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Numerical study on the dissipation of water waves over a viscous fluid-mud layer

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ABSTRACT

Direct simulations of the Navier–Stokes equations are performed to investigate the interaction between a nonlinear wave at the water surface and an interfacial wave at the fluid-mud layer below. A level-set method is employed to capture the air–water and water–mud interfaces. Despite the nonlinearity of the governing equations, the direct numerical simulation shows that the total wave-damping rate exhibits a remarkable consistency with the prediction of the linear theory. To reveal the underlying mechanism, we analyze the velocity and vortcity fields, energy transfer from the water to the mud, and energy dissipation. The detailed analysis of velocity and vorticity fields shows an appreciable nonlinear effect in the water but a relatively weak nonlinear effect in the fluid mud. The major pathway of transferring energy from the water to the mud is the pressure acting on the water–mud interface. The viscous dissipation of the energy also exhibits a local, significant nonlinear effect in the water. However, the excess and deficiency in the dissipation rate at different wave phases compared with the linear theory largely cancel each other, resulting in an overall wave-damping rate close to the prediction of the linear theory. Furthermore, the analysis of energy budgets elucidates a comprehensive picture of energy transport and dissipation in the wave–mud system. In the water, the horizontal motion first loses energy to the vertical motion through the pressure–strain correlation. The energy of the vertical motion is then transported downwards by the pressure and vertical advection. Across the water–mud interface, the vertical motion of the water transmits energy to the mud through the pressure work. In the mud, the energy of the vertical motion is transported downwards by the pressure and then redistributed to the horizontal motion through the pressure–strain correlation again. The energy of the horizontal motion is transported towards the mud bottom through the viscous diffusion and is finally dissipated.

1. Introduction

Fluid mud exists in many rivers, estuaries, and coasts around the world. A muddy layer can significantly attenuate water waves within several wavelengths [1–4]. The forcing of water waves can deform the lutoclines, and the Stokes drift can cause a horizontal transport of the mud [2,5,6]. The interaction between water waves and muddy seafloor is of great importance to the sediment transport in coastal and estuarine waters, remoting sensing of nearshore regions, and foundation of coastal structures, among many other environmental and engineering applications. These problems have motivated considerable studies on the underlying mechanism of wave–mud interactions.

Various theoretical models have been proposed to predict the damping rate of water waves propagating over fluid mud. Gade [1] firstly proposed a two-layer analytical model, with the upper layer of inviscid water and the lower layer of highly viscous fluid mud, to predict the attenuation of linear shallow water waves. Gade's model was extended to linear intermediate-depth water waves by Dalrymple and Liu [7] (referred to as DL hereinafter), and the viscosity of water was considered in DL's theory. This model agrees well with Gade's laboratory experiment [1]. In addition, Ng [5] developed a two-fluid Stokes boundary layer model based on an asymptotic theory for a thin layer of fluid mud under water waves. All of these models show an exponential decay of linear sinusoidal waves with the propagating distance. DL [7] found that the pressure working on the water–mud interface plays an important role in attenuating water waves and in the energy transfer from water waves to fluid mud.

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While the interaction between linear water waves and mud has been studied extensively, waves in reality have finite amplitudes and the nonlinearity often needs to be considered. The nonlinearity is caused by the quadratic terms in the boundary conditions at the wave surface, which is neglected in the linear wave theory by only retaining the leading-order terms of the expansion with respect to the wave steepness. Nonlinear wave models account for the effects of higher-order terms. For example, Stokes [8] expanded the governing equations to the second order, and Schwartz [9] further extended the Stokes' expansion to arbitrary order with the solution given numerically. Nonlinear waves differ from linear waves in the wave geometry and strain rate, among other quantities. The wave crest and trough of nonlinear waves are respectively steeper and flatter than those of linear waves with the same steepness [10]. The magnitude of the strain rate below the wave crest of a nonlinear wave is larger than that below the wave trough [10]. As a result, the dissipation rate, which is proportional to the square of the strain rate, is also stronger under the wave crest. Furthermore, wave nonlinearity causes the fluid particles under a water wave to drift towards the wave propagation direction, leading to a mean mass transport known as the Stokes drift [11].

Nonlinear wave models have been employed to study the wave damping by mud. Jiang and Zhao [12] and Jiang et al. [13] proposed a first-order analytical model to predict the attenuation of cnoidal waves with finite amplitudes in shallow water. In their model, Prandtl's boundary-layer equations were used to describe energy dissipation in three boundary layers, one above the water–mud interface, one below the interface, and one near the rigid bottom of the viscous fluid mud. The fluid motions outside of the boundary layers were assumed to be potential flows. In the absence of wave–wave interactions, their model [12,13] revealed the influence of the wave height on the damping rate. Liu and Chan [14] replaced linear sinusoidal water waves with Boussinesq-type waves, and derived a set of Boussinesq equations.

The above-mentioned models describe the damping of long waves, which can directly interact with mud seafloor. Sheremet and Stone [3] and Elgar and Raubenheimer [4] showed strong dissipation in both long and short waves in Louisiana Shelf. Sheremet et al. [15] ascribed this phenomenon to the coupling of short waves with the long waves directly impacted by the mud layer. Combing Ng's wave dissipation model [5] for thin mud layers with a parabolic nonlinear wave model, Kaihatu et al. [16] related the damping of short waves to subharmonic interactions between short waves and actively-dissipated long waves. Alam et al. [17] performed a perturbation based simulation of a three-wave system, and proposed quantitative prediction of energy transfer from short waves to long subharmonic waves via their near-resonant interactions for the dissipation by the mud.

In addition to the theoretical analyses, numerical modeling of water waves traveling over fluid mud has also been developed. Damping rates of water waves based on theoretical models of wave–mud interactions are implemented as a dissipation term in numerical models of water waves [18,19]. Winterwerp et al. [18] and Rogers and Holland [20] used the dissipation models of Ng [5] and Gade [1], respectively, to determine the dissipation term in the Simulating Waves Nearshore (SWAN) model. SWAN is a phase-averaged wave model in which each wave component is described using an energy density function in the spectral space, and it is capable of tracking the evolution of large-scale wave fields in both open sea and coastal areas involving various physical processes, such as the wind input, dissipation, and nonlinear wave–wave interactions [21,22]. Some others used the Navier–Stokes equations to simulate the wave damping. Huang and Chen [23] expanded the Navier–Stokes equations to the first-order and second-order of a perturbation to develop a numerical model. Their model was used to simulate the damping of solitary waves propagating over mud. Niu and Yu [24] performed simulations of water waves propagating over muddy slopes using the volume of fluid (VOF) method for surface capturing and the $k-\varepsilon$ model for the turbulence closure. Torres-Freyermuth and Hsu [25] also used the $k-\varepsilon$ model, but the governing Reynolds-Averaged Navier–Stokes (RANS) equations were derived from Eulerian two-phase flow equations with the equilibrium Eulerian approximation for sediment-laden flows. In the work of Hejazi et al. [26], the Navier–Stokes equations based on a Lagrangian–Eulerian description were simulated to capture the damping of nonlinear waves over fluid mud.

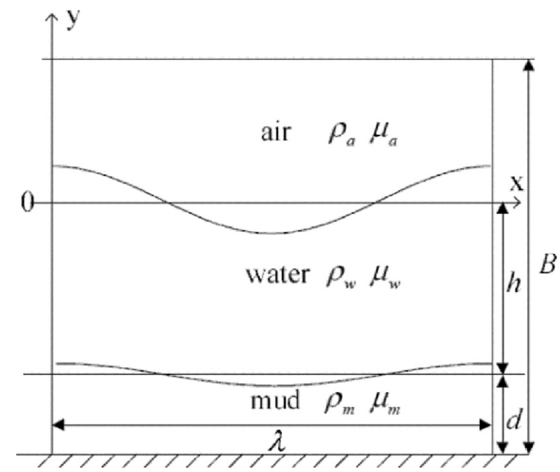

Fig. 1. Sketch of the domain for a water surface wave traveling over a mud layer.

Although a variety of theoretical and numerical models have been proposed to predict the attenuation rate of water waves over fluid mud, direct descriptions of the wave-damping process are rare in the literature. In the work of Hu et al. [27], the interaction of breaking waves with a fluid mud layer was investigated based on the results of large-eddy simulations. In the present study, we perform direct simulations of the Navier–Stokes equations for non-breaking water waves with finite amplitudes propagating over viscous fluid mud, with the aim to directly resolve the flow details and to improve the understanding of the essential mechanism of the wave–mud interaction.

The rest of this paper is organized as follows. The numerical method for the water–mud interaction problem is introduced in Section 2. The temporal evolution of the water surface and the wave–mud interface is examined in Section 3.1. Velocity and vorticity fields in the water and mud are analyzed in Section 3.2, followed by analyses of water–mud energy transfer in Section 3.3, energy dissipation in Section 3.4, and budget of energy in Section 3.5. Finally, conclusions are presented in Section 4.

2. Numerical simulations

2.1. Governing equations and numerical methods

The sketch of a two-dimensional water surface wave traveling over a fluid-mud layer is shown in Fig. 1. Following many previous investigations [1,5,7,14,23], we treat the mud at the bottom as a Newtonian fluid with larger density and viscosity than those of the water. The governing equations are solved in a fixed Cartesian coordinate system (Fig. 1). The wave propagation direction and vertical direction are denoted as x and y, respectively. The undisturbed water surface is located at $y = 0$. The height of the whole computation domain including air, water, and mud is B, and the depths of water and mud are h and d, respectively. The wavelength of the water surface wave is λ.