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## Applied Ocean Physics and Engineering

Memorandum

TO: ONR

FROM: John Trowbridge

DATE: November 4, 2009

SUBJ: Grant/Contract No. N00014-05-1-0082

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# CROSSTEX – Wave breaking, boundary layer processes, the resulting sediment transport and beach profile evolution

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Award Number: N00014-07-1-0154, N00014-05-1-0082

## LONG-TERM GOALS

To develop and test with laboratory and field data a robust modeling framework that predicts hydrodynamics and the fate of terrestrial and marine sediment in the heterogeneous environment.

## OBJECTIVES

- Identify the role of steep waves and breaking wave turbulence on sediment suspension events and its implication on on/offshore sediment transport rate.
- Develop phase/depth-resolving numerical models for bottom sediment transport and surf zone hydrodynamics. Validate these models using data measured in CROSSTEX and other experiments.
- Develop simplified phase-resolving formulations for concentrated sediment transport, suspended load transport and its near-bed boundary conditions under breaking waves.

## APPROACH

A two-phase flow model (Hsu et al 2004; Amoudry et al. 2008) is extended to model sand transport driven by measured random wave-current forcing during CROSSTEX (Scott et al. 2007). Measured near-bed time series of flow velocities are analyzed to extract (approximately) the time series of wave velocities and turbulence quantities (TKE and dissipation rate). These time series are then used to drive the two-phase flow model and to calculate and resulting sand transport from immobile sand bed to the dilute region of about 5 cm above the immobile bed. Physical experiments also provide measured suspended sand concentration in the intermediate to dilute region (volume concentration ~<15%), which can be used to identify the suspension event and to validate the numerical model. On the other hand, two-phase model results for concentrated sediment dynamics can bridge the missing information at the regime of concentration from about 15% to random-close packing (~63%), which is difficult to measure in the physical experiment.

Because it is non-trivial to separate turbulence from the wave motion in the measured velocity time series, also because it is perhaps unclear at this point what is the major cause (e.g., steep wave or breaking wave turbulence) of the strong sediment suspension event, it is critical to utilize a more powerful data analysis tool than commonly used Fourier analysis. Wavelet analysis is able to identify not only the steep

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oscillation events but also their (temporal) scale (Scott 2005; Scott et al. 2005). Hence, more information can be extracted from the measured time-series when using wavelet analysis in conjunction with Fourier analysis. Wavelet analysis on the CROSSTEX data is investigated by Research Scientist Dr. Nicolas Scott of University of Florida funded by this project.

## WORK COMPLETED

CROSSTEX is a collaborative research project aiming at quantifying various mechanisms of wave- and current-induced sediment transport in the surf zone. The physical experiment of CROSSTEX was completed in Sep 2005 at O. H. Hinsdale Wave Laboratory of Oregon State University (Scott 2006; Scott et al. 2007). The experimental design of CROSSTEX is to mimic the field condition of onshore/offshore sandbar migration events observed during Duck 94 (Gallagher et al. 1998) so that possible mechanisms controlling the onshore/offshore sediment flux can be carefully studied.

Even in a well-controlled laboratory facility, detailed sediment transport in the concentrated regime near the bed cannot be measured with high temporal and spatial resolution. In this study, we utilize a two-phase model, which resolves both the bedload and suspended load, to link the missing information in the concentrated regime of transport. The two-phase model for sand transport has been validated in the past two years with published laboratory U-tube results (Amoudry et al. 2008; Hsu and Yu 2008). This year, we also extend the model with nonlinear boundary layer terms (i.e., approximate $\partial/\partial x \approx c^{-1}\, \partial/\partial t$ in the 2DV two-phase equations with $c$ the wave celerity) to mimic sediment transport under progressive waves. The model is validated with SISTEX99 data (Dohmen-Janssen and Hanes 2004) in order to investigate the effect of nonlinear boundary streaming on wave-induced transport (Trowbridge and Young 1989; Henderson et al. 2004) in comparison with wave skewness/asymmetry (e.g., Hsu and Hanes 2004). It is found that for the grain diameter (0.24 mm) and wave condition used during SISTEX99, nonlinear wave shape (e.g., skewness) is the dominant mechanism for onshore transport; nevertheless, nonlinear boundary layer streaming effect causes additional 36% of the onshore transport. Numerical experiments further suggest that nonlinear streaming effect becomes increasingly important for finer grain and nonlinear boundary layer process can increase onshore transport in the shoaling zone and bar crest regime by about 80~90%, which contributes a non-negligible portion of onshore transport to that purely due to nonlinear wave shape. Research results on this topic are summarized in a manuscript that shall be submitted for publication in the near future.

Starting in FY08, CROSSTEX data is analyzed using wavelet transform and statistical analysis. Morlet wavelet transform has been previously shown to be effective in identifying steep wave in open ocean (Scott et al. 2005). Similar method is applied here to the measured velocity time-series (50 Hz sampling rate). Measured cross-shore (x) velocity component has both wave and turbulence information in the frequency range 1-2 Hz, while the alongshore (y) velocity component has clean turbulence information. This suggests that the wavelet analysis must be applied concurrently to x and y components to obtain a better understanding of steep wave and breaking wave turbulence. When plotting the wavelet transform results for velocities along with measured sediment concentration time series at given location above the bed, we can identify suspension events correlated with different scenarios of steep wave and/or breaking wave turbulence events (see Figure 1). Our goal is to come up with useful statistics on the occurrence frequencies of sand suspension events due these scenarios (see Table 1). This information can be used to interpret model results calculated by the 1DV two-phase model that only captures locally generated events as opposed to nonlocal advective processes. Research results on this topic were presented in 2008 AGU Ocean Science Meeting and 31st International Conference on Coastal Engineering. In addition, a manuscript is also submitted for publication.

## RESULTS

Figure 1a shows a U component velocity time series from the erosive case, a contour plot of its wavelet transform, and the concurrently measured sediment concentration time series. The asterisks identify high acceleration events at small and large frequencies that have accelerations above 0.3 $\mathrm{m/s^2}$ and they are visibly correlated with the local maxima of velocity variation in the velocity signal. The algorithm is able to perform a multi-scale filtration of the data to reveal high acceleration events associated with cohesive wave groups at both large and small scales. Figure 1b shows a V component velocity time series from the erosive case, a contour plot of the wavelet transform, and the sediment concentration time series taken from the same instant. The asterisks identify high turbulent velocity events that have a velocity above $0.03\,\mathrm{m/s}$. Combining results in both Figure 1a and 1b, we can identify a typical scenario that a steep wave causing significant breaking wave turbulence approaching the bed and induces strong sand suspension.

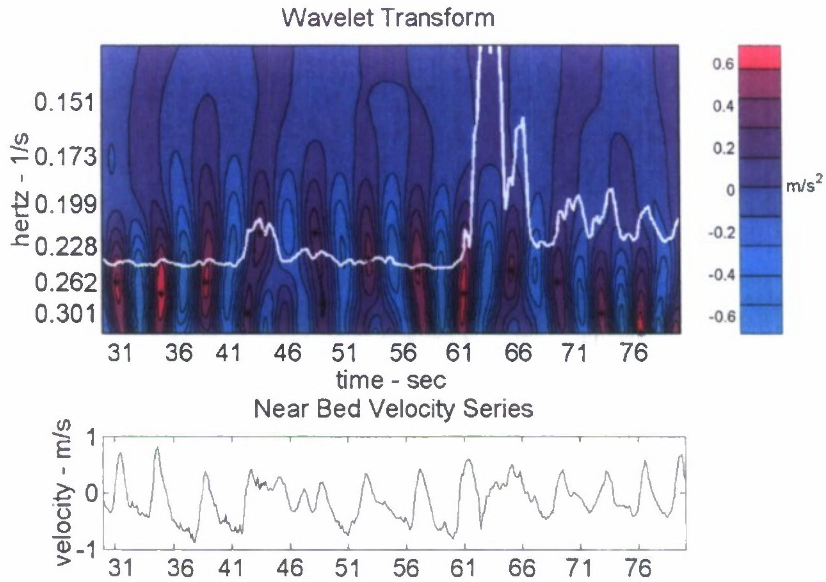
Table 1 shows the steep wave, turbulence, and concentration statistics for the erosive and accretive conditions at 1 cmab obtained using the wave-breaking advective timescale, which is taken to be the ratio of average breaking wave height and RMS wave velocity associated with each case. The top part of Table 1 show the statistics of the scenarios (shown in the 1st column) associated with the passage of steep waves. On the other hand, the bottom part of Table 1 comprises the statistics of the scenarios associated with the occurrence of high sediment concentration events. During the erosive condition, only 31% of the steep wave events have breaking wave turbulent events that approach 1 cmab (see the 3rd row of Table 1). For accretive case, this statistic further decreases to 18%. In addition, for the erosive condition, only 14 % of steep waves are associated with turbulence and high concentration events while this statistic is 5 % for accretive condition. This last statistical category shows that based on local point measurements within the wave boundary layer for both cases, the percentage of steep waves associated with turbulence and high concentration events is a small fraction of the total amount of steep waves. The classic scenario that steep breaking waves cause high turbulence approaching the bed and directly induced sand suspension is also a fraction of the total amount of sediment suspension events. For the erosive condition 30% of high concentration events are associated with steep wave events and turbulent events (see the 7th row). This same statistic for the accretive condition drops to 15%. All three categories discussed here suggest that steep waves are breaking intermittently causing intermittent bottom wave boundary layer sediment suspension. The intermittency of wave breaking and sediment suspension is qualitatively consistent with results reported in the literature (e.g. Cox and Kobayashi 2000). It is also noted that while the accretive case has a larger number (33) of steep waves exceeding acceleration threshold than the erosive case (27.7), the erosive case has a larger percentage of steep waves associated with high concentration and turbulence events. In other words, erosive case appears to have more intense or localized (the sensors are collocated at one cross-shore location x=63.7 m) breaking wave turbulence and more frequent suspension events than those of accretive case despite the fact that the RMS wave velocity is greater for the accretive case. Further analyses suggest that these statistics are sensitive to the choice of time window size for accretive condition and measurement location above the bed (for both erosive and accretive condition). It is concluded in this study that when large time window size is utilized and data measured at higher locations are studied, more nonlocal processes, such as turbulence and sediment advected from the upstream, can change the results. Therefore, statistical results shown in Table 1 are thought to better represent locally-generated processes, which is consistent with the 1DV two-phase modeling results. It is also note here that according to Table 1, only about 1/3 of the suspension events are locally-generated and significant portion of the suspension events are possibly due to nonlocal advective processes.

Numerical modeling results for total load transport display agreement with observed laboratory measurements of bathymetry evolution for the erosive condition. The model incorporating breaking wave turbulence is able to reproduce suspension events caused by local steep wave and breaking wave turbulence that give sand concentration profiles in agreement with measured data. Model results suggest mean undertow current causes offshore transport which work against the onshore directed wave-induced transport to finally give a net offshore sediment flux. Model results also suggest under a steep wave breaking event, the breaking wave turbulence can enhance net transport by 50~150%. However, the direction of the enhanced transport is determined by the relative timing between the breaking wave turbulence event and wave phase. Correlation and statistical analysis of measured data suggest that about 2/3 of the high breaking wave turbulence events are negatively correlated with the wave velocity (see the last row of Table 1). Hence, our data analysis support breaking wave turbulence tends to enhance offshore sand transport. Model results of net transport rate disagree with the measured (small) beach profile change for accretive condition. The onshore sediment transport in present 1DV numerical model is mainly caused by nonlinear wave shape, such as wave velocity skewness and asymmetry. It is possible that other onshore sediment transport mechanism, such as non-local advection and nonlinear boundary layer streaming, which are not captured by the present model, are likely mechanisms for the onshore sediment transport observed in this wave flume experiment during accretive condition.

## IMPACT/APPLICATIONS

The present research efforts focus on new data analysis techniques for surf zone sediment transport developing/validating detailed numerical models for sediment transport and wave hydrodynamics. We have focused on refining the numerical schemes in the 1DV two-phase model and 2DV RANS wave model so that they will be more robust and user-friendly in the future. Recent effort using wavelet analysis to study sediment transport under breaking wave is also new to the coastal sediment transport community.

(a)




(b)

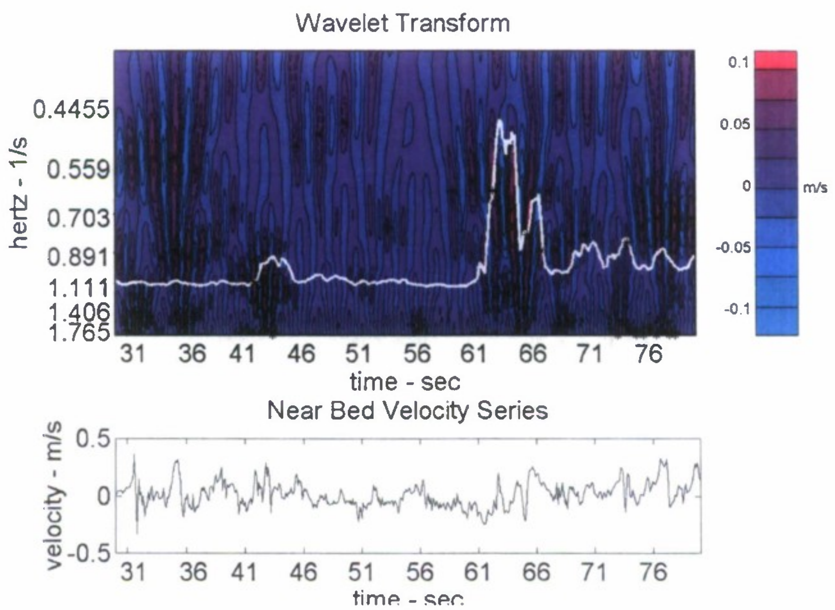



Figure 1: Wavelet transform for U (represents wave) and V (represent turbulent fluctuation) velocity components at 1 cmab during erosive condition. (a) Wavelet transform for U component with asterisks delineate high acceleration events. Acceleration threshold of 0.3 $m/s^2$ is designated by dotted line. Contours drawn at every 0.12 interval. (b) Wavelet transform for V component with Asterisks delineate high velocity events. Velocity threshold of 0.03 $m/s$ is designated by dotted line. Contours drawn at every 0.017 interval. Thick-solid curve in the wavelet transform plots are corresponding measured concentration time series at 1cmab.

| Erosive Case<br><br>Accretive Case | Run1 | Run2 | Run3 | Average |
|---|---|---|---|---|
| **Total # of Steep Wave Events** | **28.6**<br>**33.75** | **27.2** | **27.4**<br>**32.2** | **27.7** ± 1.4<br>**33** ± 3.9 |
| % of steep waves with turbulent events | 8.6, 30 %<br>6.25,19% | 7.4, 27% | 10.2, 37%<br>5.4, 17 % | 31 % ± 7.0%<br>18% ± 6.2% |
| % of steep waves & high conc. events | 6.8, 24%<br>4.25,13% | 7, 26% | 7, 26%<br>3.4, 11 % | 25 % ± 8.7%<br>12% ± 5.1% |
| % of steep waves with turbulent & high conc. events | 3.8, 13%<br>2.5, 7% | 3.4, 13% | 4, 15%<br>1.2, 3.7% | 14 % ± 4.6%<br>5 % ± 3.6% |
| **Total # of High Conc. Events** | **16.2**<br>**12.75** | **19** | **18.2**<br>**8.6** | **17.8** ± 6.8<br>**10** ± 4.0 |
| % of high conc. events with steep & turbulent events | 5.2, 32%<br>2.75,22% | 4.8, 25% | 6.0, 33%<br>0.6, 7% | 30% ± 10%<br>15% ± 6.2% |
| % of high conc. events near nothing | 3.2, 20%<br>4.75, 37% | 4.8, 25% | 4.2, 23 %<br>4.2, 49% | 22 % ± 6.9%<br>43% ± 15% |
| % of high conc. events near steep waves only | 4.8, 30 %<br>3.5, 27% | 4.6, 24 % | 4.6, 25%<br>1.6, 19% | 26 % ± 9.1%<br>23 % ± 12% |
| % of high conc. events near turbulent events only | 3, 19%<br>1.75, 13% | 4.8, 26 % | 8.8, 19%<br>2.2, 26% | 21 % ± 13.6%<br>19% ± 9.1% |
| **% of turbulent events in negative phase** | **68 %**<br>**65%** | **74%** | **75%**<br>**61%** | **72%** ± 7.5%<br>**63%** ± 6.1% |

Table 1: Statistics of each scenario for steep wave, high turbulence, and high sand concentration events for both erosive (upper) and accretive (lower) conditions. Scenario descriptions are shown at the 1st column followed by the resulting statistics for each run (2nd to 4th columns) and averages over all runs (5th column). Statistics are for time series measured 1 cmab. Wave-breaking advective timescale are used for detection window size (1.8 sec for erosive case and 1.2 sec for accretive case).

## REFERENCES


Amoudry, L., Hsu, T-J, and Liu, P. L.-F., 2008. Two-phase model for sand transport in sheet flow regime, *J. Geophys. Res*., 113, C03011, doi:10.1029/2007JC004179.

Cox, D.T. and Kobayashi, N., 2000, Identification of Intense, Intermittent Coherent Motions under Shoaling and Breaking Waves, *J. Geophys. Res.*, 105, C6, 14223-14236.

Dohmen-Janssen C.M., & D.M. Hanes, 2005, Sheet flow and suspended sediment due to wave groups in a large wave flume. *Cont. Shelf Res, 25*, 333–347.

Gallagher E.L., S. Elgar, & R.T. Guza, 1998, Observations of sand bar evolution on a natural beach. *J. Geophys. Res., 103,* 3203–3215.

Henderson S.M., J.S. Allen, & P.A. Newberger, 2004, Nearshore sandbar migration by an eddy-diffusive boundary layer model. *J. Geophys. Res., 109*, C06024, doi:10.1029/2003JC002137.

Hsu, T.-J., J.T. Jenkins, and P.L.-F. Liu, 2004. Two-phase sediment transport: sheet flow of massive particles. *Proc. Roy. Soc. Lond. (A)*, 460, doi:10.1098/rspa.2003.1273.

Hsu, T-J and Hanes, D.M., (2004) The effects of wave shape on sheet flow sediment transport, *J. Geophys. Res., 109(C5), C05025,* doi:10.1029/2003JC002075.

Lin, P., and Liu, P. L.-F. 1998. A numerical study of breaking waves in the surf zone, *J. Fluids Mech., 359,* 239–264,

Scott, N., Hara, T., Walsh, E. J., and Hwang P. A., 2005, Observations of steep wave statistics in open ocean waters, J. Atmos. Oceanic Technol., 22, 258-271.

Scott, N. V., 2005. Estimating Steep Wave Statistics Using a Wave Gauge Array, *Applied Ocean Research.* 27, 1: 23-38.

Scott, C. P., 2006. CROSSTEX Wave Breaking Turbulence Study Instrument Deployment and Data Collection Report, O.H. Hinsdale Wave Research Laboratory, Oregon State University, March 2006.

Scott, C. P., Cox, D. T., Shin, S., Maddux, T. B., 2006. The role of wave breaking turbulence in sediment suspension observed during CROSSTEX, *Proceedings 30th International Conference on Coastal Engineering*, 2537-2546.

Trowbridge, J., Young, D., 1989. Sand transport by unbroken waves under sheet flow conditions. *J. Geophys. Res.,* 94, 10971–10991.

**PUBLICATIONS**


- Long, W., Hsu, T-J, and Kirby, J. T. 2005. Modeling cross-shore sediment transport processes with a time domain Boussinesq model, *Proceedings 29th International Conference on Coastal Engineering*, Vol. 2, 1874-1886. [PUBLISHED]
- Amoudry, L., Hsu, T-J, and Liu, P. L.-F. 2005. Schmidt number and near-bed boundary condition effects on a two-phase dilute sediment transport model, *J. Geophys. Res.*, 110(C9), C09003. [PUBLISHED, REFERRED]
- Hsu, T.-J., Raubenheimer, B. 2005. A numerical and field study on inner-surf and swash sediment transport, *Cont. Shelf Res., 26, 589-598.* [PUBLISHED, REFERRED]
- Hsu, T-J, Elgar, S. and Guza, R. T., Wave-induced sediment transport and onshore sandbar migration, *Coastal Engineering, 53, 817-824.* [PUBLISHED, REFERRED]
- Long, W., Kirby, J. T., Hsu, T.-J., 2006.Cross shore sandbar migration predicted by a time domain Boussinesq model incorporating undertow, *Proceedings 30th International Conference on Coastal Engineering*, Vol. 3, p2655-2667, World Scientific. [PUBLISHED]
- Amoudry, L., Hsu, T-J, and Liu, P. L.-F., 2007. Two-phase model for sand transport in sheet flow regime, *J. Geophys. Res.*, 113, C03011, doi:10.1029/2007JC004179. [PUBLISHED, REFERRED]
- Hsu T-J, Yu, X, 2008. Sand transport under nearshore wave and current and its implication to sandbar migration, *Nonlinear Wave Dynamics, Selected paper of the symposium hold in honor of Prof. Philip L.-F. Liu's 60th birthday, Editor: Patrick Lynett*, World Scientific. [PUBLISHED]
- Scott N. V., Hsu, T.-J., Cox, D. Steep wave, turbulence, and sediment concentration statistics and their implications to sediment transport, *Cont. Shelf Res.* [SUBMITTED].