (ripples) while clearly depicting the behavior of the larger-scale bar formations. Additionally, the initial smoothed profile at 00 hrs is plotted for each time profile to serve as a reference to assist in visualizing the bed change.
Figure 8.4: Example of surface wave measurements graphed directly over the resulting bathymetry for experiment ID 2009-07-15 at block 12.

from the initial state. In certain experiments, e.g., 2009-09-08, a portion of the temporal records may be unavailable (e.g., shots 13 to 16); however, the following shots (e.g., 17) are plotted with proper offsets as if prior records were obtained.

Based on the resulting timestacks, growth rate curves, indicating the maximum height of the bar for each vegetative case, are shown in Figure 8.6. For clarity, the title on top of each subplot denotes the vegetative condition, corresponding experiment ID, and fitting parameters. Measured values of the maximum bar heights are denoted on each subplot by “o” markers and dashed-dotted lines represent the moving average of the measured points. To aid in visualization, data points and moving averages have different color in various subplots based on the bar number where the information was obtained: black color for bar 03 and blue color for bar 05. A red solid line based on fitting (8.1) to all the measured data points (with the exception of
Figure 8.5: Example timestack of bar profiles for experiment 2009-07-15. Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.

case Dx6) is displayed on each subplot. For case Dx6 which exhibited a large change in elevations, two fits were computed: one based on all measurement points (red dotted line) and another line based on a subset which only used data points less than 30 hrs (solid red line). (Note: subsequent analysis will indicate which fit is being used.)

As mentioned, since the waves slightly changed as they propagated along the tank, vegetation cases on bar 03 are compared to the base case of bar 03 for each time (similarly for cases on bar 05) to ensure proper references for comparisons. These normalized referenced relative growth curves are shown in Figure 8.7 for the entire 36 hr record of the base case (limited by duration measurements on base case, although it appears equilibrium has been reached). Since the ordinate is the fitted height of the bars minus the
fitted height of the respective bar for the base case,

\[
\frac{H_{\text{fit}}(t) - H_{\text{base fit}}(t)}{H_{\text{base fit}}(t = 36 \text{ hrs})},
\]

a negative value indicates relative reduction in bar height from the base case and positive values denote increases in height relative to the no vegetation condition.
Figure 8.6: Evolution curves showing the maximum bar height over time. Measure points for bar at location 03 and 05 are denoted with black and blue "o" markers, respectively. A dashed-dotted line represents the moving average through the measured points and solid or dotted red lines indicated the resulting fit from equation (8.1).
Figure 8.7: Normalized relative growth curves for each vegetation case. For clarity, subplots group the cases by type: staggered vegetation (left), non-staggered vegetation (middle), and non-staggered vegetation fully covering the bar (right).
Due to variabilities in final height between measured data and fitting, two computations of relative growth ratios are done to better understand the behavior at critical points in time throughout the evolution. Table 8.3 presents the relative growth ratios computed based on fits at 27 hrs and final asymptotic height limit, in columns 5 and 6, respectively. In addition, $\lambda_f$ versus each of the relative ratios are plotted in Figure 8.8 based on type of vegetation configuration, e.g., “S” for staggered, “N-S” for non-staggered. Note that additional points are plotted on Figure 8.8 to highlight the variability for certain configuration. The light gray circle and dashed light in the right subplot, is for case 4x4S which experienced considerable variability near the end, in which a lower max scour height (~4.5 cm) than the final fit height $H_f = 5.6$ cm is used to be more representative of the terminal behavior. The other additional point occurs for the case of 2Dx12 where a circular point is inscribed by a square point on both subplots. This is actually the same point plotted twice to indicate that although it is a non-staggered point its behavior is similar behavior to that of the staggered configurations. A light horizontal line at relative height equal to one is drawn for reference on each subplot.

<table>
<thead>
<tr>
<th>case</th>
<th>$a$ [cm$^{-1}$]</th>
<th>$\lambda_f$</th>
<th>$\lambda_p$</th>
<th>$H_{fit}(t=27hrs)$</th>
<th>$H_{base}(t=27hrs)$</th>
<th>$H_f$</th>
<th>$H_{Base}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>1.16E-05</td>
<td>0</td>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
<td></td>
<td>1.000</td>
</tr>
<tr>
<td>4x4S</td>
<td>3.97E-02</td>
<td>0.302</td>
<td>0.020</td>
<td>0.708</td>
<td>0.985</td>
<td></td>
<td>0.985</td>
</tr>
<tr>
<td>2Dx12</td>
<td>4.17E-02</td>
<td>0.318</td>
<td>0.021</td>
<td>0.777</td>
<td>0.838</td>
<td></td>
<td>0.838</td>
</tr>
<tr>
<td>3x3S</td>
<td>7.06E-02</td>
<td>0.538</td>
<td>0.035</td>
<td>0.921</td>
<td>0.929</td>
<td></td>
<td>0.929</td>
</tr>
<tr>
<td>Dx12</td>
<td>8.33E-02</td>
<td>0.635</td>
<td>0.042</td>
<td>1.065</td>
<td>1.379</td>
<td></td>
<td>1.379</td>
</tr>
<tr>
<td>2x2S</td>
<td>1.59E-01</td>
<td>1.210</td>
<td>0.079</td>
<td>1.067</td>
<td>1.129</td>
<td></td>
<td>1.129</td>
</tr>
<tr>
<td>Dx6</td>
<td>1.67E-01</td>
<td>1.270</td>
<td>0.083</td>
<td>0.949</td>
<td>1.581</td>
<td></td>
<td>1.581</td>
</tr>
<tr>
<td>Dx6Full</td>
<td>1.67E-01</td>
<td>1.270</td>
<td>0.083</td>
<td>0.065</td>
<td>0.069</td>
<td></td>
<td>0.069</td>
</tr>
</tbody>
</table>

Table 8.3: Relative growth heights ratios computed at 27 hrs and final asymptotic height limit of fits.

8.5 Discussion

Based on the results of Figure D.8 and Figure 8.6 it is evident that having a dense spacing of case Dx6Full over the entire bar shelters the bed from global migration of sediment and inhibits bar growth. The minor measured
changes in elevation are due only to local scour by the rows of vegetation. The essentially solid wall of vegetation blocked bedload, forcing the primary mode of transport to become suspended load. However, due to the dense row spacing of 6 cm which is smaller than the height of the vegetation above the sediment bed, e.g., 7.62 cm (3 in), turbulent structures had limited penetration depth. Thus, the flow could not cause significant sediment to be lifted high enough from the bed to clear the elevation of the surrounding vegetation, so it remained trapped within the rows.

If we consider the same density spacing and changing only the placement of the vegetation as in case Dx6, significant changes occur in the bed evolution. While the vegetation configuration blocks bedload transport, the bar is no longer uniformly covered, and the flow can reach and transport sediment in the middle section of the bar. However, as the flow transports sediment
by the rows nearest to the bar crest (higher near bed horizontal velocity regions), the bedload is forced into suspension due to redirection by the wall of plants. At this point, the sediment no longer migrates toward the wave node, but migrates to the antinode following the well understood theory of mass transport under standing waves (Longuet-Higgins, 1953; Carter et al., 1973). Once the sediment settles between the rows it becomes trapped, and gradually the bed loses sediment under the wave node, which would have become a bar crest under conditions with no vegetation. The resulting condition is a bar profile similar to that of suspended load dominated conditions of finer sediment as depicted in subplot (e) in Figure 2.4. However, since the plants have a finite depth, if scour becomes excessive on the side of the rows facing the bar crest, failure of the vegetation will occur. The details of this type of failure is discussed in detail in Section 8.5.1. (Note: Although the relative elevation to the base case is computed, the reader should remember that the overall bar geometry is different and can not be taken as an absolute comparison.)

If the longitudinal spacing is double as in the case Dx12, similar transport mechanisms occur as in the Dx6 configuration; however, due to the increased spacing (which is almost double the extended plant height) the turbulent structures are not as limited and can more readily move sediment between the vegetation. It should be noted that dominant suspended transport was maintained as a result of the bed profiles (bar 05 in Figure D.6) although due to the increased turbulent structures, bed aggradation was slightly less than case Dx6 (7.9 cm versus 9.1 cm).

Increasing the lateral spacing by only one plant diameter, as in the case of 2Dx12, significantly changed the bed profile. The additional lateral spacing no longer inhibited bedload transport and altered the dominant transport from suspended load to bedload as can be seen in Figure D.6 (bar 03). Furthermore, the uniform array of vegetation controlled the ripple geometry with the canopy as indicated by the well formed ripples between the uniforms rows of vegetation in Figure 8.9. Singular ripples formed within each row of vegetation with the crest centered between the rows and the troughs at the local scour around each of the vegetation rows. The increased resistance of the vegetation resulted in an overall height reduction of $\approx 1$ cm ($\approx 20\%$) relative to the base, as seen in Figures 8.6, 8.7, and 8.8.

The reduction in bar height for the 2Dx12 case was also similar to the
result of the 4x4S case, which is promising since both cases have similar $\lambda_f$ parameters. It should be noted that in the right subplot in Figure 8.8, the light gray solid circle marker is probably more representative of the final behavior as previously mentioned. This allows for similar results for 4x4S and 2Dx12 even at the asymptotic limit of bar growth. The slightly lower relative growth value of 4x4s compared to 2Dx12 is suspected to be attributed to the staggered array spacing impeding the flow more than the non-staggered spacing, thus reducing the bar growth.

As the staggered array density increased to 3x3S, the bar growth is at $\approx 90\%$ of the base case which is $\approx 30\%$ higher than the 4x4S case. Further increasing the vegetation density to 2x2S actually results in an increase in bar height rather than a reduction which resulted in composite vegetation failure as discussed in Section 8.5.1. Unlike unidirectional flows through submerged canopies, the higher plant density under oscillatory flow does not necessarily shelter the bed from the flow. Since the water is only oscillating around a point and does not have to travel along the entire patch of vegetation, the inviscid core velocities can penetrate deeper into the canopy and enhance intra-plant velocities due to the reduced spacing (increasing streaming within the canopy). Thus, there is a trade off between reduction in inviscid core velocities and enhancement of local velocities with the canopy due to streaming. Based on Figure 8.8, it appears that $\lambda_f \approx 0.9$ (or 2.25x2.25S spacing) is the vegetated condition which should balance between the aforementioned effects, resulting in net minor changes from the non-vegetated condition.

On a final note, it should be mentioned that the trend of relative bar growth reduction as the staggered vegetation density increases cannot continue indefinitely since in the limit of increased spacing, the bed should approach the base case condition ($H_{fit}/H_{base fit} = 1$, as $\lambda_f$ goes to zero.) Thus, additional experiments with staggered spacings greater than 4x4S (e.g., 5x5S and 6x6S) should be conducted in the future to better resolve sparse density effects on bed growth.
8.5.1 Dataset Abnormalities

While the vast majority of the data obtained from the profiles were indicative of behavior in the transversal direction, a small subset of profiles exhibited significant deviations which can be attributed to two major causes, presented in order of increasing severity.

1) Local scour due to enhanced streaming:

Enhanced streaming effects became apparent at one or two positions along the plexiglas sidewall in densely spaced vegetation configurations (e.g., Dx6, Dx6 Full, and Dx12). While vegetation was carefully positioned, slight geometric variations (due to swelling and contracting of the wood) made it difficult to ensure that the entire length of the cylinders were completely flush with one another or the plexiglas sidewall. Even if flush placement was achieved, the movable bed did not allow for complete absence of gaps along the entire length of the adjacent cylindrical vegetation segments. As a result, after the development of ripples (on the order of 30 mins) local streaming was observed at these few points near the wall which increased the local scour immediately surrounding the vegetation and measured by the profiling camera. An example result of the aforementioned phenomena can been seen in Figure 8.10 which shows the zoomed-in region near the wall of the 2010-04-22 shot 01 profile around \( x =11.4 \) m. One can vaguely see that the bed away from the wall is slightly higher, and it is not experiencing this local effect.
The local spacing gap allowed the bedload transport to move in the direction of the incident wave until it encountered a row which was sufficiently near the wall to completely block transport. Typically, this enhanced local scour region reached a quasi-equilibrium and was maintained for the duration of the experiment. A sharp spike persisted around $x = 11.4\,\text{m}$ in the timestack for vegetation spacing of Dx6Full (Figure D.8) throughout the duration of the experiment. However, since the effects were localized, smoothing of the bed profile (red line) easily filtered out these small problematic regions.

Figure 8.10: Photograph for case Dx6Full (2010-04-22; shot 01; near $x = 11.4\,\text{m}$) illustrating the local scour induced by slight gaps through the plants near the wall which migrates as bedload until it encounters a row that is sufficiently close the wall to stop transport. Measurement profile for case Dx6Full at 3 hrs are shown in blue.

2) Vegetation Failure:

While it was not intentional for the vegetation to fail, due to the finite length of the dowel rods, failure was inevitable if the scour approached the 3-inch burial depth of the plants. Depending on the plant-spacing, near bed water velocities, a degree of relative buoyancy of the plant, and reduced skin friction supporting the cylinder with increasing scour, the vegetation started to show signs of motion once scour exceeded about 2.5 inches and generally failed beyond scour of 2.75 inches. Depending on the configuration of the vegetation, failure occurred either due to composite scour or due to local scour. The majority of the failures were observed in plan view since it was not possible to measure the failure progression via the profiling camera, thus limiting the negative impact on the profile measurements. However, the impact of the failure and release of the sediment significantly alters the bathymetry in the influenced region.

(i) Composite scour failure:
This type of failure results from the composition of global scour due to the
bar formation and the local effect due to the placement of the vegetation. The composite scour failure was observed only in the 2x2S case in which the vegetation failure occurred directly over the seaward trough of the bar with the onset of failure around 21 hrs throughout the lateral extent of the observed failed region near the wall. Due to the staggered arrangement of the vegetation, bedload transport was not blocked; however, based on bed evolution, it is suspected that the dense spacing of the canopy slightly reduced near bed stress but enhanced turbulence (more uniform flow) which extended the depth of bar scour at which significant bedload can be achieved. Furthermore, the tight spacing allowed for the local scour around each plant to interact with the nearby holes, adding to the overall scour. Thus, as a composite of global and local scour, the bar trough surpassed the scour of the base case, eventually causing failure of the vegetation in the region. Once failure occurred, the plants rested on other nearby plants thereby altering the spacing and further enhancing scour.

(ii) Local scour failure:
This failure type was observed for vegetated cases that covered only the trough regions of the bars and had dense lateral spacings (e.g., cases Dx6, Dx12, and 2Dx12). Unlike the composite scour failure, the local scour failure initially occurred as early as 6 hrs at the lateral centerline of rows nearest to bar crest and not at the trough. While failure was observed for the 2Dx12 case, it occurred 30 hrs later, and the impact was noticeably less than cases Dx6 and Dx12.

In vegetation configurations Dx6 and Dx12, the plants essentially became a solid wall that hindered any bedload transport, increased vorticity around the plants and caused sediment to be suspended, moving as suspended load toward the wave antinode regions. As a result, the side of the vegetation
facing the bar crest or the rows nearest to the bar crest became starved of sediment and failure was initiated.

Typically, the onset of this failure type occurred at the center of the vegetation rows closest to the bar crest, and the failure quickly propagated in a seemingly triangular or parabolic way, e.g., similar to water incising a channel when overtopping an earthen levee. Figure 8.12 presents a visual overview of the local failure process for case Dx6 at various times. Once the initial failure is present, vegetation laterally adjacent to the failed area started to fall. Sediment that had been built up between the rows was released, and it migrated to the bar crest. The following row (second away from the bar crest) soon started to experience failure along its centerline. This failure behavior continued until the vertex of the failure reached either the second to last or final row away from the bar crest. Note that the failure is contained in the central portion and does not affect the near wall regions.

8.6 Conclusion

This laboratory based experimental effort focused on furthering the understanding of coastal morphodynamics in which the interactions between sand ripples, bars, and vegetation impacts the sediment transport processes. While it was found that vegetation typically reduced the rate of bar development and equilibrium bar height, the configuration and integrity of the vegetation play significant roles in determining the resulting large scale morphodynamic changes. Staggered arrays reduced bar growth in the initial development (< 24 hrs); however, exceeding a critical density spacing of \( \lambda_f = 0.9 \) for the staggered array increased the final overall scour of the bar. In other conditions of closely spaced lateral arrays, e.g., Dx6 and Dx12, the natural mode of sediment transport changed from bedload dominated to a mode that was primarily suspended load dominated. This change in transport resulted in a complete change of the bar profiles where the bar crest was no longer under the wave node but moved closer to the wave antinodes, similar to profiles illustrated in Figure 2.4(e). In the extreme case of a fully covered bar, Dx6Full, the bar formation was completely mitigated and the sand bed only experienced slight perturbations due to local scour around the vegetation. Finally, the importance of proper installation of plants is high-
lighted since failure propagation is rapid and any effects of the plants (e.g., sheltering or sediment capturing) is quickly lost, returning the bed profile to that of the no vegetation case.
Figure 8.12: Progression of local failure for seaward side of case Dx6: a) 33 hrs, b) 39 hrs, and c) 45 hrs.
9.1 Summary of Main Results

The intent of this large-scale laboratory study was to better elucidate bedform morphodynamics under wave conditions which exhibited spatial variation in the surface envelope (e.g., partially progressive to fully reflected waves), as well as various configurations of near-deeply submerged vegetated canopies (present study, $H_p/h_p = 7.9$). A brief summary of the key contributions of this study are listed as follows:

Development of an extensive large-scale laboratory experimental dataset for wave conditions: Large-scale laboratory measurements in which detailed measurements over the entire test section are very rare, but are vital to providing insights into environmental phenomena without introducing significant scale effects often associated with small-scale facilities. This dataset will provide vital information that will directly benefit coastal researchers from all tracks, experimental (lab and field), numerical, and theoretical.

Planform geometric ripple predictors have been found to provide accurate estimates of ripple geometries when superimposed on large-scale bar formations: Planform geometric ripple predictors for oscillatory flow were developed for seabeds without the presence of large-scale bedforms. It has been shown by analyzing bathymetry data herein, in cases of high and low reflection, that these predictors can be applied to obtain accurate estimates of the ripple lengths and amplitudes even when superimposed on larger sand bars.
Variations in ripple migration velocities have been related to variation in near bed Lagrangian mass transport velocities for partially progressive waves: Of the limited prior work on ripple migration velocities, all migration predictors are based on purely progressive waves. The predictors do not adequately describe general observations of ripples having large velocities near wave quasi-nodes and lower velocities around quasi-antinodes (Landry, 2004; Cataño-Lopera and García, 2006b). Furthermore, there is a general consensus among researchers that migration rates are not well understood and still require much work. This study provides detailed results of spatial distributions of ripple velocities relative to wave forcing which has never been reported before. Through the spatial comparison of wave and ripple velocities for a former detailed dataset obtained by the writer, this study found that when considering the generalized Lagrangian mass transport velocities for arbitrary reflection, ripple migration velocities can be associated with near bed locally computed Lagrangian mass transport velocities within the bottom boundary layer.

Near-deeply submerged vegetation has been shown to control dominant mode of sediment transport: Based on bathymetry measurements, vegetation cases which had dense lateral spacings hindered bedload transport and resulted in suspended load dominated transport. This was clearly apparent due to two bar crests forming near each wave antinode region instead of a single crest under the wave node.

Vegetation has been shown to decrease bar growth rates but also can enhance final bar height: Introduction of vegetation resulted in decreased bar growth when compared to the non-vegetated case within the initial 24 hrs. However, during the subsequent time, the trending behavior and final state of the bar height was dependent on the vegetation configuration. Configuration of 2x2S enhance scour at bar troughs; configurations of 3x3S and less dense reduce scour.

Ripples geometries have been shown to be controlled by vegetated canopy spacing: In the presence of standing wave conditions, there exists a range of ripple sizes superimposed over the sand bar (larger ripples at the bar crest, cascading to smaller ripples near wave antinodes). However, in
vegetated conditions, all of the resulting ripple bedforms within the canopies were directly controlled by the turbulence and local scour associated with the vegetation, as shown in the 3-dimensional laser bathymetry scans.

**Rapid system failure response was observed which highlights the implications of natural plant spacing and the need for adequate design:** In occasions where the vegetation failed due to excessive scour, the propagation of failure was quite rapid and any trapped sediment was released. Provided all the vegetation fail at once (or removed at once) the system will tend to the base case condition (within < 12 hrs). The failure mode based on density may shed key insight regarding the natural spacing of vegetation in a given coastal region with specific wave climate, plant type, and soil type.

### 9.2 Technical Contributions

**Surface Wave Measurement Software, WaveAR:** Development of a generalized surface wave processing code was a requisite of the study. The final software is a friendly graphical user interface (GUI) which allows the user to enter water wave amplitude time series at various locations along a tank (as standard text files). The program will estimate reach-wise wave parameters for the facility as well as provide a detailed overview of wave field spatial variability. This code is intended to be implemented as common practice when conducting wave experiments in order to establish a level a consistency among reported wave parameters within the research community.

**Bathymetry processing algorithms:** In order to process the plethora of image and laser data obtained throughout the study, generalized “in-house” software was developed. The code is based in MATLAB® and has already been used in other studies (Tanana River scour project at UIUC and ripple migration experiments at the Naval Research Laboratory-Stennis).

**Instrumentation of the large wave current (LWCF) facility:** As a direct result of this study, the LWCF has been outfitted with numerous instruments and control systems to obtain detailed measurements and help
automate tasks when possible. New acoustic wave gages were implemented along with a customized MATLAB® code and GUI to allow for quick acquisition of surface waves. A direction sensing triggering system (DSTS) was developed to synchronize sampling of various instrumentation. Lastly, a Keyence laser displacement system was installed and automated to obtain detailed 3-D measurements of the bed.

9.3 Future Work

While this study provides detailed insight regarding the impact of the wave field variability and vegetation on the bedform morphodynamics, additional experiments are required. Specifically, more experiments are required in the intermediate range of reflection coefficients to link low- and high-reflection results and develop a unified relation for ripple velocities. Significant effort will be needed for these experiments since a new beach will be required. The new beach design should allow for the possibility of producing a wide range of reflections through minor user modifications (e.g., a long sloped beach which allows the user to gradually increment the slope).

Regarding oscillatory flows through vegetated conditions with a movable bed, since this was the first study of its kind, numerous additional experiments can be conducted such as changing plant properties (spacing, type, diameter, height), and/or flow conditions. However, to enhance the findings of the current work, additional key experiments are required to confirm the reported behavior. Spacings of staggered vegetation sparser than the 4x4S configuration (e.g., 6x6S and 8x8S) need to be implemented to determine the critical limit at which decreasing vegetation density no longer decreases bar growth and approaches the no vegetation limit. Also, an experiment with an approximate spacing of 2.25x2.25S configuration needs to be conducted to verify the trend (Figure 8.8) which implies this new spacing should not result in significant change in final bar height from the base case.

Acquired velocity profile data which were synchronized with wave measurements need to be processed (filtered and phase averaged) to provide a complete picture of the experimental conditions. The velocity data will provide insight into the flow structure around the vegetated canopy which results in the various bed profile conditions. Furthermore, numerical model-
ing of these conditions will be explored to provide additional detailed insight into the variation in coherent turbulent structures with varying plant density.

A permanent website will be developed to serve as a data repository and will be available to the general scientific community. The entire dataset (wave, velocity, and bathymetry measurements) for each of the vegetated conditions, as well as documented photographs, will be published online. In addition, all developed software (e.g., WaveAR program and processing algorithms) will be uploaded as well. It is hoped that researchers will find this robust and unique dataset invaluable in a variety of aspects such as aiding design of future laboratory studies, calibration/validation of numerical models, and various engineering educational purposes.
APPENDIX A

DIRECTION SENSING TRIGGERING SYSTEM (DSTS) CIRCUIT DESIGN
Figure A.1: Latch circuit diagram for direction sensing triggering system, DSTS, (Page 1/2)
Note: Currently implemented circuit which WORKS, however NOT the best design.
Refer to LatchingProject/inrelay_rev1_13.pn for BETTER design with no Relay.

Note: In order to SYNC BOTH, the ADV and NI-DAQ USB must be powered and connected.
Since NI-DAQ 6009 USB has 5V on the trigger port, triggering occurs on both devices after an enabled trigger signal from latch goes off (i.e., when LED goes off, returning the 5V on the NI-DAQ terminal which is a rising edge trigger).

Advisory: IF NOT syncing BOTH, plug the single device directly to "C" and "D" from the latch system on page 1/2 and adjust the trigger accordingly (rising or falling edge).

Figure A.2: Relay circuit diagram for direction sensing triggering system, DSTS, (Page 2/2)
APPENDIX B

DIRECTIONS FOR PROCESSING BAR IMAGES

1. **PTLENS:**
   
   (a) Find folder containing images to be converted by selecting a data “Directory”
   
   (b) Highlight all images
   
   (c) Options: check “Preview” and “Distortion”
   
   (d) Click “Apply”
   
   (e) The newly created files should be appended with pt

2. **PANAVUE Pro V3**
   
   (a) New Project ’ ”Mosaic Stitching”
   
   (b) Set Options: Under Stitching options: select ”Manual stitch with flags”
   
   (c) Under Image options: Check ”Adjust colors”, ”Anti-Aliasing”, and ”Force first row and first column to have no rotation”. Choose Image blending to be between 40-60
   
   (d) Add Images
      - From folder of interest, select all _pt files
      - Sort the files by Detail and then by Ascending Time
      - Select ”Add” and then ”Done”

3. **AutoHotKey**
   
   (a) Open AutoHotKey
   
   (b) Load “panvue.ahk” (located in script folder)
      - Up arrow= zooms all the way out
      - Down arrow= zooms in
- Left arrow = auto correlation flag
- Right arrow = switch to next image pair

(c) Stitch the images using the flags

(d) After stitching, compile panoramic image using “full run” and save resulting image as “shotsXX.tif” & “shotsXX.jpg”, where “XX” is the shot number

4. GIMP

(a) Open shotsXX.tif

(b) Threshold image
   - Draw a rectangular region (ctrl+r) over half the span between tank beams
   - In “Colors” menu select “Threshold”
   - Move black cursor in threshold box until image is adequately threshold
   - Continue region based thresholding over entire image

(c) Clean up image (using Erase tool, e.g., Shift + E)

(d) Choose brush and scale

(e) Check ”Hard edge” under Brush Dynamics

(f) After erasing is completed: set “Image Mode Index” to black and white palette.

(g) Save image as shotsXX_bw.pcx, where XX refers to shot number

(h) Helpful hints:
   Ctrl + scroll on mouse: zoom in or out
   Shift + scroll on mouse: pans image
   Ctrl + Shift + ’a’ allows erasing outside of selected rectangular regions
   To draw a straight line with eraser:
   Left click once
   Hold shift and move mouse
   Left click again
5. MATLAB®

(a) Run “Readbar_v3.m”
Open image shotsXX_bw.pcx
Select lower and upper boundary points
Resulting image will be saved as shotsXX_bw.mat

(b) Run “Barpan_digitize.m”
- Load data: select shotsXX_bw.mat
- Load image: select shotsXX.tif (original image)
- Modify points (delete or add) in the following categories:
  i. Sand points: Review automated sand points which were com-
     puted via “Readbar_v3.m”
  ii. Flat points: Add many points over all flat regions
  iii. Calibration points:
    - Add many points over the dotted horizontal line below sand
      surface
    - Add 3 points to form axes (1125, -4), (1125, 0), (1000, 0)
- Save data (file will be saved as shotsXX_c.mat)
APPENDIX C

WAVE AND RIPPLE VELOCITY PLOTS
Figure C.1: Experiment 123 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.2: Experiment 123 complete timestack. (Refer to Section 7.5 for a detailed description.)

1.23.03 timestack (subset 2.49 to 2.91 hrs)
Figure C.3: Experiment 123 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.4: Experiment 123 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr.

(Refer to Section 7.5 for a detailed description.)
Figure C.5: Ripple velocity distribution boxplot statistics for experiment 123 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.6: Experiment 123 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.7: Experiment 124 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.8: Experiment 124 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.9: Experiment 124 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.10: Experiment 124 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.11: Ripple velocity distribution boxplot statistics for experiment 124 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.12: Experiment 124 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)

$max(v_{rip}) = 15.89 \text{ cm/hr}$

$max(u_i) \text{ at } (\xi = 0.25; 0.5; 6) = 4.47E-003; \ 9.53E-003; \ 3.01E-002 \text{ m/s}$

$\frac{v_{rip}}{\max(v_{rip})}$

$\frac{u_i}{\max(u_i)}$

Fraction of wave beat ($\lambda_{beat} = \lambda/2 = 3.00 \text{ m}$)
Figure C.13: Experiment 212 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.14: Experiment 212 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.15: Experiment 212: Complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.16: Experiment 212 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.17: Ripple velocity distribution boxplot statistics for experiment 212 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.18: Experiment 212 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.19: Experiment 226 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.20: Experiment 226 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.21: Experiment 226 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.22: Experiment 226 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.23: Ripple velocity distribution boxplot statistics for experiment 226 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.24: Experiment 226 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.25: Experiment 324 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.26: Experiment 324 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.27: Experiment 324 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.28: Experiment 324 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.29: Ripple velocity distribution boxplot statistics for experiment 324 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.30: Experiment 324 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.31: Experiment 407 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.32: Experiment 407 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.33: Experiment 407 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.34: Experiment 407 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.35: Ripple velocity distribution boxplot statistics for experiment 407 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.36: Experiment 407 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.37: Experiment 414 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.38: Experiment 414 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.39: Experiment 414 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.40: Experiment 414 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.41: Ripple velocity distribution boxplot statistics for experiment 414 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.42: Experiment 414 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.43: Experiment 416 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.44: Experiment 416 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.45: Experiment 416 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.46: Experiment 416 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.47: Ripple velocity distribution boxplot statistics for experiment 416 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.48: Experiment 416 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.49: Experiment 430 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.50: Experiment 430 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.51: Experiment 430 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.52: Experiment 430 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr.

(Refer to Section 7.5 for a detailed description.)
Figure C.53: Ripple velocity distribution boxplot statistics for experiment 430 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.54: Experiment 430 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.55: Experiment 508 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.56: Experiment 508 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.57: Experiment 508 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.58: Experiment 508 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.59: Ripple velocity distribution boxplot statistics for experiment 508 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.60: Experiment 508 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.61: Experiment 513 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.62: Experiment 513 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.63: Experiment 513 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.64: Experiment 513 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.65: Ripple velocity distribution boxplot statistics for experiment 513 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.66: Experiment 513 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.67: Experiment 519 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.68: Experiment 519 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.69: Experiment 519 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.70: Experiment 519 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.71: Ripple velocity distribution boxplot statistics for experiment 519 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.72: Experiment 519 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)

max($v_{\text{rip}}$) = 5.20 cm/hr

max($u_1$) at ($\zeta$ = 0.25; 0.5; 6) = 1.51E-003; 2.13E-003; 1.20E-002 m/s
Figure C.73: Experiment 525 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.74: Experiment 525 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.75: Experiment 525 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.76: Experiment 525 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.77: Ripple velocity distribution boxplot statistics for experiment 525 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.78: Experiment 525 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
Figure C.79: Experiment 527 composite wave and bed information plot. (Refer to Section 7.5 for a detailed description.)
Figure C.80: Experiment 527 complete timestack. (Refer to Section 7.5 for a detailed description.)
Figure C.81: Experiment 527 complete ripple velocity contour map. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.82: Experiment 527 ripple velocity contour map for selected subset. Colorbar indicates ripple velocities in cm/hr. (Refer to Section 7.5 for a detailed description.)
Figure C.83: Ripple velocity distribution boxplot statistics for experiment 527 selected subset. (Refer to Section 7.5 for a detailed description.)
Figure C.84: Experiment 527 normalized plot of ripple velocities and Lagrangian mass transport velocities subset. (Refer to Section 7.5 for a detailed description.)
APPENDIX D

EFFECTS OF VEGETATION ON BAR GROWTH

D.1 Tank Conditions
<table>
<thead>
<tr>
<th>Exp. ID</th>
<th>wavemaker settings</th>
<th>measured waves</th>
<th>tank conditions</th>
<th>bed profile shots</th>
<th>plant height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>span [Hz]</td>
<td>freq [cm]</td>
<td>$a_i$ [cm]</td>
<td>T [sec]</td>
<td>$h_{swl}$ [m]</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>2.5</td>
<td>0.315</td>
<td>3.93</td>
<td>2.61</td>
<td>0.60</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>2.5</td>
<td>0.315</td>
<td>4.05</td>
<td>2.62</td>
<td>0.60</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>2.5</td>
<td>0.315</td>
<td>4.22</td>
<td>2.61</td>
<td>0.60</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>2.5</td>
<td>0.315</td>
<td>4.06</td>
<td>2.61</td>
<td>0.60</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>2.5</td>
<td>0.315</td>
<td>4.46</td>
<td>2.61</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table D.1: Additional conditions for vegetation experiments. Column one is the experiment identification name. Column two lists the captured 3-hr block bed profile shots. Columns 2 and 3 list the facility’s wavemaker settings for span and frequency, respectively. Columns 4 and 5 list averaged wave parameters, incident wave amplitude and wave period, respectively, obtained from measurements analyzed with WaveAR. Still water level, $h_{swl}$, and average water temperature are reported in columns 7 and 8. Column 9 lists the captured 3-hr block bed profile shots. Initial plant height above the sand bed is displayed in column 10. (Refer to Table 8.1 and 8.2 more experimental conditions.)
<table>
<thead>
<tr>
<th>Exp. ID Block</th>
<th>$a_{11}$ [cm]</th>
<th>$a_{21}$ [cm]</th>
<th>$R_1$ [°]</th>
<th>$T_1$ [sec]</th>
<th>$T_2$ [sec]</th>
<th>$L_1$ [m]</th>
<th>$L_2$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-07-15</td>
<td>3.7</td>
<td>0.2</td>
<td>0.92</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.0</td>
<td>0.2</td>
<td>0.87</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.5</td>
<td>0.5</td>
<td>0.83</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>4.1</td>
<td>0.4</td>
<td>0.85</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.3</td>
<td>0.4</td>
<td>0.88</td>
<td>2.61</td>
<td>1.31</td>
<td>5.87</td>
<td>2.42</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>3.8</td>
<td>0.3</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>3.8</td>
<td>0.3</td>
<td>0.98</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.3</td>
<td>0.8</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>3.9</td>
<td>0.5</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.4</td>
<td>0.5</td>
<td>0.92</td>
<td>2.61</td>
<td>1.31</td>
<td>5.86</td>
<td>2.41</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>3.7</td>
<td>0.3</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.0</td>
<td>0.5</td>
<td>1.00</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.5</td>
<td>1.3</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>3.9</td>
<td>0.5</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.6</td>
<td>0.7</td>
<td>0.92</td>
<td>2.61</td>
<td>1.31</td>
<td>5.86</td>
<td>2.41</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>3.9</td>
<td>0.4</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.1</td>
<td>0.6</td>
<td>1.00</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.1</td>
<td>0.7</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>4.1</td>
<td>0.7</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.4</td>
<td>0.6</td>
<td>0.92</td>
<td>2.61</td>
<td>1.31</td>
<td>5.86</td>
<td>2.41</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>4.0</td>
<td>0.4</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.1</td>
<td>0.6</td>
<td>1.00</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.1</td>
<td>0.7</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>4.1</td>
<td>0.6</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.4</td>
<td>0.6</td>
<td>0.92</td>
<td>2.61</td>
<td>1.31</td>
<td>5.86</td>
<td>2.41</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>4.3</td>
<td>0.5</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.1</td>
<td>0.6</td>
<td>1.00</td>
<td>2.62</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.1</td>
<td>0.7</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>4.1</td>
<td>0.7</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.7</td>
<td>0.8</td>
<td>0.91</td>
<td>2.61</td>
<td>1.31</td>
<td>5.85</td>
<td>2.41</td>
</tr>
<tr>
<td>2009-07-15</td>
<td>4.2</td>
<td>0.8</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-09-08</td>
<td>4.2</td>
<td>0.8</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2009-12-10</td>
<td>4.2</td>
<td>0.8</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.97</td>
<td>2.44</td>
</tr>
<tr>
<td>2010-02-11</td>
<td>4.2</td>
<td>0.8</td>
<td>1.00</td>
<td>2.61</td>
<td>1.31</td>
<td>5.96</td>
<td>2.43</td>
</tr>
<tr>
<td>2010-04-22</td>
<td>4.6</td>
<td>0.8</td>
<td>0.91</td>
<td>2.61</td>
<td>1.31</td>
<td>5.86</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Table D.2: Results of the first harmonic amplitudes (via WaveAR code) for the first nine 3-hr blocks of the experiments (e.g., up to 27 hrs). Refer to Chapter 5 for details of the code.
Figure D.1: Plot of first harmonic incident amplitudes throughout each experiment. Incident amplitude was resolved using WaveAR program (Chapter 5) for each of the measured water wave surface envelopes. Time blocks were in 3-hr intervals throughout the experiments.
Figure D.2: Superposition of wave conditions for all experiments for block 01 (first 3 hrs). Measurement points, in middle plot, are indicated with “o” and “.” markers for first and second harmonics, respectively. WaveAR code was used for the fitting seen in the middle plot as solid blue line for first harmonic and dotted black line for second harmonic amplitudes. Near bed velocities were computed from linear wave theory.
Figure D.3: Superposition of wave conditions for all experiments for block 05 (15 hrs). Measurement points, in middle plot, are indicated with “o” and “.” markers for first and second harmonics, respectively. WaveAR code was used for the fitting seen in the middle plot as solid blue line for first harmonic and dotted black line for second harmonic amplitudes. Near bed velocities were computed from linear wave theory.
D.2 Bar Evolution Stacks
Figure D.4: Experiment 2009-07-15 timestack of bar profiles: base case of no vegetation on all bars. Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.
Figure D.5: Experiment 2009-09-08 timestack of bar profiles: 2x2S (bar 03) and 4x4S (bar05). Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.
Figure D.6: Experiment 2009-12-10 timestack of bar profiles: 3x3S (bar 03) and Dx6 (bar 05). Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.
Figure D.7: Experiment 2010-02-11 timestack of bar profiles: 2Dx12 (bar 03) and Dx12 (bar05). Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.
Figure D.8: Experiment 2010-04-22 timestack of bar profiles: Dx6Full (bar 03). Complete bed profile and smoothed mean elevation are denoted by blue and red lines, respectively. Shaded dotted line denoting the mean initial bed profile is plotted on subsequent time profiles for reference.
D.3 Laser Bathymetry Scans of Final Bedforms
Figure D.9: Laser bathymetry scan with image texture map of 2x2S case (Exp. ID: 2009-09-08, bar03)
Figure D.10: Laser bathymetry scan with image texture map of 4x4S case (Exp. ID: 2009-09-08, bar05)
Figure D.11: Laser bathymetry scan of 2x2S case (Exp. ID: 2009-09-08, bar03)
Figure D.12: Laser bathymetry scan of 4x4S case (Exp. ID: 2009-09-08, bar05)
Figure D.13: Laser bathymetry scan of 3x3S case (Exp. ID: 2009-12-10, bar03)
Figure D.14: Laser bathymetry scan of Dx6 case (Exp. ID: 2009-12-10, bar05)
Figure D.16: Laser bathymetry scan of Dx12 case (Exp. ID: 2010-02-11, bar05)
Figure D.17: Laser bathymetry scan of Dx6Full case (Exp. ID: 2010-04-22, bar03)
REFERENCES


Landry, B. J., Cataño-Lopera, Y. A., Hancock, M. J., Mei, C. C., and García, M. H. (2009). Effect of spatial variation of a wave field on the resulting ripple characteristics and comparison to present ripple predictors. In *Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering (OMAE)*. ASME.


268


Blake J. Landry was born in the small historical town of Saint Martinville, Louisiana. He grew up along the banks of the Bayou Teche and was always fascinated with the environmental fluid dynamics processes occurring in his backyard. He attended the University of Louisiana at Lafayette (ULL), majoring in Civil Engineering with specialization in environmental and construction sub-disciplines. After graduating summa cum laude with an Honors Baccalaureate degree in 2001, he continued to pursue a Master of Science (S.M.) degree in the Department of Civil and Environmental Engineering at Massachusetts Institute of Technology (MIT) with focus on Environmental Fluid Mechanics and Coastal Engineering. There he worked with Professor C. C. Mei, conducting large scale laboratory experiments exploring sand ripple and bar morphodynamics. Upon receiving his S.M. in 2004, he returned to his home state and worked as a project designer at a consulting firm, Fenstermaker and Associates, Inc., in Lafayette, Louisiana, for the following year. Also, during this same year, he worked as an adjunct lecturer at ULL, teaching Open Channel Hydraulics and Engineering Statics. In the Fall of 2005, he joined the University of Illinois at Urbana-Champaign to obtain a PhD in Civil and Environmental Engineering with focus in Environmental Hydraulics and Hydrology under the advisorship of Professor M. H. García.