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A study of dissipation of wind-waves by mud at Cassino Beach, Brazil: Prediction and inversion

W. Erick Rogers [a,*], K. Todd Holland [b]

[a] Naval Research Laboratory (NRL) Oceanography Division; Code 7322; Stennis Space Center, MS 39529, USA
[b] NRL Marine Geosciences Division; Code 7440.3; Stennis Space Center, MS 39529, USA

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ABSTRACT

The impact of a non-rigid seafloor on the wave climate at Cassino Beach, Brazil, May–June 2005 is studied using field measurements and a numerical wave model. The measurements consist of wave data at four locations; rheology and mud thickness from grab samples; and an estimate of the horizontal distribution of mud based on echo-soundings. The dissipation of waves by a non-rigid bottom is represented in the wave model by treating the mud layer as a viscous fluid. Applied for 431 time periods, the model without this type of dissipation has a strong tendency to overpredict nearshore wave energy, except during a period of large storm waves. Two model variations which include this dissipation have a modest tendency to underpredict the nearshore wave energy. An inversion methodology is developed and applied to infer an alternate mud distribution which, when used with the wave model, yields the observed waveheights.

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1. Introduction

Wind-generated surface waves in shallow and intermediate depths generate pressure variations at the seabed with spatial and temporal scales corresponding to the wavelength and wave period. In the case of a non-rigid bottom, such as mud, the pressure variations can result in motion of the water/seabed interface. Work is being done to generate this motion, and thus energy is lost from the wind-waves. In the case of a muddy bottom, the motion in the seabed is subsequently damped, predominately by viscosity.

Methods exist for estimating the damping of water waves by viscous mud. An early effort was made by Gade (1958), using an assumption of shallow water. Dalrymple and Liu (1978) developed a more general method without using this assumption; further, their method accounts for viscosity in the water, rather than just the mud layer. Ng (2000) proposed a numerical simplification of the Dalrymple and Liu (1978) calculation, using an assumption of a thin mud layer. Such treatments of non-rigid seafloor as a viscous fluid do have limitations: mud can also exhibit viscoelastic or plastic behavior: see Hsiao and Shemdin (1980); Jiang and Mehta (1995, 1996); Zhang and Ng (2006); Mei and Liu (1987), and references therein.

Treatment of damping by wave-bottom interaction within an analytical wave model requires the a priori assumption that unrepresented processes (refraction, shoaling, wind effects, breaking, etc.) are small. For verification with field data, this assumption means that test cases must be very carefully selected, with most data sets being unsuitable. Treatment within a numerical wave model greatly improves this situation since these processes can be efficiently incorporated. One such model is the SWAN wave model, introduced in the 1990s (Holthuijsen et al., 1993; Ris 1997; Booij et al., 1999) for the purpose of predicting wave propagation, growth, and decay in coastal regions, and has since seen considerable use by scientists and engineers. However, this model includes parameterizations for attenuation via interaction with a *rigid* seafloor only. Even in early evaluations of the model, it was noted that the absence of mud-related dissipation is a major

* Corresponding author. Tel.: +1 228 688 4727; fax: +1 228 688 4759.
E-mail addresses: rogers@nrlssc.navy.mil (W. Erick Rogers), tholland@nrlssc.navy.mil (K. Todd Holland).

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Nomenclature

T_p	peak wave period
σ	wave angular frequency
$D(\theta)$	normalized directional distribution of wave energy
k	wavenumber
h	water layer thickness (without motion)
$\delta_{m,0}$	fluidized mud layer thickness (without motion)
$\delta_{m,0,t}$	total mud layer thickness (without motion)
ρ_w	water density
ρ_m	mud density
γ	ratio $\gamma = \rho_w/\rho_m$
ν_w	kinematic viscosity of water layer
ν_m	kinematic viscosity of mud layer
Δ_m	Stokes boundary layer thickness, $\Delta_m = \sqrt{\nu_m/\sigma}$
ζ	ratio $\zeta = \Delta_m/\Delta_w = (\nu_m/\nu_w)^{1/2}$
$\tilde{d}$	normalized mud layer depth (Reynolds number), $\tilde{d} = \delta_{m,0}/\Delta_m$
k_i	imaginary part of wavenumber, equivalent to the dissipation rate
$D_{m/w}$ or k_i	dissipation rate from viscosity in the mud and water layers, in the case of Ng and DL formulae, $D_{m/w} = k_i$
D_m	dissipation rate from viscosity in the mud layer, in the case of WDGL, $D_m = k_i$
D_w	dissipation rate from viscosity in the water layer
k_s	real part of the wave number in shallow water, $k_s = \sigma/\sqrt{gh}$
$x_{a=0.5a_0}$	distance over which a wave will be reduced to 50% of its original amplitude (see Eq. (1))
$x_{a=0.5a_0}$	distance over which a wave will be reduced to 10% of its original amplitude (see Eq. (1))
S_{ds}	spectral dissipation rate
S_{bot}	spectral dissipation rate from wave-bottom interaction, a subset of S_{ds}
S_{mud}	spectral dissipation rate from mud, a subset of S_{bot}
E	spectral energy density
N	spectral action density $N = E/\sigma$

deficiency, such that in cases of non-rigid seafloor, one must apply unrealistic bottom friction parameters to get the desired dissipation (e.g. Dingemans, 1998). Representation of damping by mud was recently introduced in SWAN by Winterwerp et al. (2007), based on an extension by De Wit (1995) of the Gade (1958) formulation, though at time of writing, it has not been incorporated into publicly released versions of the code (Holthuijsen et al., 2006). Winterwerp et al. (2007) utilize laboratory experiments with measured rheology by De Wit (1995). No prior numerical wave modeling study involves the application of field measurements of rheology; in Winterwerp et al. (2007), the field rheology is assumed.

The primary objective of the present study is to use numerical wave models to simulate wave dissipation by fluid mud, utilizing field measurements of both mud and wave conditions. The field experiment was held at Cassino Beach, Brazil during May–June 2005. Large numbers of simulations with the SWAN wave model over a 35-day period are performed to identify trends and sensitivity to physics of wave dissipation by viscous mud in this application. Secondary objectives are as follows: (i) to compare two methods for representing the dissipation of wind-generated surface waves by a viscous mud layer: the method of Winterwerp et al. (2007) and that of Ng (2000), the latter implemented in an experimental version of the SWAN model in this study; (ii) to determine whether including dissipation by mud is necessary for accurately reproducing observed wave heights; (iii) to, given an estimate of rheology and mud distribution derived from field measurements, evaluate the skill of these models in predicting observed wave heights; and (iv) to develop and apply an inversion process to determine the rheology and mud distribution for which the wave model will reproduce the observed wave heights.

Section 2 of this manuscript introduces the modeling platform, SWAN, as well as the two methods of representing dissipation by mud in this platform. The methods are also verified in this section, including a comparison with results using the approach of Dalrymple and Liu (1978). In Section 3, the Cassino Beach case study is introduced. In Section 4, the two-dimensional model design is described, and results are presented. In Section 5, the one-dimensional model design is described and results given. Also in this section, the inverse methodology is introduced, applied, and results given. Discussion is given in Section 6, and conclusions in Section 7.

2. Model description and verification

2.1. SWAN wave prediction model

The so-called "third generation" (3G) of spectral wave models calculate wave spectra without a priori assumptions regarding spectral shape. For this investigation, we use the SWAN model ("Simulating WAves Nearshore"; Booij et al., 1999; Holthuijsen et al., 2006). SWAN is a 3G model designed to address the excessive computational expense of applying predecessor 3G models (such as WAM, WAMDI Group, 1988) at high resolutions, particularly in coastal regions. The governing equation of SWAN and most other 3G wave models is the action balance equation. In Cartesian coordinates, the action balance equation is

$$\frac{\partial N}{\partial t} + \frac{\partial C_x N}{\partial x} + \frac{\partial C_y N}{\partial y} + \frac{\partial C_\sigma N}{\partial \sigma} + \frac{\partial C_\theta N}{\partial \theta} = \frac{S}{\sigma}$$

where σ is the angular relative frequency, which is the wave frequency measured from the frame of reference moving with current, if current exists, N is wave action density, equal to energy density divided by relative frequency ($N = E/\sigma$), θ is wave direction, C is the wave action propagation speed in (x, y, σ, θ) space, e.g. in absence of currents, C_x is the x-component of the group velocity C_g, and S is the total of source/sink terms expressed as wave energy density. The right-hand side of the governing equation is represented by three terms, $S = S_{in}+S_{nl}+S_{ds}$ (input by wind, nonlinear interactions, and dissipation, respectively). The dissipation term can be broken into two further terms $S_{ds} = S_{br}+S_{bot}$; the S_{br} term is breaking associated with steepness and instability (whitecapping, surf breaking, etc.); the S_{bot} term includes dissipation due to bottom roughness S_{bf} (friction, scattering), percolation S_{pe}, or non-rigid bottoms S_{mud}. In released versions of SWAN (Holthuijsen et al., 2006), S_{bot} is only associated with rigid seabeds, $S_{bot} = S_{bf}$. The default S_{bf} formula is that of JONSWAP (Hasselmann and Coauthors, 1973), in which the user specifies a simple tuning coefficient that has no apparent physical connection with measurable seabed characteristics. An alternate rigid-bed formula in SWAN is that of Madsen et al. (1988), in which the user specifies a single, representative bedform amplitude at each point in the computational grid on which S_{bf} is estimated.