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A PHYSICAL AND NUMERICAL MODEL OF WAVES AND NEAR-BED VELOCITIES UNDER BICHROMATIC CONDITIONS OVER A STEEPLY SLOPING BEACH FACE

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Abstract: This study aims to further the understanding of cross-shore flows, sediment transport and beach evolution by combining physical model results with numerical predictions. The wave and morphological numerical model XBeach will be compared with laboratory results for a variety of erosive conditions, bed shear stresses and near bed velocities to understand bottom boundary layer processes. Physical model tests were performed in a 22.75 m long by 1.7 m wide by 0.4 m deep channel in a wave basin with a 0.165 mm sand beach. Detailed acoustic bottom velocity measurements along the beach profile were made in combination with wave measurements at an array of 8 capacitance wave gauges. Measurements were made under bichromatic wave conditions with a peak period of 2.15 seconds and a wave group period of 21 seconds. Velocity observations indicate an increased zone of near bed velocities 20-30cm from the dune face in the region of most intense breaking. XBeach simulations of breaking wave profiles do not agree with laboratory observations in the breaker zone and future tests will allow for more detailed comparisons.

1 Introduction

Coastal communities must be aware of and prepared for the hazards that come with living in close proximity to the ocean. Small and Nicholls (2003) estimated the population living within 100km of a coastline and 100m of sea level at 1.2 billion and growing. Hurricane Katrina in 2005 was an example of the huge costs of under-designed coastal defenses and the catastrophic results when waves and storm surges cause flooding of low lying areas (Morton & Sallenger, 2003).

To protect against storm events like hurricanes, it is important to have an accurate understanding of the capabilities of the ocean as well as the ability to plan for and protect against large storms. Physical and numerical models are useful tools that can be used to provide insight on a situation or possible event. Physical models can be great sources of information but are generally extremely expensive and require long periods of time to be built and tested. For these reasons numerical models are often preferred due to their ease of implementation. Extreme events, such as Hurricane Katrina, often highlight the need for further development of numerical models.

The numerical model XBeach (Roelvink et. al, 2009), developed after Hurricane Katrina, has shown proficiency when applied to a variety of morphological cases (ex. van Gent et al., 2008); however the results required extensive calibrations (Splinter et al., 2011 & Van Dongeren et al., 2013) and are not in perfect agreement with observations (Lindemer et al., 2010 & Van Dongeren et al., 2009). Recently, the model was tested by the authors at Salalah Beach in Oman and it was unable to reproduce the complex seasonal cross-shore erosion patterns after numerous calibration attempts. Preliminary results have suggested that XBeach could be inconsistently predicting the near bed flows and thus the extensive calibrations could be over-compensating for this in other studies. Subsequent testing of the model has shown its extreme sensitivity to certain morphological input parameters such as the threshold water depth for concentration and return flow (hmin), the critical avalanching slope under water (wetslp), the critical avalanching slope above water (dryslp) and the water depth at the interface from wetslp to dryslp (hswitch).

The objectives of this study are to:

1. Fix the bed of a channel with a large dune beach in a manner that does not affect the bottom roughness coefficient of the material so as to not change the flow pattern
2. Subject the dune to bichromatic wave conditions in its fixed bed state
3. Make precise bottom velocity measurements using an Acoustic Doppler Velocimeter (ADV) instrument and water level measurements with capacitance wave gauges.
4. Compare the observations with the modelled results produced by XBeach to evaluate the model's ability to calculate near-bottom velocities to predict erosion events at a small scale.

The purpose of this paper is to detail the preliminary results completed thus far.

2 Experimental Set-Up and Description of Measurements for this Study

Laboratory experiments were performed at the Queen's University Coastal Engineering and Research Laboratory (QUCERL). The 25m by 30m wave basin was sectioned to provide a 22.75m long by 1.7m wide channel for the tests. The nearshore beach profile including the dune is shown in Figure 1. The channel has a mild slope (approximately 1:200) from the paddle and ends at the steep beach dune face (dune slope approximately 1:1.3).

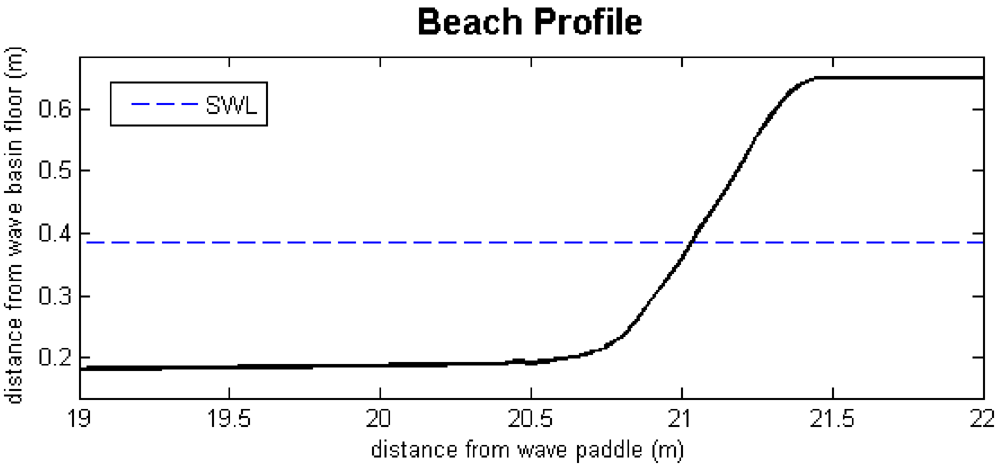

Figure 1: Profile of the fixed laboratory dune (Note the distorted scale)

A new method (Ebrahimi and da Silva, 2013) was adopted to fix the bed. The bed-fixing method, which involves coating the original mobile bed with a mixture of a larger diameter sand and a small amount of cement, retains the drag coefficient and therefore the flow conditions overtop of the bed. Ebrahimi and da Silva tested the method under a variety of uni-directional flows. In the present study, the method is tested under oscillatory flow conditions. For the series of tests the fixed bed resisted the wave forcing well with some local repairs required. Figure 2 shows the bench scale preliminary testing of the bed roughness which was performed in a 0.13m wide by 2m long flume (uni-directional flows only). For these bench scale tests, flow velocities were approximately 0.15m/s for identical flow depths over both the mobile and fixed beds. Figure 2 also shows the method as it was applied to the full-scale test section in the wave basin.

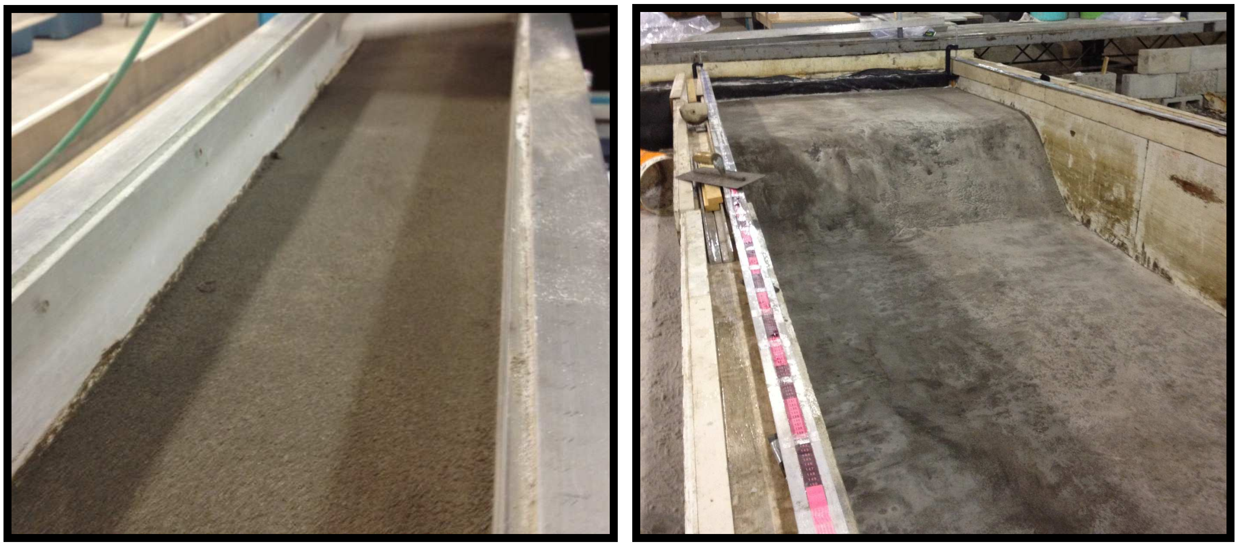

Figure 2: Bench scale tests (left) confirmed the drag coefficients were comparable between mobile (not shown) and fixed beds. The physical model (right) shows the bed fixing method after it has been applied and cured in the nearshore portion of the channel.

Preliminary morphological tests with a mobile bed were performed on various dune slopes to optimize highly erosive initial conditions that closely resembled natural beach dunes. From the preliminary tests, the distance (from the nearshore end of the channel) at which the bed was in equilibrium was determined and therefore not required to be fixed. The fixed region extended from the far back wall for approximately 5m. Silica sand with diameter 0.165mm is used for the mobile bed sections while sand with diameter 0.55mm was used in combination with cement to fix the bed. Regions of the different bed types are shown in Figure 3.

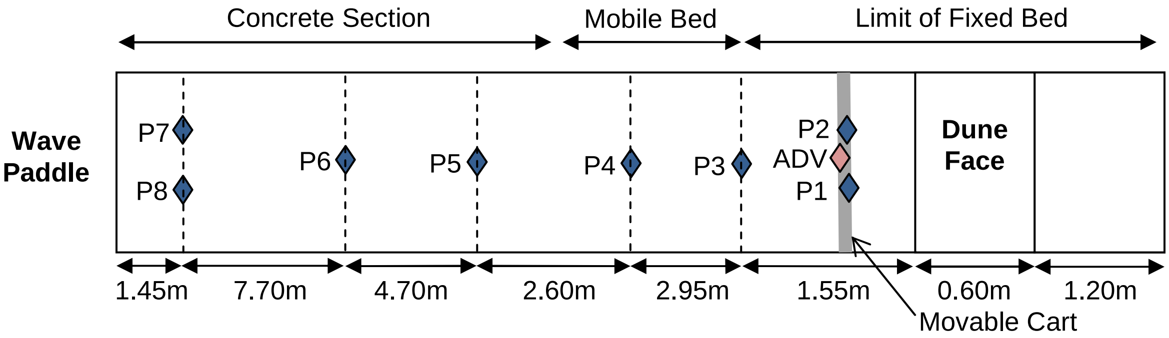

Figure 3: Physical model layout showing locations of all instrumentation. P denotes a water surface elevation probe and the ADV is shown as a red marker. P3-P8 were fixed probes mounted on tripod stands. P1, P2 and the ADV were mounted on a cart that could be moved in the alongshore channel direction to capture velocities and water surface elevations at different locations near the dune. Distances between probes (where they were constant) are shown at the bottom of the figure.

Water levels were recorded using 8 capacitance type wave gauges that sampled at 20Hz and were distributed along the channel (shown in Figure 3). Water velocities were measured using a Nortek Vectrino II that operated at 25 Hz, and recorded 30, 1mm bins over a 3cm range. Table 1 indicates the measurement locations (Locations 1-17 are where measurements were made with the movable probes 1 and 2) and which had corresponding velocity profiles. At each velocity profile measurement site, the sensor was positioned at several heights above the bed to obtain observations over the full depth of the water column (shown in the third column of Table 1). This was determined by the depth of the water at the measurement location as well the proximity of the probe to the bed for the first near bed measurement which varied. The still water level (SWL) was measured at 38.5cm above the basin floor datum.

Table 1: ADV Profile & Water Surface Level Measurement Locations

Profile Number	*Distance from Paddle (m)*	*# of ADV measurements /profile*	*Depth @ Location (m)*	*Hs (m)*
1	20.87	1	0.142	0.123/0.137
2	20.82	3	0.159	0.143/0.159
3	20.77	2	0.171	0.150/0.165
4	20.72	3	0.181	0.135/0.157
5	20.67	5	0.186	0.126/0.154
6	20.62	5	0.190	0.122/0.153
7	20.57	4	0.193	0.119/0.146
8	20.52	4	0.193	0.132/0.147
9	20.47	4	0.194	0.112/0.148
10	20.42	5	0.192	0.112/0.132
11	20.37	5	0.191	0.094/0.118*
12	20.27	6	0.195	0.094/0.118*
13	20.17	6	0.201	0.097/0.105*
14	20.07	6	0.200	0.120/0.118*
15	19.97	6	0.198	0.147/0.134*
16	19.87	6	0.201	0.178/0.164*
17	19.72	5	0.201	0.213/0.199*
P3	19.40	-	0.196	0.167
P4	17.25	-	0.214	0.136
P5	14.00	-	0.233	0.154
P6	9.35	-	0.261	0.174
P8	1.55	-	0.385	0.162

*For these locations, significant wave height was determined at a location offset by 5cm.

Each set of measurements had a duration of 320 seconds, therefore capturing approximately 150 of the individual short-period waves. The wave forcing was developed using the Generalized Experiment Control and Data Acquisition Package (GEDAP) (Miles, 1997). Digital signals from the program are converted to analogue voltage signals that drive the wave paddle. Exactly the same signal was used for each test which was confirmed by comparing significant height measurements at the same probe locations across tests. The ADV was moved before the start of every test to capture the velocity profile in a different location. Starting closest to the dune face, “stations” were identified as locations of measurement, every 5cm at near the dune face and approximately every 10cm farther from the face. The ADV was used to measure the velocities for the full duration (320s) of the test for each profile section. Measurements began at the location closest to the bed and moved up in 2cm intervals until the probe head became too exposed due to surface waves.

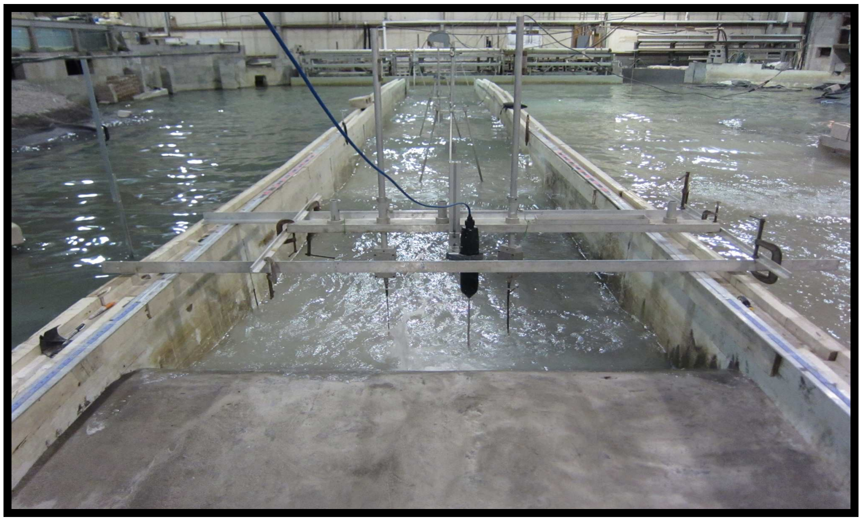

Figure 4: Physical model layout. Viewpoint is from the top of the dune looking offshore towards the wave paddle in the distance.

3 Wave Conditions

Bichromatic waves were chosen because of their relative simplicity for comparison with bottom velocities as well as their consistent nature which allowed averages to be meaningful. These waves were created using GEDAP by combining two wave trains with frequencies of 0.465 (larger amplitude wave) and 0.5 Hz (smaller amplitude wave). The smoothed spectra from 6 selected measurement locations are shown in Figure 5.

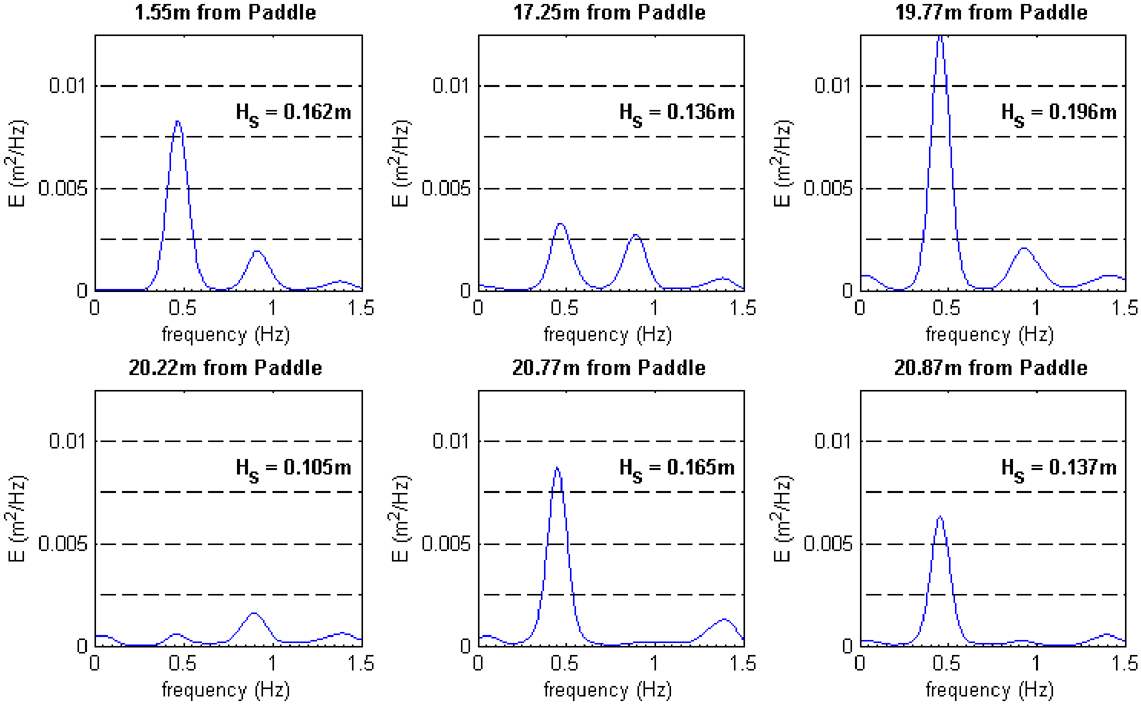

Figure 5: Selected spectral observations from wave probes. The spectrum closest to the wave paddle is shown in the upper left and the spectrum closest to the beach is shown in the lower right.

The spectra in Figure 5 indicate the transformation of the waves as they originate from the paddle (top left) until they reach the dune. The probe closest to the paddle shows some influence of harmonics associated with waves in shallow water. This is due to the limitations of the basin in that large waves generated at the paddle are not deep water waves, but are intermediate water waves. In these experiments the wavelength, L, is approximately 4 metres and the peak period, T_P, is 2.2 seconds. Waves at the paddle have a depth over length, d/L, value of approximately 0.1 which is less than the minimum of 0.5 for deep water waves (Kamphuis, 2010).

Figure 5 also shows an interesting phenomenon observed in the laboratory. There was not only one distinct region of breaking observed but instead three separate regions that showed evidence of breaking. This is best described by the increasing and decreasing pattern in wave height along channel. Wave heights initially decreased from the paddle towards the dune but quickly increased to the highest wave overall heights observed at 19.77m from the paddle. These waves were again quickly dissipated only to shoal again a metre away, at 20.77m from the paddle, where they broke for a third time at the dune face. Large reflections were observed during laboratory experiments from the steep dune as well which could be a possible explanation for the wave height profile.

4 Near Bed Velocity Measurements

Figure 6 shows a sample of cross shore velocities from a near bottom measurement. The bed location was determined for all near bed measurements using the bottom detection feature of the ADV and confirming with backscatter and correlation values.

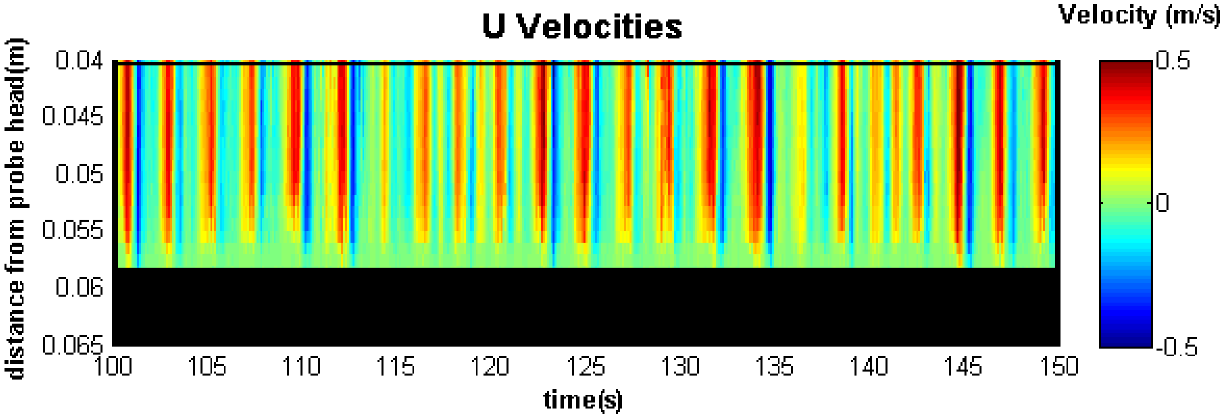

Figure 6: Example of velocity measurements taken near the bed for a 50s time period. This measurement was taken at 20.17m from the paddle (0.87m from the dune crest). The black region indicates the location of the fixed bed.

Figure 6 shows the oscillatory flow due to the bichromatic waves. Locations of stronger positive/negative oscillations correlate with the higher waves in the groups while the regions of low velocities correspond with regions between wave groups. Also clearly visible is the region near the bed where the velocities rapidly approach zero. The velocity profile at this location is close to uniform, except where it decays to zero in the wave bottom boundary layer which varied in height up to 5 mm in this experiment.

Figure 7 shows a selection of along channel RMS velocity profiles. Raw data from the ADV was filtered to remove any points with a correlation less than 50%. Figure 7 d) is the closest to the dune face and therefore the shallowest location. Average RMS velocities through the water column at this location were around 0.23m/s. These measurements were collected in an area of heavy wave breaking, and it is likely that the top of the second profile here was affected by bubble injection. This is likely also the case for the other three profiles whose top measurement locations were skewed due to probe exposure in air (measurements above the red line in Figure were removed). Observations during laboratory tests showed that the ADV head was often exposed in the wave troughs which led to incorrect values for profiles above the red line in Figure .

As the distance from the dune increases, a maximum RMS velocity region occurs between 20.62m and 20.37m. Average RMS velocities in this region are around 0.3m/s. Outside of this nearshore zone, the velocities decrease and the velocity profiles become more defined as these less turbulent regions of the channel are encountered as shown in Figure 7 a).

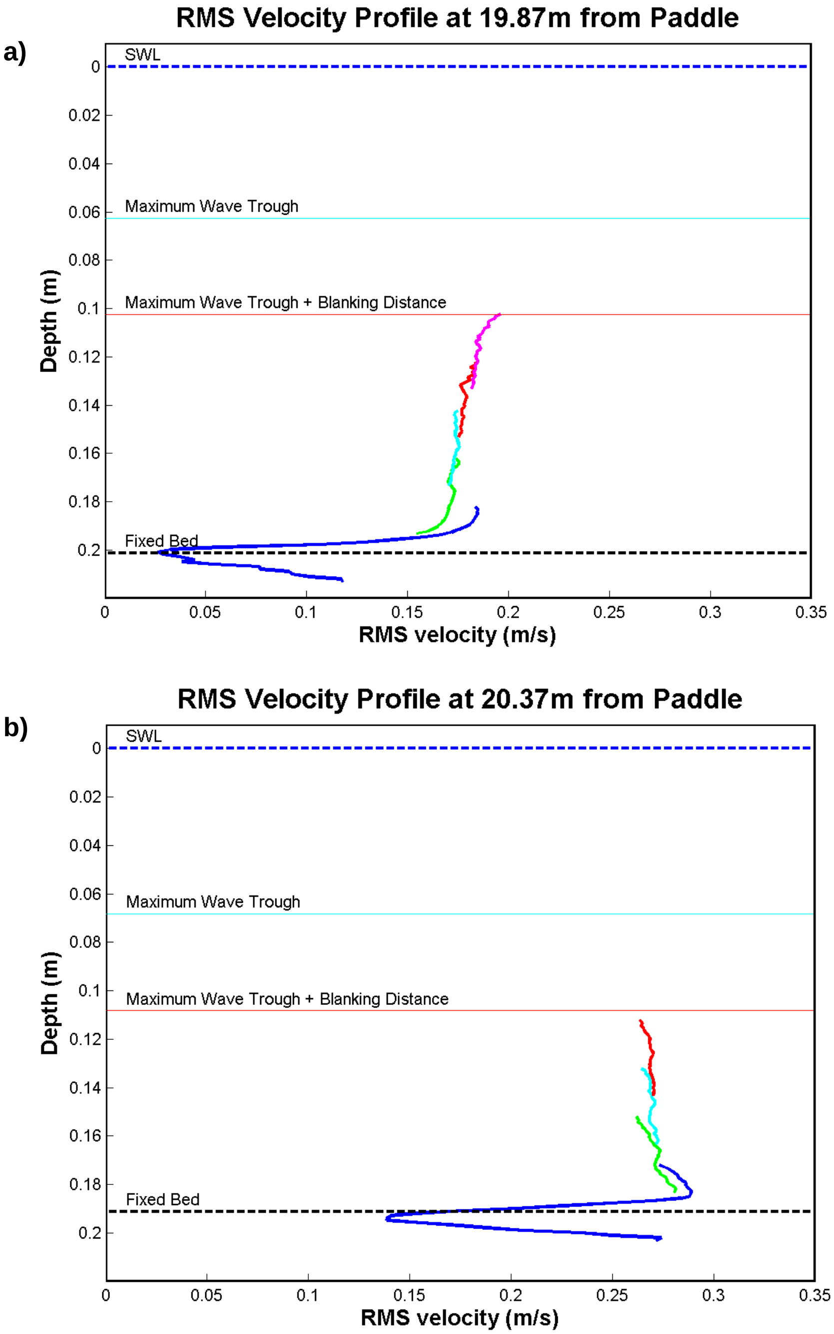

Figure 7: Selected plots of velocity profiles using filtered ADV data. Maximum Wave Trough is the lowest water level recorded from corresponding wave probes and Maximum Wave Trough + Blanking Distance takes into account the blanking distance of the ADV from the lowest water level.

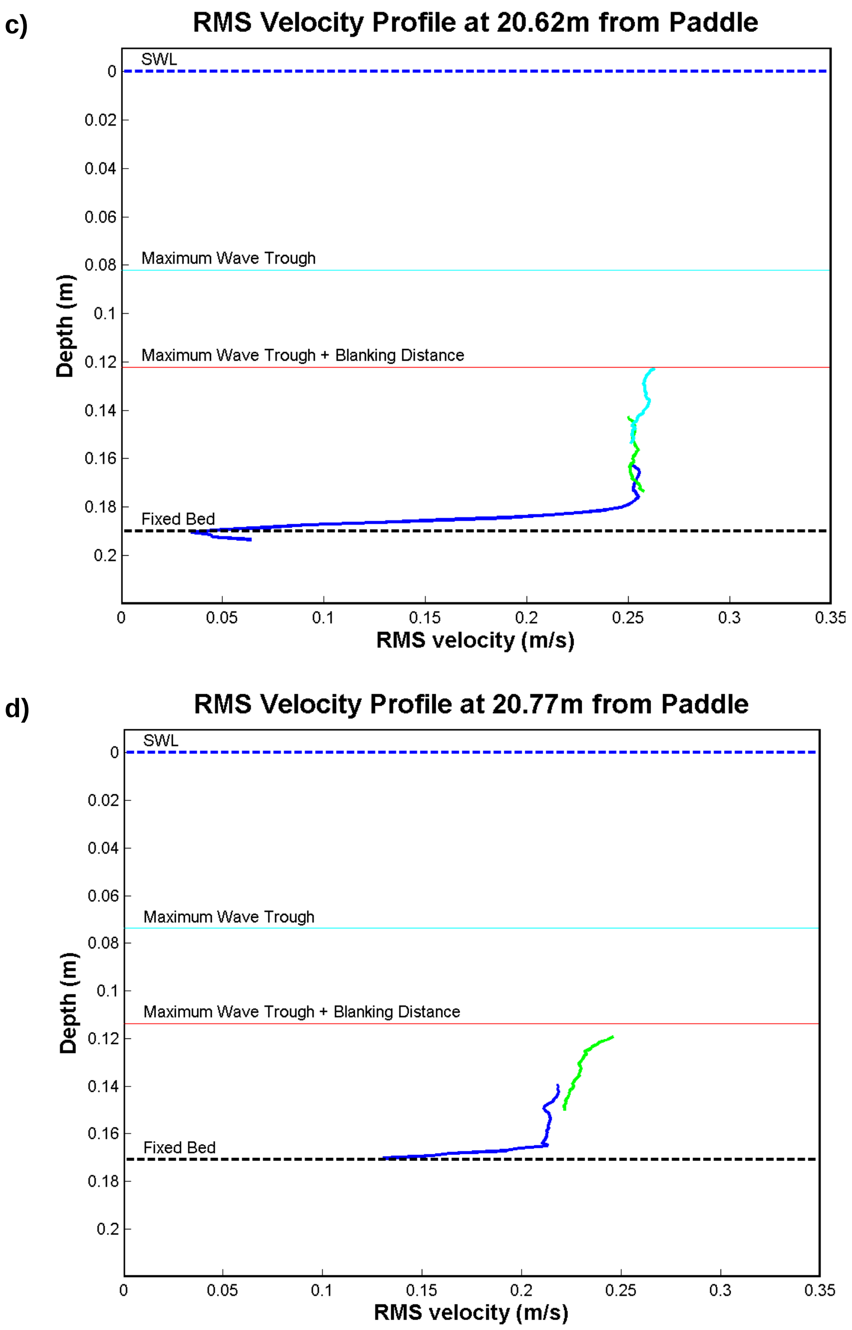

Figure 7: (continued) Selected plots of velocity profiles using filtered ADV data. Maximum Wave Trough is the lowest water level recorded from corresponding wave probes and Maximum Wave Trough + Blanking Distance takes into account the blanking distance of the ADV from the lowest water level.

5 Numerical Modelling: Application of XBeach

Preliminary XBeach runs were performed, and the wave conditions in the physical and numerical models are compared in this study. XBeach was run using a 459x18 grid which covered from the paddle to end point of the 22.75 meters channel as well as the full 1.7m width of the channel. Spacing in the alongshore direction was 5cm and in the cross shore direction was 10cm. Morphology was switched off to represent the fixed nature of the bed and to allow the mean wave conditions over the 320s run duration to be obtained and compared to lab results. The wave input was bichromatic and required both the short wave peak period and long wave peak period which were determined from the laboratory wave spectra using probe closest to the paddle (top left in Figure 5).

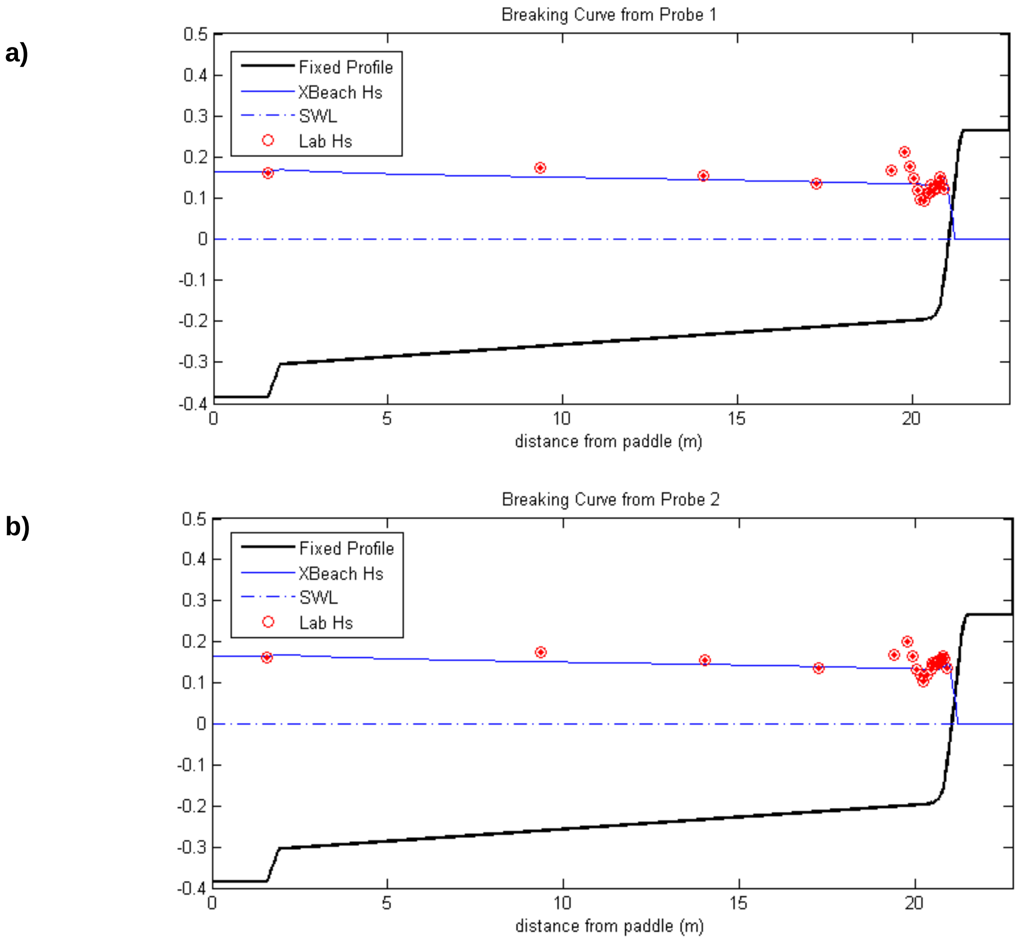

Figure 8: XBeach comparison with lab measurements: a) H_S observations from Probe 1 in the nearshore zone b) H_S observations from Probe 2. (Note the exaggerated scaling)

Figure 8 shows the results averaged over the 320 second XBeach simulation. The laboratory results (red circles) in the longitudinal view show the three regions of breaking discussed in the Section 3. These three regions are not well represented by XBeach which has a small percent of breaking occur over the length of the channel (more than observed in the lab) and none of the large shoaling peak a metre from the dune face (approximately 19m from the paddle). The final region of breaking at the dune is weaker in XBeach simulations for both of the probes recording at the dune. The wave height profile was adjusted by changing the gamma value (breaking parameter) to 0.78 (closer to the value discussed by Battjes & Janssen (1978)) from the default value of 0.55 (Roelvink, 1993 for non-stationary waves) to better represent the bichromatic wave conditions.

XBeach does not accurately represent the breaking wave conditions observed in the steep beach experiment. One explanation for this is the input wave boundary condition. Bichromatic conditions in the laboratory were made with two very close frequency short period waves, while XBeach bichromatic input conditions dictate that only the peak short wave frequency should be entered along with its corresponding wave group period as the long wave period. In future simulations the observed wave time series will be used to force the model and a direct comparison will be able to be made.

6 Conclusions and Future Work

High resolution velocity measurements under bichromatic wave conditions were performed together with corresponding water surface elevation measurements. ADV measurements in regions near the water surface have lower correlation values and will need to be either removed or statistically interpolated before future use. Corresponding water surface elevation measurements were also made, with significant frequency in what was shown to be the breaking region. XBeach runs using the bichromatic waves input method did not yield good agreement, although bottom velocities have not yet been compared at this stage of the project. Ultimately the bottom velocities and shear stresses between XBeach runs and the physical model tests will be compared; however, further work is required to determine the reason XBeach is not correctly predicting the wave height profile in the breaking region. Finally, subsequent tests at the equilibrium beach profile after morphological evolution and at higher water levels will allow velocity profile comparisons for different experimental conditions.

Acknowledgements

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