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A study on mud particle velocities and mass transport in wave-current-mud interaction

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ABSTRACT

The upper fluid mud layer in muddy environments absorbs wave energy and, in turn, moves due to the wave action. In addition to these two major phenomena of wave-mud interaction, introduction of current in the wave field also changes the wave characteristics as well as the rates of mud mass transport. The present study offers an experimental investigation of wave-current-mud interaction to address the wave transformation and mud mass transport on a horizontal bed. A number of laboratory tests were conducted to measure the mud particle velocities as well as wave attenuation rates under following, opposing, and no current conditions. Both the wave energy dissipation and mud mass transport increase with the presence of opposing currents and decrease when following currents are introduced. A semi-analytical model was also presented and the numerical results are compared with the laboratory experiments, showing acceptable agreements.

1. Introduction

Although muddy coasts are not too common, there are many coastal areas, normally adjacent to big rivers, where the bottom layer has been covered with soft mud. Ariake Sea in Japan, north western part of the Persian Gulf in Iran, Haihe Estuary of China, and Louisiana Coast in United States are some typical examples of muddy beaches. In these environments, the discharges of the big adjacent rivers usually play a significant role on the supply of fine sediments. In addition to the wave attenuation, which is an important phenomenon in muddy coasts, fine sediment transport and accumulations in harbors and coastal areas need to be studied as the resulting bathymetric changes reduce navigability and makes costly dredging operations necessary to keep the required navigable depth. In particular, fine sediment transport requires a higher scrutiny as mud is often heavily polluted, due to its ability of absorption of various types of pollutants from the water.

Mud mass transport within fluid mud layer, under the influences of waves and gravity, as well as suspended mud transport in water layer are considered to be the main mechanisms of sediment transport in muddy environments. It is expected that the former mode is quantitatively predominant as the sediment concentration in mud layer is often in the order of a few hundred kg/m^3, comparing to the normal sediment concentration in the water column, which is in the order of a few tenths of kg/m^3 [1,2]. Mud mass transport might be partially responsible for huge rapid sedimentation in access channels of the ports in muddy areas after the storms (e.g. [3],).

Since Gade [4], the interaction of waves and muddy beds has been studied in several ways. Wave attenuation and mud mass transport are two major phenomena that have received the most attentions. Review of past researches shows that the effects of mud thickness, water content ratio and different rheological models of fluid mud on the dissipation rate of a sinusoidal wave have been widely studied.

Dalrymple and Liu [5] developed a two-layer fluid model to examine the attenuation of waves over a mud bottom, which was characterized as a laminar viscous fluid. Considering the 2D linearized momentum equations, they proposed a numerical model for different mud thicknesses, as one of the effective parameters on wave-mud interaction, and an analytical boundary layer approximation for the case of a thin mud layer. Model outputs consisted of wave attenuation rate, modified wave length, mud particle velocities, and amplitude of interfacial wave. Although this pioneer study was highly referred by a large number of researchers, the simple rheology of viscous fluid was not a proper choice for laboratory and field applications. Moreover, the second order parameters, e.g. mud mass transport, were not provided in this study. The developed two-layered system, on the other hand, was also not capable to implement the vertical variations of mud properties,

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such as density or viscosity, in fluid mud layer.

Sakakiyama and Bijker [6] conducted experiments on wave damping and mass transport associated with non-Newtonian mud. They reported quantitative discrepancies comparing the data with numerical results of the viscous fluid model of Dalrymple and Liu [5]. Literature shows a number of other researches on wave attenuation over the muddy beds including the effects of non-linearity and irregularity of waves (e.g [7,8].).

Mud mass transport in a two-layer water-mud system was first mathematically determined by Dore [9]. He used a matched asymptotic expansion to investigate the mass transport rates in a two-layered viscous system. Piedra-Cueva [10] provided an analytical solution for the mud mass transport in a closed channel with an unbounded domain. The effects of viscous damping on mud mass transport rates were also considered by some researchers (e.g [11,12].). In these studies, the mud thicknesses were assumed to be large enough so that the fluid domains could be divided into distinct regions of Stokes' boundary layer and inviscid core. Ng [13] presented an analytical perturbation solution for the first and second order (mean) velocities inside the viscous mud and water layers assuming that the mud thickness is in the same order to its Stokes' boundary layer thickness. However, different viscous and rheological models have been adopted by other researchers to study various aspects of mud mass transport under surface waves (e.g [10,14,15].). Ng and Zhang [15] presented a theory for the mud mass transport, induced by a small amplitude progressive wave propagating in water over a thin layer of Voigt viscoelastic mud. They found that the near bed mass transport rate has non-trivial dependence on the mud thickness.

There have been some efforts to measure the mud mass transport rates through experimental tests (e.g [6,16,12,17].). As common methods of measuring fluid particle velocities (e.g. ADV, laser Doppler, and PIV) cannot be employed in a relatively dense fluid mud layer, all of these researchers used the inaccurate method of using colored mud, as a tracer, in the mud layer. The details of this method can be found in Sakakiyama and Bijker [6]. Mud tracer provides a vertical distribution of displaced mud, which represents mean particle velocities, the averaged particle velocities over the wave period, considering the duration of wave action. However, the selection of proper duration of wave generation is crucial in this method. The short duration cannot be adopted since the effects of inertial force and thixotropy become large. For the longer duration, on the other hand, the circulation of the mud occurs. Regardless of the difficulties of taking the mud samples out of the mud section, this procedure only results to an estimation of mean, not the instantaneous, particle velocities.

Recently, Hsu et al. [18] investigated the wave attenuation and particle velocities in the mud layer through both laboratory experiments on kaolinite and numerical modeling. Using one Electromagnetic Current Meter (ECM, ACM2-RS), horizontal and vertical velocities at preselected locations were measured. A wave gauge, located some distances away from the ECM, was used to record the simultaneous free-surface elevation and synchronization technique was employed to reconstruct the time-dependent particle velocities at different elevations although the reported phase lags (see Fig. 5b of [18]) reveal the existing error of using the this technique.

There have also been some efforts to formulate the combined effects of wave-current-mud interactions. Wave-current interaction is a phenomenon of considerable practical interest in coastal and ocean dynamics. It is well known that a strong current influences a wave field in several ways, such as frequency shift and amplitude changes, and it plays a significant role in the development of the waves of unusual character. A current can also refract waves, change the direction of wave propagation and consequently affect the nearshore hydrodynamics. An and Shibayama [16] conducted some laboratory wave flume experiments to observe wave-mud interaction with current. Both wave height attenuation rates and vertical distributions of mean velocities were measured. The effect of current was simulated by changing the wave characteristics, using the conservation equation of wave action, to be applied on fluid mud layer. Their numerical modeling and laboratory experiments revealed that both the wave attenuation rate and mud mass transport, integrated mean particle velocities over the mud thickness, decrease in the following current and increase when an opposing current is applied.

Introducing a following current to the wave flume, Nakano [19] performed laboratory experiments to measure wave height attenuation on a horizontal mud bed. An extended multi-layered fluid system was employed to model the wave-current-mud interaction. The effect of current on wave-mud interaction has also been included in a few other studies [12,20]. Samsami et al. [8] investigated the dissipation of irregular waves passing over muddy beds through series of wave flume laboratory experiments with and without currents. The changes in spectral characteristics of waves along the muddy bed were also investigated. Except the studies conducted by Zhao et al. [12], the other analytical studies did not directly include the current field into the governing equations. They assumed that the current field is developed in the lower layer of the soft fluid mud and a mean shear flow is formed in the fluid mud. Additionally, rheology of viscoelastic material was adopted for fluid mud behavior, which is questionable in modeling of the steady non-harmonic motion of mud mass transport [16].

The present study offers a comprehensive laboratory experiments and a semi-analytical wave-mud-current interaction model to study wave transformation and mud mass transport with the presence of following and opposing currents. The current field is directly included in the system of governing equations and the two-layered system of fluid mud and water layer is solved. Using commercial kaolinite as the mud bed, the complicated behavior of wave and current over fluid mud is examined through series of wave flume laboratory experiments with different wave characteristics and current velocities. In addition to the damping of wave energy, the instantaneous particle velocities were also measured to define the time-dependent velocity profiles in the fluid mud layer and the resultant mud mass transport under the concurrent actions of wave and current. Four wave gauges at free surface and five Electromagnetic current meters (ECM VM-801 H) inside the mud layer and the overlying water layer were employed. The current meters were installed in a vertical line to measure the vertical profile of particle velocities. The outputs of the developed analytical model were compared with the results of the present laboratory experiments.

2. Laboratory experiments

2.1. Experimental setup

The experiments were conducted in the wave flume of the Coastal Engineering Laboratory of the Department of Civil and Environmental Engineering at Waseda University, Japan (Fig. 1). It is equipped with a flap-type wave maker and two glass sidewalls. False beds were constructed at the wave flume, creating a trench to hold the fluid mud. A mixture of kaolinite and tap water was used as the fluid mud layer. Considering the depth of wave flume, the mud thickness of 11 cm was selected for all test runs. This thickness is large enough to place three ECM sensors within the mud layer.

The conducted pretests showed that the fluid mud layer hardly moves when the water content ratio is lower than 100%. An intended water content ratio of 160% was selected for all test cases, based on the rheological tests on the same kaolinite and past experiences of wave-flume experiments [21]. The flume was then slowly filled with tap water, up to the total depth of 0.41 m, in order to avoid disturbing the mud layer. Before and after the test runs, the water content ratios of the mud layer at three different locations were sampled. Following and opposing currents are regulated by two valves at the flume bed and the flap-type wave maker generates the wave. The current is driven at the beginning of the tests and the wave is generated when the current meters record a steady current velocity.