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Damping of waves propagating over a muddy bottom in deep water: Experiment and theory

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ABSTRACT

Surprisingly, deep water waves in the ocean propagating over mud bottoms can attenuate if wave groups are formed. This is shown in wave tank experiments, where two superimposed short waves with slightly different frequencies were generated to create the wave groups. Associated with the wave groups are long bound second order waves, which can exert wave pressure on the mud bottom, dissipating energy. Attenuation coefficients were measured by using Prony's method for each wave component as a function of distance down the tank. We develop an analytic expression for the nonlinear interaction between the two waves in deep water propagating at arbitrary angles by using Stokes' theory to second order. Finally, we show that the attenuation can be explained by the rate of work at bottom done by the long bound wave using the visco-elastic model MacPherson (1980). The results show that the dissipation depends on the incident wave periods, the bottom pressure and the vertical velocity of the long bound wave at the bottom.

1. Introduction

The interaction of water waves and bottom sediment can be critical for numerous aspects of marine activity. Many field campaigns on muddy coastal shelves have been carried out in highly trafficked and vital parts of the globe, such as the Gulf of Mexico, the Gulf of Aden, the Mississippi River, off the coasts of Kuwait, India, and north-western South America, for example (Matthew et al., 1995; Robillard, 2009; Vinson et., 2009), showing significant wave damping over the mud; that is, waves decaying significantly in a distance of several wavelength.

Previous studies examined the mechanisms of wave attenuation of shallow and intermediate depth waves over a muddy bottom through field measurements (Tubman and Suhayda, 1976; Wells and Coleman, 1981; Wells, 1983; Mathew et al., 1995; Sheremet and Stone, 2003; Elgar and Raubenheimer, 2008; Jaramillo et al., 2009; Vinzon et al., 2009; Rogers and Holland, 2009); laboratory experiments (Gade, 1957; Nagai et al., 1984; Yamamoto and Schuckman, 1984; Tsuruya and Nakano, 1987; Sakakiyama and Bijker, 1989; Zhang and Zhao, 1999; Hu and Wai, 2001; Soltanpour et al., 2010; Hsu et al., 2013; Traykovski et al., 2015). Previous studies observed significant wave attenuation and concluded that the wave attenuation depends on the wave amplitude, wave period and water depth.

Moreover, wave attenuation is very dependent on the mud rheology, its mobilization into the water column, settling, and consolidation. A variety of theoretical models of wave damping have been developed that differ in their treatment of the rheology of the mud (Chan and Liu, 2009; Jain and Mehta, 2009; Torres-Freyermuth and Hsu, 2010; Xia and Zhu, 2010). The viscous mud model (Gade, 1958; Dalrymple and Liu, 1978; Jiang and Zhao, 1989; Ng, 2000) is very widely used and is often used for comparisons with field experiments because of its simplicity. MacPherson (1980), Shibayama et al. (1989), Zhang and Ng (2006b), Zhao et al. (2006), and Liu and Chan (2007) all use a visco-elastic representation of the mud. A visco-plastic model, or Bingham fluid model, was developed by Krone (1963), Tsuruya et al. (1986), Otsubo and Muraoka (1988), and Zhang et al. (2003). Other models such as elastic (non-damping) (Mallard and Dalrymple, 1977), poro-elastic (Yamamoto and Takahashi, 1985), and visco-elastic–plastic (Shibayama et al., 1990) have also been used. We can conclude that the correct model to use requires a determination of the rheological properties of the mud layer.

For a single wave train in deep water we expect that waves propagating over a mud bottom are not affected by the bottom; hence there will be no damping. Sheremet and Stone (2003) observed significant damping of high frequency short waves over mud in deep water. They looked at wave propagation on the Louisiana inner shelf using simultaneous measurements at two shallow water ocean observatory sites. One site was mostly a muddy bottom and the other was mostly a sandy bottom. Contrary to the expectation that wave dissipation via mud is important only for longer waves that directly interact with the bottom, their study showed significant damping of high frequency short waves.

In this paper, we shall explore a mechanism for short wave dissipation in deep water. The basic concept is that bound second order waves associated with the presence of wave groups can (Longuet-Higgins and Stewart, 1960) create a bottom pressure and induce damping of the deep water waves.

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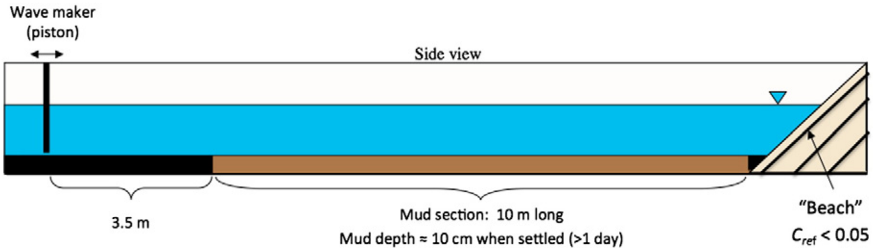

Fig. 1. Side view of the Johns Hopkins University laboratory wave tank with length = 18.3 m, width = 2.5 m and depth = 1.8 m. Also shown is the false bottom and mud section that is 10 m long and about 10 cm of consolidated mud height.

The first part of this paper examines wave damping in deep water in the absence of breaking. Since a monochromatic short wave train propagating in deep water does not interact with the bottom, any damping of the waves in deep water is caused by other mechanisms, such as sidewall friction or damping by a contaminated surface. Experiments using monochromatic waves were conducted to determine this damping.

Two short waves with slightly different periods (with angular frequencies σ_1 and σ_1) propagating in the same direction were created in the laboratory. These waves formed a wave group with its associated nonlinear bound long waves with frequencies $\sigma_1 - \sigma_2$ and $\sigma_1 + \sigma_2$ as shown in the second part of this paper. In our tests, the $\sigma_1 - \sigma_2$ wave dominates and we examine its interaction with the bottom. In particular, we will demonstrate that the length of the difference frequency bound wave can be long enough such that it is in intermediate or shallow water, therefore exerting pressure in the bottom, leading to energy dissipation.

Longuet-Higgins (1950) studied the relationship of the second order bound long wave pressure variations and 'microseisms', which are faint earth tremors caused by water waves. He derived the expression of the bottom pressure for two short wave trains propagating in exactly opposite directions. He concluded that microseisms are caused by the pressure variation of standing surface water waves, even in deep water.

The second part of this paper develops a theoretical expression the velocity potential for two short wave trains superimposed with arbitrary angles of propagation in deep and intermediate water depths, following Longuet-Higgins (1950) and Phillips (1960). Longuet-Higgins and Stewart (1960) examined two wave trains traveling in the same direction using the Stokes' expansion method. They calculated the change in wavelength and amplitude arising from the non-linear interactions between the two wave trains as well as the bound long waves. Our results collapse to Longuet-Higgins and Stewart (1960) for the case when the two wave trains are traveling in the same direction.

Table 1
Parameters of experimental tests of monochromatic and bio-chromatic waves over mud.

Test #	Stroke (S_1) (cm)	Period (T_1) (s)	Stroke (S_2) (cm)	Period (T_2) (s)	Water depth (h) (cm)	Lutocline depth (d_2) (cm)	Mud density (kg/m^3)
1	2	0.6	2	0.65	44	12	1291
2	2	0.6	0	0	44	12	1291
3	2	0.65	0	0	44	12	1291
4	2	0.6	2.2	0.65	44	12	1301
5	2.2	0.65	0	0	44	12	1301
6	2	0.6	1	0.65	44	12	1288
7	1	0.65	0	0	44	12	1288
8	2	0.6	2	0.63	44	12	1294
9	2	0.6	0	0	44	12	1294
10	2	0.63	0	0	44	12	1294
11	2	0.6	2.2	0.63	44	12	1303
12	2.2	0.63	0	0	44	12	1303
13	2	0.6	1	0.63	44	12	1249
14	1	0.63	0	0	44	12	1249
15	2	0.62	2	0.66	44	12	1311
16	2	0.6	0	0	44	12	1311
17	2	0.66	0	0	44	12	1311
18	2	0.62	2.2	0.66	44	12	1299
19	2.2	0.66	0	0	44	12	1299
20	2	0.62	1	0.66	44	12	1301
21	1	0.66	0	0	44	12	1301

2. Experimental study of waves propagating over muddy bottom in deep water

A wave train of short waves propagating over a mud bottom in deep water cannot interact with the bottom. However, Sheremet and Stone (2003) observed an apparent wave attenuation in water depths of 5 m, which is equivalent to $kh = \pi$ (the deep water limit of Dean and Dalrymple (1991), where k is the wave number and h is the water depth). However, according to linear theory, at $kh = \pi$, the pressure at the bottom under a deep water wave is about 9% of the maximum value. This is a surprisingly large value and calls into question the use of the deep water limit of $kh = \pi$ for pressure. A better deep water limit is perhaps 1.5 π, when the pressures at the bottom under a deep water wave are about 2% of the maximum. Our tests are carried out with $kh = \pi$ $1.5\,\pi$ to guarantee that there is no pressure exerted on the bottom by single frequency wave trains.

2.1. Facility and experiments

All experiments were performed at the Coastal Engineering Laboratory at Johns Hopkins University. The laboratory wave tank measures 18.3 m long by 2.5 m wide with walls measuring 1.8 m high (see Fig. 1).

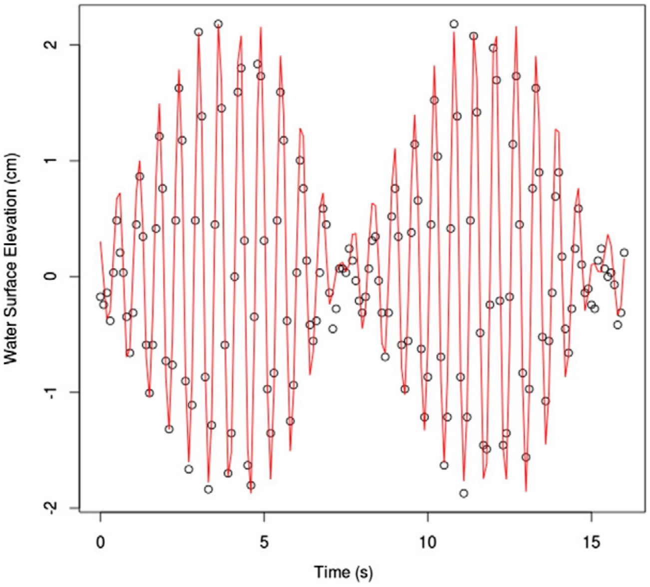

Fig. 2. Experimental data of the water surface elevation with time (◦) and the fitted line is the solution by using the extended Prony method for test #1 and sensor #1 with water depth 44 cm and lutocline elevation of 12 cm, with two short waves.