Wave Forecasts in Muddy Coastal Environments: Model Development and Real-Time Applications

Alexandru Sheremet
Civil & Coastal Engineering, 365 Weil Hall,
University of Florida, Gainesville, FL 32611
phone: (352) 392-9537/1518 fax: (352) 392-3394

Gregory W. Stone
Coastal Studies Institute, 331 Howe-Russell Geoscience Complex,
Louisiana State University, Baton Rouge, LA 70803
phone: (225) 578-6188 fax: (225) 578-2520 email: gagreg@lsu.edu

James M. Kaihatu
Oceanography Division, Code 7322,
Naval Research Laboratory
Stennis Space Center, MS 39529-5004
phone: (228) 688-5710 fax: (228) 688-4759 email: kaihatu@nrlssc.navy.mil

Award Number: N00014-03-1-0200

LONG-TERM GOALS

The objective of the work is to study wave evolution in cohesive sedimentary environments, toward the development of an effective, stochastic model for wave dissipation in these environments. The project will focus on prediction of surface wave evolution over relatively large spatial scales (scales of 100 wavelengths), intermediate depth to shallow water.

OBJECTIVES

The strong dissipative effects cohesive sedimentary environments have on waves are well known, but little understood. The commonly accepted long wave paradigm (only low frequency motion is affected due to strong interaction with the bottom) is contradicted by observations (Sheremet and Stone 2003) showing strong dissipation also in high frequency bands, where the direct wave-bottom interaction is weak. The goal of this project is to investigate short wave dissipation and develop a theoretical formulation for its mechanisms, and is the results to develop a numerical formulation of dissipation terms, amenable to implementation into existing stochastic spectral wave models (e.g. SWAN).

APPROACH

The observational component of this project is based on WAVCIS, a large ocean observing systems in operation at Louisiana State University. The system is operational and provides comprehensive real-time in-situ measurements. The project enhances WAVCIS' capabilities with sediment monitoring sensors.

The simulation component will consist of a fully detailed pilot model, integrated in a quasi-operational, nowcast mode, with the observation systems. The pilot model will implement theoretical approaches derived from the study, and will serve as a benchmark for skill assessing subsequent parameterizations

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
30 SEP 2005

2. REPORT TYPE

3. DATES COVERED
00-00-2005 to 00-00-2005

4. TITLE AND SUBTITLE
Wave Forecasts in Muddy Coastal Environments: Model Development and Real-Time Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Florida,Civil & Coastal Engineering, 365 Weil Hall,Gainesville,FL,32611

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The objective of the work is to study wave evolution in cohesive sedimentary environments, toward the development of an effective, stochastic model for wave dissipation in these environments. The project will focus on prediction of surface wave evolution over relatively large spatial scales (scales of 100 wavelengths), intermediate depth to shallow water.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

of wave dissipation developed as modules for operational use. The resulting simulation/observation system (workbench) will help identify the dominant energy exchange mechanisms, their time/spatial scales, and ways to uncouple the surface wave and fluid mud/seabed motions. It will also maximize the exposure of development ideas to field data. The database of test cases will be established during the project.

WORK COMPLETED

Recent field observations show unexpected short-wave sensitivity to sediment type. Sheremet and Stone (2003) studied the effects of sediment type on wave propagation by comparing synchronous wave observations from two locations along the same isobath (5 m), one sandy and the other muddy. The locations were on a very mild sloping shelf (slope < 1/1000), and subject to nearly identical meteorological and offshore wave conditions. Comparable short-wave ($f > 0.2$ Hz) energy levels were recorded at the two sites when wind forcing was significant. However, during calmer periods, such as in the wake of a frontal passage, short waves dissipated much faster at the muddy site. Understanding wave dissipation processes in muddy environments has been hampered by the scarcity of field data.

Suspended sediment concentration (SSC) monitoring devices (OBS - Optical Backscatter Sensor) have been deployed at a WAVCIS station located on a muddy shelf (near 5-m isobath). To understand the formation of the fluid-mud layer, SSC data were analyzed using a one-dimensional numerical model proposed by Li and Parchure (1998) to simulate a non-equilibrium suspension profile. The focus of simulations was to describe the regime dominated by settling during the waning stage of the storm, when the gradual decrease in wave-induced turbulence shuts down the resuspension processes. The increase in concentration in the fluid mud layer suppresses the turbulence further, accelerating the decay. Net bottom resuspension mass flux and key parameters controlling sediment settling were estimated using previously published data (Kemp and Wells,1987; Wolanski, 1989; Hwang, 1989). The analysis suggested the formation of a sharp lutocline at the top of a layer with concentrations higher than 10 kg/m^3 and thickness about 1 m. The fluid-mud layer formation coincided with strong dissipation of both swell and high-frequency (period < 5s) seas.

The short-wave dissipation mechanism is unknown. Sheremet et al. (2004) hypothesize that nonlinear spectral transfer effectively couples short waves to the dissipative muddy bottom, resulting in a spectrum-wide influence of this bottom. To investigate this hypothesis, a fully detailed unidirectional pilot model was developed which incorporates quadratic nonlinear wave interactions and wave dissipation effects induced by the presence of a fluid mud layer. Mud induced wave dissipation is modeled using the approach of Jiang and Mehta (1996). The wave model is based on the fully dispersive deterministic mild slope equation developed by Agnon et al. (1993), and Agnon and Sheremet (1997).

A major difficulty of the fully detailed model is the necessity to solve a very complicated linear dispersion relation with a complex wavenumbers (e.g. Dalrymple et al. 1991), which would be inconvenient in the context of a numerical wave model. As a first attempt, we used the simplified model of Ng (2000), a boundary layer asymptote of that of Dalrymple and Liu (1978), which expresses the wavenumber as a perturbation expansion, allowing complex dissipative wavenumbers to be functions of the nondissipative, real-valued wavenumber. This mechanism was added to the model of Kaihatu and Kirby (1995), a nonlinear wave model for simulating the triad interactions redolent of waves in the nearshore and surf zones.

RESULTS

Figure 1 shows wave dissipation characteristics based on typical values of parameters for the Louisiana shelf (mud-layer thickness of 0.3 m, water depth is 5 m, and mud density of 1,100 kg/m^3). Figure 2 shows the dissipative effects of this mud layer on the evolution of a single "difference" wave triad (frequencies f_1 =0.05 Hz, f_2=0.5 Hz, and f_3=0.55 Hz). Long wave dissipation is very strong - amplitude transmission (fraction of initial amplitude) after 1,000 m propagation is <1%. The short waves are barely dissipated (amplitude transmission factors of 93% and 99% respectively). Evolution with nonlinear 3-wave interactions (solid lines) deviate from the linear evolution (dashed lines). With high-frequency modes 2 and 3 having comparable strong transmission, energy is pumped from the shortest mode (2, magenta) which decays faster than linearly, into the middle mode (2, blue), which decays slower than linearly (Figure 2a). Compared with linear evolution, the low frequency mode 1 is sustained for a longer distance (Figure 2b) by energy transferred from the shorter modes, consistent with a steady energy flux directed toward long waves. Different dissipation rates for the long wave affect the short waves (not shown), while the nonlinear rate of decay of the long wave appears to be very similar - slightly slower in the case of weaker long wave dissipation.

Numerical results for a full-spectrum simulation are presented in Figure 3. for the same water/fluid-mud conditions) . The spectrum is characteristic of locally forced short wind waves in deep water, a JONSWAP spectrum with a peak period of T_{peak}=4 s, and significant height of H_{sig}=1 m. Figure 4 represents the evolution of the energy flux spectrum, normalized by the initial spectrum. In the absence of dissipation, linear evolution conserves modal spectrum. Figure 4a shows the effect of dissipation on the evolution of the spectral flux. Long waves are strongly attenuated and disappear from the spectrum within the first 1 km of propagation. Higher frequencies are less affected by the presence of mud. Figure 4b shows the nonlinear (3-wave interactions) evolution of the same spectrum. Mediated by the 3-wave interaction energy exchange mechanism, the strong dissipation in the long wave band is draining energy from modes with f > 0.5 Hz which otherwise would experience practically no dissipation.

In parallel to the development of a fully detailed model we also implemented the Ng (2000) model. The simplified boundary-layer mechanism was added to the model of Kaihatu and Kirby (1995), a nonlinear wave model for simulating nonlinear wave propagation in the shoaling and surf zone. Figure 4 shows numerical simulations of the evolution of a narrow banded spectrum (JONSWAP, peak period 10 s, significant height 1 m) of waves over a mildly (1%) sloping beach. The figure is comprised of two false color plots of the log of spectral density, with water depth on the abscissa and frequency on the ordinate. Figure 4a shows the shoaling of the spectrum over a sandy slope; the amplification of the second harmonic of the spectral peak are apparent as the shoreline is approached. Additionally there is a strong spreading of the energy to higher frequencies due to nonlinear energy transfer. Figure 4b shows the evolution of the same spectrum over a muddy beach, with a mud layer of 1100 kg/m^3. In contrast to the sandy case, the second harmonic amplification occurs much earlier in the shoaling process; this is likely due to boundary effects as the (detuned) phase-locking adjusts from a random phase distribution, rather than nonlinear triad effects. The overall energy damping is greater in the mud case, and the equilibration of the energy transfer to fill in "valleys" between distinct peaks in the spectrum occurs at an earlier stage in shoaling.

IMPACT/APPLICATIONS

Much of the present and near-future Navy capability on predicting regional and nearshore processes assumes a sandy-non-cohesive sedimentary environment. The present research enhances this capability by identifying processes and developing mechanisms which allow expansion into areas which deviate from this.

RELATED PROJECTS

The project is closely related to the ongoing ONR project "Coupled dynamics of waves and fluid mud layers" (PI Sheremet, UFL and Dr. M. Allison, Tulane), and also closely aligned with the large multi-year NRL ARI entitled "Coastal Dynamics of Heterogeneous Sedimentary Environments" (PI. Dr. K. Todd Holland).

REFERENCES:

Agnon, Y., A. Sheremet, J. Gonsalves, and M. Stiassnie, A unidirectional model for shoaling gravity waves. Coastal Eng., 20, 29-58, 1993.

Agnon, Y. and A. Sheremet, Stochastic nonlinear shoaling of directional spectra. J. Fluid Mech., 345, 79-99, 1997.

Dalrymple, R.A. and Liu, P.L.-F. 1978. Waves over soft muds: a two layer fluid model. J. Phys. Oc., 8, 1121-1131.

Dalrymple, R.A., Losada, M.A., and Martin, P.A. 1991. Reflection and transmission from porous structures under oblique wave attack. J. Fluid Mech. 224, 625-644.

Hwang K.-N., Erodibility of fine sediment in wave dominated environments, M.S. Thesis, University of Florida, Gainesville FL, 166 pp., 1989

Jiang, F., and A.J. Mehta, Mudbanks of the Southwest Coast of India V: Wave attenuation. J. Coast. Res., 12(4), 890-897, 1996.

Kaihatu, J.M., and Kirby, J.T. 1995. Nonlinear wave transformation over finite water depth. Phys. Fluids. 7, 1903-1914.

Kemp G. P. and J. T. Wells, Observations of shallow water waves over a fluid mud bottom: implications to sediment transport, Proceedings of Coastal Sediments '87, N. C. Kraus ed., ASCE, New York, p. 363-378, 1987.

Li Y., and T. M. Parchure, Mudbanks of the southwest coast of India VI: Suspended sediment profiles. Journal of Coastal Research, 14(4), 1,363-1,372, 1998.

Ng C.-O., Water waves over a muddy bed: a two layer Stokes' boundary layer Model. Coastal Engineering, 40, p. 221-242, 2000.

Sheremet A. and G. W. Stone, Observations of nearshore wave dissipation over muddy sea beds, JGR Vol 108, C11, 24, DOI 10.1029/2003JC001885, 2003.

Sheremet A., A. J. Mehta, B. Liu, and G. W. Stone, Observations of nearshore wave dissipation

over muddy sea beds, submitted to Estuarine, Coast and Shelf Science.

Wolanski E, T. Asaeda, and J. Imberger, Mixing across a lutocline, Limnology and Oceanography, 34(5), 931-938, 1989.

PUBLICATIONS

Sheremet A., A. J. Mehta, B. Liu, and G. W. Stone, Observations of nearshore wave dissipation over muddy sea beds, Estuarine, Coast and Shelf Science, 63, pp. 225-233, 2005. [refereed]

Allison, M., A. Sheremet, M. A. Goni and G. W. Stone, Storm layer deposition on the Mississippi-Atchafalaya subaqueous delta generated by Hurricane Lili in 2002, Continental Shelf Research 25, p. 2213-2232, 2005 [refereed].

ASCE Task Committee on Management of Fluid Mud, Management of fluid mud in estuaries, bays, and lakes. PART I: Present State of Understanding and Modeling [in press, refereed, Journal of Hydraulic Engineering]

ASCE Task Committee on Management of Fluid Mud, Management of fluid mud in estuaries, bays, and lakes. PART II: Measurement, Modeling, and Management [in press, Journal of Hydraulic Engineering, refereed]

Stone G. W., B. P. Kumar, A. Sheremet, and D. Watzke , Complex morphodynamic response of estuaries and bays to winter storms: North-central Gulf of Mexico, USA. In "High resolution morphodynamics and sedimentary evolution of estuaries", J. Knight and D. Fitzgerald (eds), Kluwer Academic Publishers, Dordrecht, The Netherlands 2005. [non-refereed].

Roberts, H. H., N. D. Walker, and A. Sheremet, Effects of Cold Fronts on Bayhead Development: Atchafalaya Bay, Louisiana. In "High resolution morphodynamics and sedimentary evolution of estuaries", J. Knight and D. Fitzgerald (eds), Kluwer Academic Publishers, Dordrecht, The Netherlands, 2005. [non-refereed]

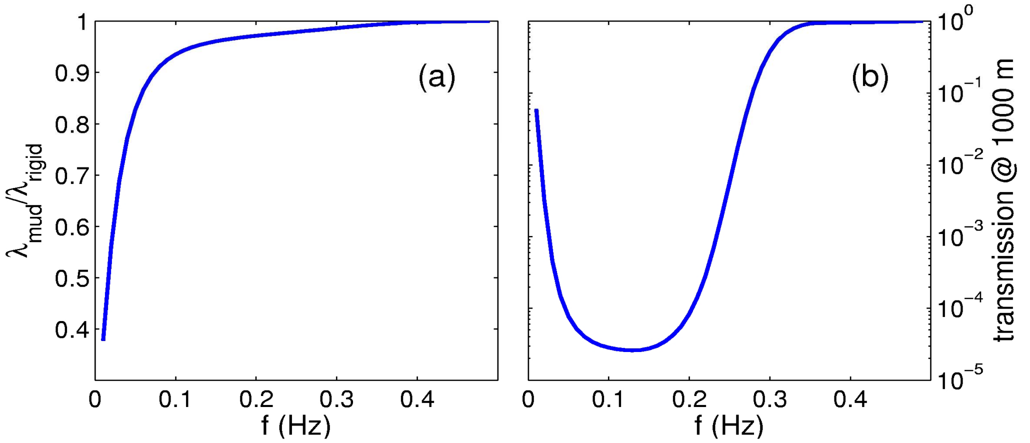

Figure 1: Linear characteristics of wave dissipation induced by the presence of a fluid-mud layer (in this example water depth is 5 m, mud layer thickness is 30 cm, mud density is 1100 kg/m^3). a) wavelength change with respect to a rigid (e.g. sandy bottom). b) amplitude transmission at 1 km (ratio of amplitude after 1 km propagation to initial amplitude) as a function of frequency.

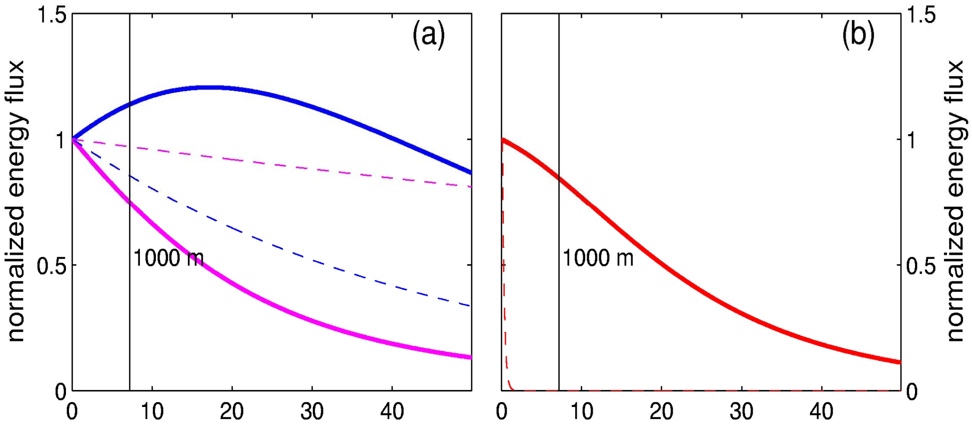

Figure 2: Nonlinear evolution of a triad over a fluid mud layer. Water depth and mud layer thickness and density are the same as in Figure 1. Frequencies are f_1 =0.05 Hz (red), f_2=0.5 Hz (blue), and f_3=0.55 Hz (magenta). Transmission factors at x=1 km are (a,b) (< 1%, 93%, 99%), and (c,d) (10%, 93%, 99%) for f_1, f_2, and f_3, respectively. Linear long wave dissipation is more than ten times larger in (a,b) than (c,d). Dashed lines represent the linear (i.e. non-coupled modes) evolution.

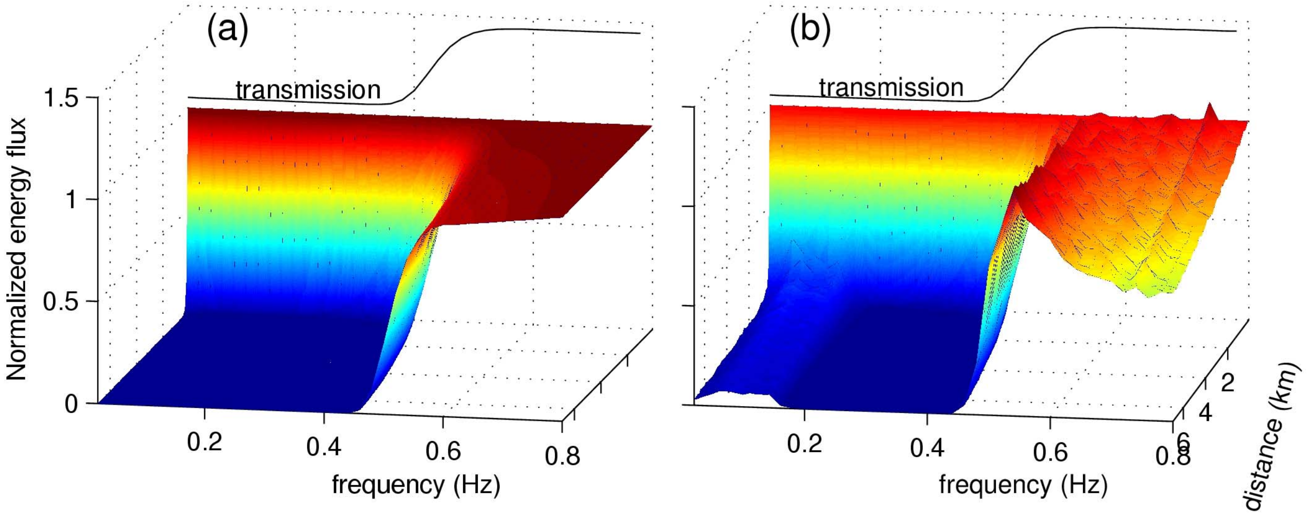

Figure 3: Simulated evolution of a short wave spectrum JONSWAP (peak T=4 s, significant height H=1 m) for a spectrum over a fluid-mud layer (same parameters as in Figure 1). Energy flux density is normalized by initial value. a) Linear model (including dissipation). b) Nonlinear model. A normalized plot of amplitude transmission at 1 km (Figure 1b) is also shown.

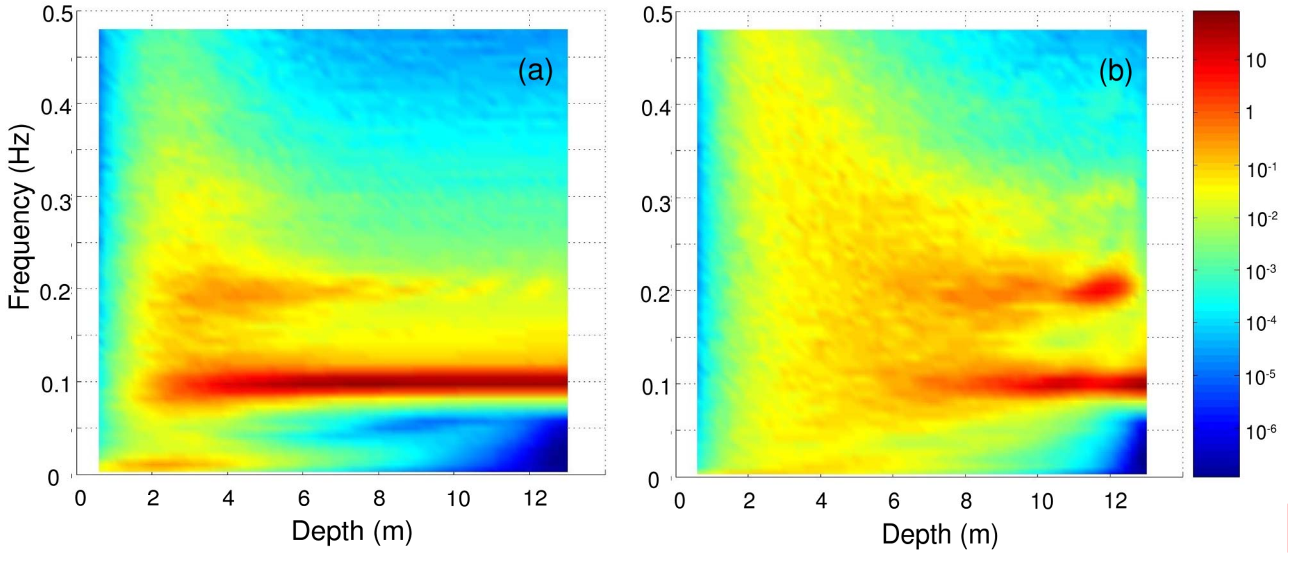

Figure 4: Numerical simulation (Kaihatu & Kirby, 1995; Ng, 2000) of spectral density evolution over a mildly sloping beach (log scale spectral density vs. depth and frequency). The shoreline is on to the right of the plots. a) A sandy beach. a) A muddy beach (fluid mud density 1100 kg/m^3).