# NUMERICAL MODELLING OF SWASH ZONE HYDRODYNAMICS

Jack A. Puleo[1] K. Todd Holland[2], Don N. Slinn[3], Ernie Smith[4] and Bret M. Webb[5]

**Abstract:** Laboratory measurements of surf and swash zone hydrodynamics were recorded in the US Army Corps of Engineer's Large-scale Sediment Transport Facility and compared to 2 numerical models to investigate the model's ability to predict water surface elevation and wave orbital and swash velocities. One numerical model relies on the depth averaged non-linear shallow water equations (1D), while the second is based on the full Navier-Stokes equations and uses a volume of fluid approach in the numerical solution (2D). Both models were able to adequately predict the sea surface elevation across the inner surf zone. In general, there was strong similarity between both models and observed velocities with some potential over prediction of observations during bore passage. Similarity between the 2 models and only small differences between vertically separated near bed ($z$ = 1, 3 cm) velocity time series suggests that the flow in the swash zone is nearly depth uniform for most of the swash cycle implying a thin boundary layer. The 2D model may improve on the 1D model by allowing for predictions of this boundary layer structure in addition to a more accurate representation of wave breaking and shear stress calculations based on near bed velocity gradients.

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## INTRODUCTION

The swash zone is the area of the nearshore that is intermittently covered and uncovered by wave run-up. Since swash hydrodynamics control the evolution of beach morphology, understanding these motions is of paramount importance. Typical studies of swash zone hydrodynamics involve the deployment of several instruments (current meters, e.g. Puleo *et al*., 2000; Doppler devices, e.g. Petti and Longo, 2001; among other methods) to measure the swash zone fluid velocity. While the Doppler devices have the ability to readily distinguish vertical flow structure, instrument deployment is necessarily sparse due to cost and logistics, and intermittent exposure and bubbles may cause difficulties in the swash zone. Recently a video-based remote sensing technique has also been developed that is capable of quantifying surface swash velocities over a fairly large spatial domain, but yields no information regarding subsurface flows (Holland *et al*., 2001).

Another possibility for understanding swash hydrodynamics is through numerical simulations. A one dimensional (1D) numerical model, RBREAK (Wurjanto and Kobayashi, 1991), based on the viscid non-linear depth-averaged shallow water equations accurately models observations (van der Meer and Breteler, 1990; Raubenheimer *et al*., 1995). But, the depth-averaged nature limits the information (no quantification of flow characteristics such as shear stresses, vorticity etc.) gleaned from the model. However, Slinn *et al*. (2000), have utilized an existing 2D model, RIPPLE (Kothe *et al*., 1991), for simulating swash zone hydrodynamics that does allow for quantification of these swash zone flow characteristics. The purpose of this paper is investigate the predictive capabilities of an extended version of the 1D model, RBREAK2 and the 2D model, RIPPLE, by comparison to laboratory measurements.

### Large-scale Sediment Transport Facility

In June 2001, laboratory studies were carried out in the Large-scale Sediment Transport Facility (LSTF) at the Coastal Hydraulics Laboratory of the Army Corps of Engineers in Vicksburg, MS (Hamilton and Ebersole, 2001). The LSTF is 30 m cross-shore by 50 m alongshore by 1.4 m deep wave basin with a nominal offshore slope of roughly 1:30 with a steeper foreshore (Figure 1). Waves are forced with 4 unidirectional spectral wave generators. A moveable instrumentation bridge spans the cross-shore expanse of the basin and is outfitted with 12 wave gages and acoustic Doppler velocimeter (ADV's) pairs separated by approximately every 1.5 m. Four ADV sensors were also deployed at 3 locations in the swash zone. At the outer swash location, 2 ADV's were stacked vertically, separated by roughly 2 centimeters.

Figure 2 shows a cross-shore profile of the inner surf and swash zones of the LSTF beach. The actual beach extends out to a cross-shore location of about $x$ = 20 m, but only the region that will be used as the model domain is shown here. The vertical lines show the locations of the wave gages and ADV's that will be used in the model to data comparisons.

Figure 1. LSTF showing waves, the instrumentation bridge, wave gages and ADV's.

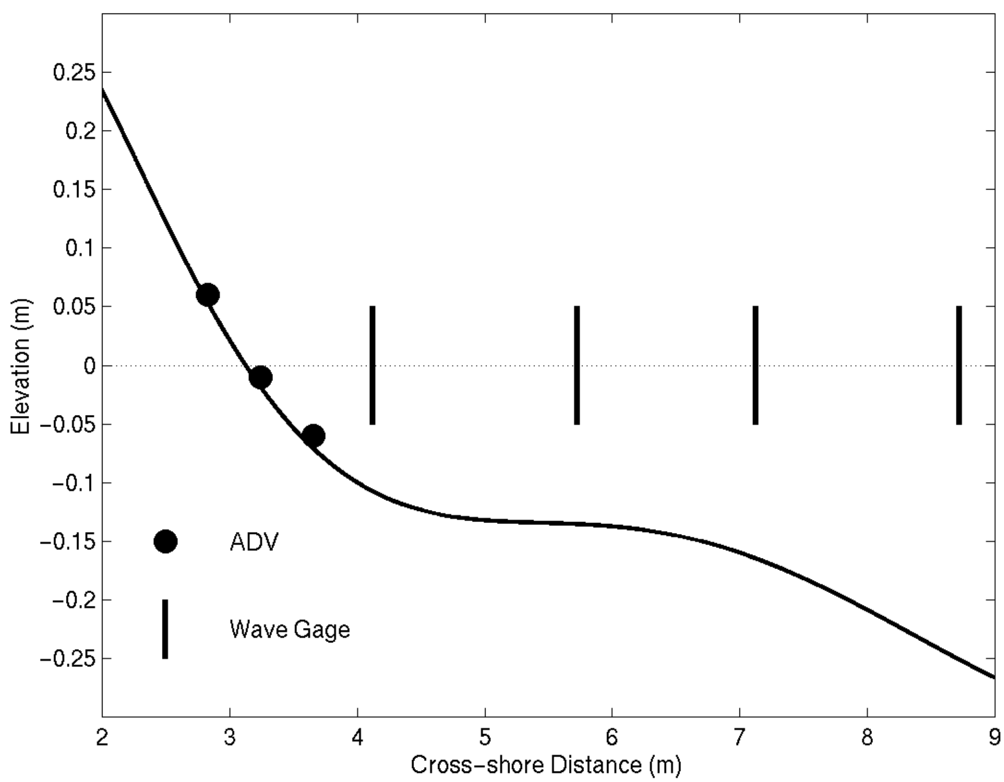


Figure 2. LSTF inner surf profile and model domain showing location of *in situ* instrumentation.

## Numerical Models

RBREAK2

The 1D model, RBREAK2 (Kobayashi and Poff, 1994) is based on the depth averaged non-linear shallow water equations (NLSWE)

$$\begin{aligned} &\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(hu)=0 \\ &\frac{\partial}{\partial t}(hu)+\frac{\partial}{\partial x}\left(hu^2\right)=-gh\frac{\partial \eta}{\partial x}-\frac{1}{2}f|u|u \end{aligned} \tag{1}$$

where $h$ is the water depth, $u$ is the depth averaged cross-shore velocity, $g$ is gravitational acceleration, $\eta$ is the sea surface, $f$ is an empirical friction factor, $x$ is the cross-shore distance and $t$ is time. The first equation in (1) represents conservation of mass and the second conservation of momentum. The last term in the second equation is the bottom shear stress parameterized through a quadratic drag law. In this model broken waves are modeled as shocks (bores) and hence the sea surface cannot be multi-valued at any given cross-shore location. In other words, plunging breakers and wave faces curling over prior to breaking cannot be visualized with this model.

This model and its predecessor (RBREAK) have been compared to field data (Raubenheimer *et al*., this issue) and laboratory data (Kobayashi and Poff, 1994) and showed good agreement when compared to measured sea surface elevations, but velocity comparisons showed more discrepancy.

RIPPLE

The RIPPLE model was developed by researchers at Los Alamos and NASA laboratories for incompressible flows with free surfaces (Kothe *et al*., 1991). It is based on the 2D Navier-Stokes equations

$$\begin{aligned} &\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \\ &\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\frac{\partial \tau}{\partial x}+g_x+\frac{1}{\rho}F_{bx} \\ &\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{1}{\rho}\frac{\partial \tau}{\partial z}+g_z+\frac{1}{\rho}F_{bz} \end{aligned} \tag{2}$$

where $u$ and $w$ are the velocity components, $p$ is the pressure, $\tau$, is the shear stress, $\rho$ is the fluid density, $F_b$ is a body force used to force the model, and subscripts $x$,$z$ denote direction. In using the full Navier-Stokes equations (unlike NLSWE), the pressure is not required to be hydrostatic, the vertical velocity remains in the equations, the model is not restricted to shallow water and the horizontal velocity is not depth averaged.

The model domain is discretized into individual control volumes, that may be empty, full or partially filled with water. This volume of fluid (VOF) approach enables the capture of breaking waves and other swash hydrodynamics by calculating the appropriate force balances in each control volume and the flux of water across each of the control volume surfaces. Presently, model domains are typically several meters in the cross-shore with very small control volumes (3 millimeters in the vertical and 5 millimeters in the horizontal) and time steps of generally 1/100 of a second such that the detailed structure of the boundary layer, shear stresses and breaking processes can be calculated.

Monochromatic Case

An example of both models can be seen in Figure 3. Here, both models were forced with monochromatic waves with a period of 0.8 s, and wave amplitude of 2 cm. The planar beach is oriented with a slope of 20 degrees. The upper panel is from RBREAK2 while the lower is a nearly corresponding time from the RIPPLE simulation. The vectors in the upper panel represent the depth-averaged velocity and are placed a constant distance above the bed for visual convenience (only every 20th vector is shown).

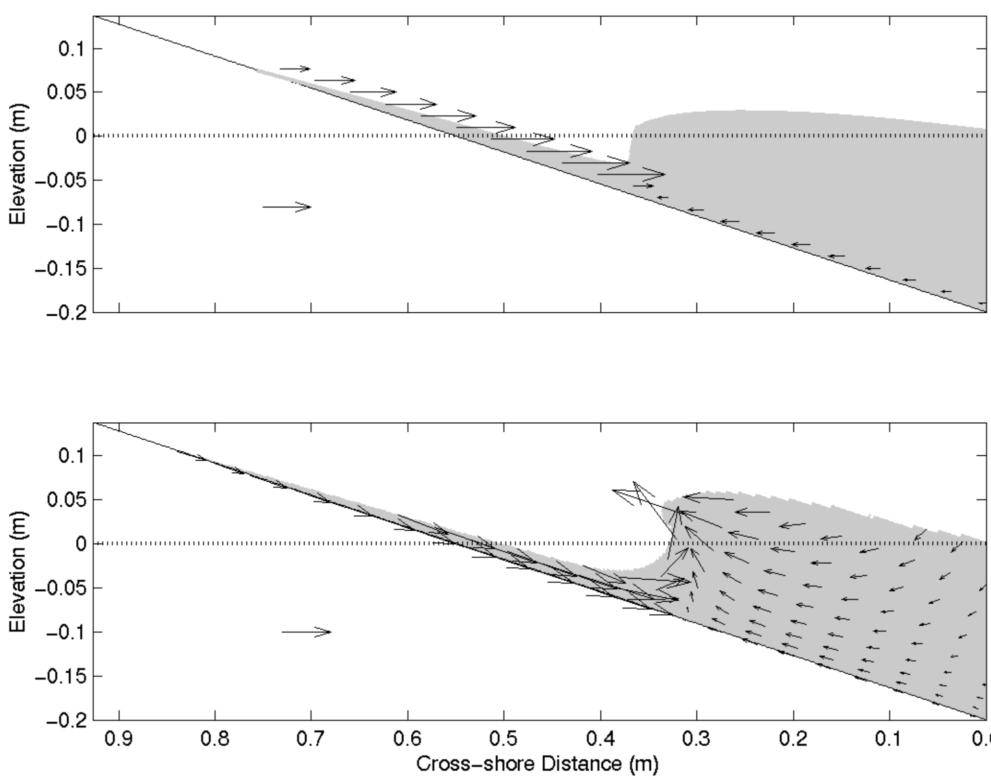


Figure 3. Flat beach (20°) simulations for RBREAK2 (upper) and RIPPLE (lower). Vectors are depth-averaged (upper) and depth dependent (lower) fluid velocities. A 50 cm $s^{-1}$ scale vector is shown in the lower left. Gray shading represents fluid in the model domain.

The vectors in the lower panel correspond to the depth-dependent velocity (only every 10th vector is shown). In both cases, a 50 cm $s^{-1}$ scale vector is shown in the lower left. The light gray shading represents the fluid in each domain.

The fluid portions of the model have the same general appearance. Both have an elongated thin swash tongue and predict wave breaking at about the same location. The volume of water above the still water line varies between the 2 with the RIPPLE model showing more fluid concentrated towards the breaking region. One striking difference is the overturning nature of the wave in the RIPPLE simulation compared to the vertical face in the RBREAK2 model. As mentioned earlier, RBREAK2 models breaking waves as shocks and cannot reproduce this overturning behavior. The velocity magnitudes are very similar but the depth-dependent nature of the velocities from the RIPPLE simulation yield a more complete picture of the velocity field and show the velocity convergence near the breakpoint, especially the vertical component of the flow.

**Model/Data Comparison**

Data collected at the LSTF was used to force both numerical models to test their ability to reproduce observations within the surf and swash zones. Wave conditions were monochromatic with a period of 3 s and an rms wave height of 16.5 cm. However, the models were forced at the edge our domain (Figure 2), landward of the wave breakpoint (over a sand bar at roughly $x$ = 12 m), such that the forcing wave height was smaller than this. The time step for both models is variable and controlled internally by numerical stability criteria. In general the RBREAK2 model has time steps of roughly 0.05 to 0.1 s while the RIPPLE model has time steps of roughly 0.01 s. Because of the smaller time step and the increase in grid nodes and numerical complexity, a 40 second simulation of LSTF data using the RIPPLE model required approximately 18 hours of computation time on a dedicated processor on a SUN Ultrasparc workstation. The analogous simulation using RBREAK2 took approximately 15 minutes.

Sea Surface

Figure 4 shows the comparisons between the measured surface elevation in the inner surf zone at x = 4.125 m (dotted), and those from RBREAK2 (black) and RIPPLE (gray). In both cases, the models match the data in terms of magnitude of sea surface oscillations. They also tend to capture the correct phase of wave passage by the instrument. At times, however, the RIPPLE model does show a slight lag or lead to the measured data. The RIPPLE sea surface prediction has more high frequency structure than does RBREAK2, that at times mimics high frequency structure seen in the measured data. For instance, near 10:33:33 as the sea surface elevation is decreasing, there is a short duration increase in elevation (likely due to a reflected wave form) that is also captured by the RIPPLE model.

Cross-Shore Velocity

Velocity comparisons at the outer and middle swash locations are shown in Figure 5 (ADV-dotted; RBREAK2-black; RIPPLE-gray). Based on our coordinate system, uprush velocities are negative and backwash velocities are positive. Note that the RBREAK2 velocities do not go to zero because of the depth averaged nature and the fact that the model predicted these locations to be continually wetted. In contrast, the RIPPLE velocities do, at times, go to zero because the vertical location of time series was above the bed (at the elevation of the current meter) and the swash elevation occasionally drops below this level.

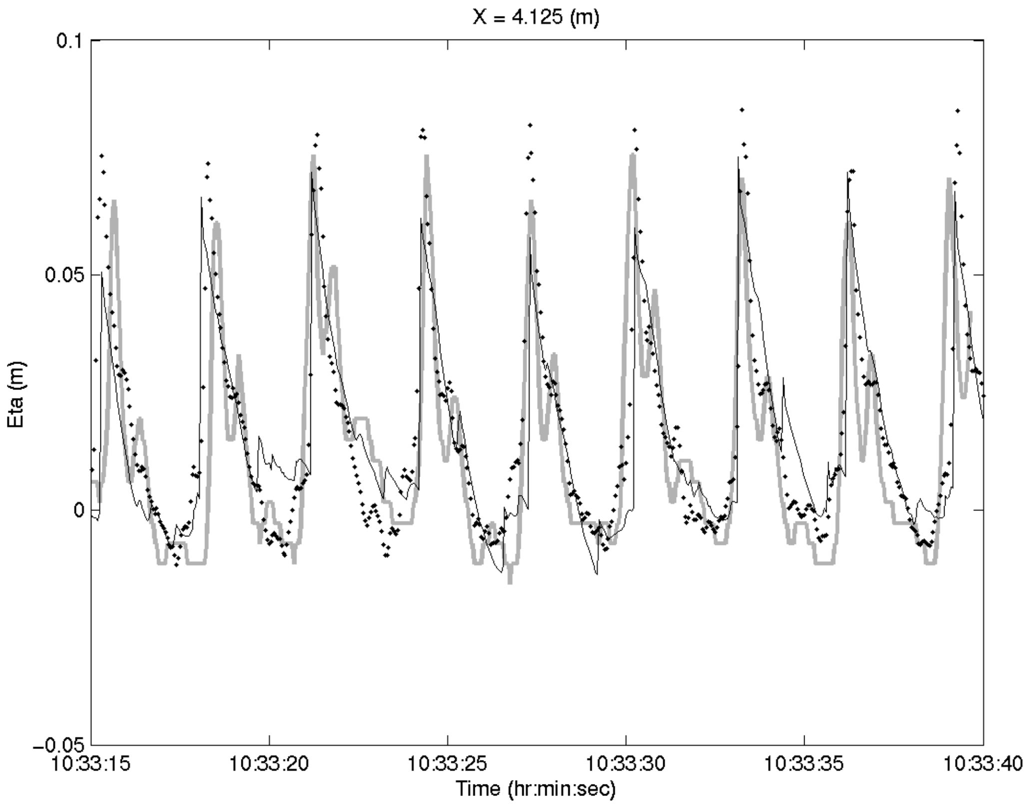


Figure 4. Sea surface comparison between ADV data (dots), RIPPLE (gray), and RBREAK2 (black) in the inner surf zone.

At the outer swash location ($x$ = 3.658 m), the depth averaged RBREAK2 velocity compares well with the measured ADV data (lower of the 2 stacked current meters). The ADV data is quite noisy and has been subjected to some post-processing to remove spurious data when the signal to noise ratio was small. The comparisons between these 2 time series and the small differences between the 2 stacked ADV's (not shown) lends credence to previous assertions that the flow in the swash must be nearly depth uniform for most of its duration (e.g. Petti and Longo, 2001), except very close to the bed in a thin boundary layer. For if this were not the case here, the depth-averaged velocity should have been larger than that measured near the bed. At this location the RIPPLE estimates have roughly the correct magnitude during the backwash when compared to measured data, but exceed RBREAK2 and ADV during the uprush. This implies that RIPPLE is over-predicting the velocity near the bed when the bore passes. Closer to shore at $x$ = 3.239, the ADV data has many gaps. At this region, the instrument is often exposed or influenced by bubbles in the swash such that the signal to noise ratio is small and data is culled. This emphasizes how difficult it is to obtain fluid velocity measurements in the swash zone. Even though the measurements are sparse, they suggest that the RBEAK2 model is doing a better job at predicting the swash velocity during the last part of uprush and initial stages of backwash than is RIPPLE. The magnitudes predicted by RIPPLE and RBREAK2 during backwash are roughly the same with RIPPLE occasionally estimating a larger value. During uprush, both models predict a large spike in velocity as the bore passes, that cannot be verified due to a lack of ADV data. At this location, the RIPPLE model has some error in the phase of swash flow, generally lagging RBREAK2 and ADV data.

Shear Stress

A benefit of the RIPPLE model over the RBREAK2 model is the ability to estimate the shear stress based on the vertical velocity profile rather than through a quadratic drag law. Figure 6A shows a space-time contour of estimated shear stress (also known as a shear stress time stack) for the LSTF data. Negative values are onshore directed shear stress and positive values are offshore-directed shear stress in N $m^{-2}$. The alternating negative/positive values are due to the passage of individual waves and the patterns appear regular because the forcing was monochromatic.

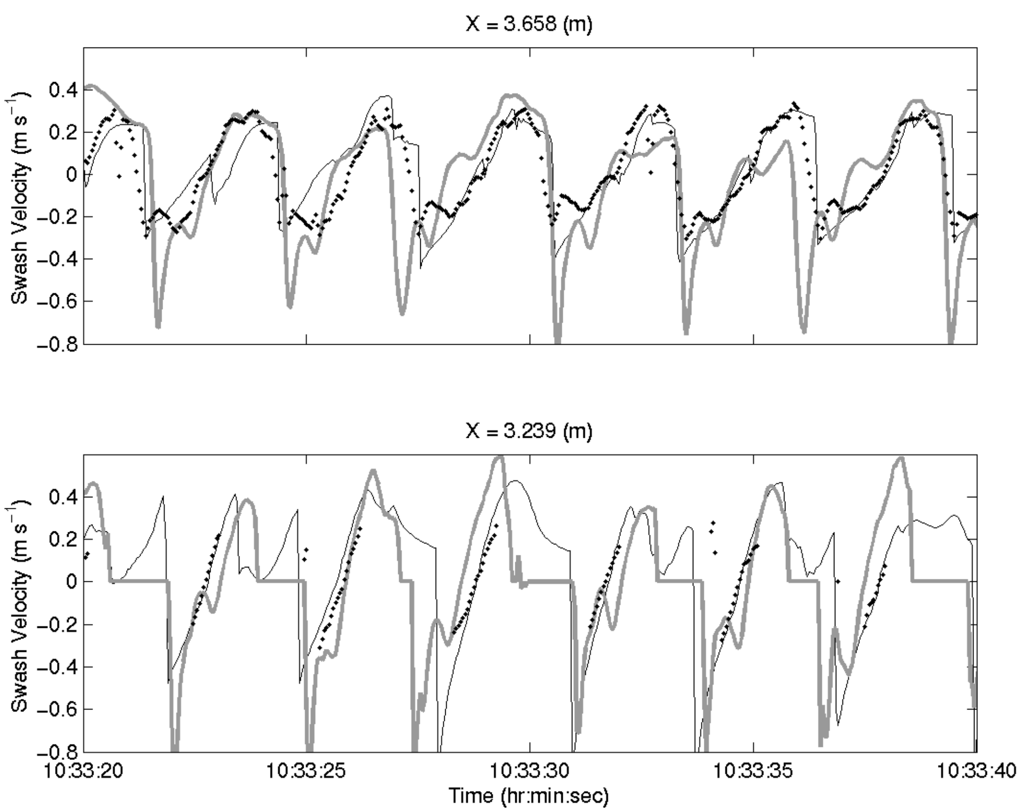


Figure 5. Velocity comparison for ADV (dotted), RBREAK2 (depth averaged; black) and RIPPLE (gray). Upper panel is for outer swash zone and lower panel for middle swash zone. Negative velocities are onshore, positive velocities offshore.

Individual shear stress time series can be extracted at any cross-shore location by taking a horizontal slice across the space-time shear stress matrix. Two time series extracted from the cross-shore location of the outer and middle swash ADV locations (The solid and dashed lines in Figure 6A respectively) are shown in Figure 6B. This type of shear stress information may be used to conceptualize sediment transport. For instance, comparing the 2 curves, we see that during uprush (negative values), the magnitude of the stress is nearly double the magnitude of the stress during backwash. If sediment transport is a function of shear stress, then it might suggest that more sediment transport occurs during the uprush than backwash. Of course this statement oversimplifies sediment transport since it has not considered initiation of motion criteria, duration of uprush vs. backwash flow, sloping bed or other effects, that are known to be important to sediment transport, but may still give insight as to the dominant sediment transport processes. In addition, comparing the 2 curves, the dashed line is greater than the solid line during backwash implying a spatial gradient in stress. If gradients in sediment transport lead to bed change and as before we assume sediment transport is a function of bed stress, then these gradients in bed stress might yield information as to what expected bed level changes might occur. Again, accurately describing the bed level change would require the consideration of the effects as mentioned above. But these calculations, when coupled with a proper sediment transport formulation, can lead to a better understanding of beach morphological change.

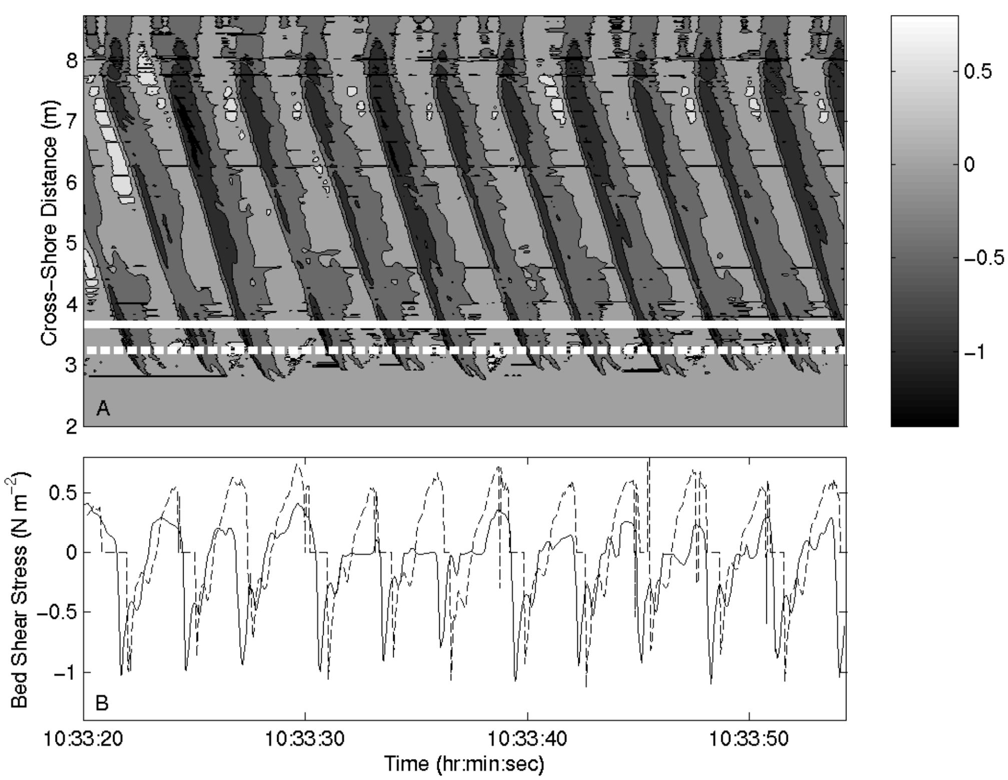


Figure 6. Bed shear stress from RIPPLE. A) Shear stress time stack for nearshore profile. Dark (light) shades are onshore (offshore) directed shear stress in N m$^{-2}$. White lines

show location of outer (solid) and middle (dashed) swash ADV sensors. B) Shear stress time series extracted at location of outer (solid) and middle (dashed) swash ADV sensors.

## SUMMARY AND CONCLUSIONS

Numerical simulations of inner surf and swash zone motions were carried out using both 1D (RBREAK2) and 2D (RIPPLE) models. It was shown that the 2D model more accurately displays wave breaking and yields information regarding depth dependent fluid velocities in both the cross-shore and vertical direction. Comparisons with measurements showed that both models predicted the free surface elevation well, however more discrepancy was observed for swash velocities. The depth averaged velocity from the 1D model in the outer swash zone had the same magnitude as the measured near bed data, but did not closely match the measured velocity time series. The magnitude comparison yielded more evidence that the flow in the swash zone is depth uniform for most of the duration of the swash cycle except in a very thin boundary layer. The velocities from the RIPPLE model had the same magnitude as those from the measured velocity data during backwash, but had a large spike below the shoreward propagating bore that exceeded the measured data. Furthermore, the RIPPLE velocity estimates show small lag/lead relationships as compared to the measured data.

Since the output from the 2 models was similar, one may ask, "What is the benefit to using a higher dimension model with increasing complexity especially when there is about a 70 fold increase in the required computation time?" Obviously it is a cost/benefit problem, but the 2D model is not restricted to shallow water environments and yields information as to the flow structure within the water column as opposed to being depth-averaged. Because of this information, one can now look into boundary layer structure, the time dependent nature of boundary layer formation over variable bathymetry and within the swash zone and ultimately begin to simulate time dependent bed shear stress (obtained from velocity profiles near the bed) across the nearshore profile. These processes *cannot* be extracted from a 1D model. These processes will in turn help to steer our knowledge of the important processes like wave breaking and propagation and potentially lead us to better methods for predicting sediment transport in the nearshore (where modeling capabilities severely lack those of nearshore hydrodynamics). Hence, we feel the benefit to using a model like RIPPLE far outweighs the cost (especially considering that inexpensive processor speed doubles every few years).

The simulations performed here did not utilize the RIPPLE model in its "out of the box" form and considerable work went into making the model appropriate for the surf and swash zones. However, more work needs to be done to tailor the model for nearshore hydrodynamics. Our future efforts will focus on incorporating a 2-equation turbulence closure scheme. The present model utilizes a constant eddy viscosity approach at present and we feel a 2 equation scheme such as the often used k-ε scheme will more accurately model the subgrid turbulence and may help in dissipating some of the high velocity spikes that were observed under the bore in the swash zone. Furthermore, this scheme will enable a larger model domain with larger fluid volumes to be used such that the model can be forced from deep water allowing prediction of wave breaking, propagation, reformation, swash processes and boundary layer structure all from one model. Other work will involve the testing of several methods for forcing the model and the insertion of tracer particles to visualize where and how sediment is transported during the breaking process and in the turbulent swash zone bore.

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Volume of fluid
Navier-Stokes equations
Non-linear shallow water equations
Bed shear stress
Breaking waves
Uprush
Backwash
LSTF
RIPPLE
RBREAK2