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A LABORATORY STUDY ON MUD TRANSPORT INDUCED BY SOLITARY WAVE

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ABSTRACT

Wave attenuation on a soft mud layer and velocity field in water and mud layers are investigated through series of wave-flume laboratory experiments. The dissipation of nonlinear solitary waves along a mud section of commercial kaolinite and the mud mass transport in fluid mud layer are measured. Electromagnetic Current Meters are employed to measure the particle velocities in both water layer and fluid mud layer. The study offers a comprehensive data set of wave transformation on the soft mud layer and particle velocities in fluid mud, as two of the major phenomena of wave-mud interaction. The results show that there is a clear phase shift between the particle velocities in water layer and the corresponding velocities in mud layer. Negative velocities were also observed, which might be attributed to the return flow due to mud surface slope.

KEYWORDS: Solitary wave, Wave-mud interaction, Particle velocities, Wave steepness

1 INTRODUCTION

It is well known that water surface waves and muddy bed interact and affect each other. While wave dissipation is enhanced by the acts of a soft mud layer, the fluid mud can be transported under the wave action, called mass transport. Both effects are of practical importance, and the problem of interaction between water waves and muddy bed has long been drawing attention.

Despite the various conducted researches in past decades (e.g. Sakakiyama and Bijker, 1989; Huang and Chen, 2009), the mud mass transport under the wave action is still a challenging phenomenon and more comprehensive studies are needed to reveal the complex movement of fluid mud. During recent years, several theoretical models have been presented to investigate the solitary wave-mud interaction on both phenomena of the wave energy dissipation and mud mass transport. For example, Liu (1973) and Liu, Park & Lara (2007b) examined the effects of wave-induced percolation in seabed with coarse sediments. Other models consider the seabed with finer sediments as elastic (e.g. Foda 1989; Wen & Liu 1995), poro-elastic (e.g. Yamamoto et al.1978), viscous (e.g. Gade 1958; Dalrymple & Liu 1978; Liu & Chan 2007) or visco-elastic (e.g. MacPherson 1980) materials. Huang and Chen (2009) modeled the wave attenuation and mass transport of a water-mud system under a solitary wave on the free surface by using the Chebyshev-Chebyshev collocation spectral method for spatial discretization and a fourth-order multistage scheme for time integration. Chan and Liu (2008) investigated the dynamics and responses of muddy-seabed motions induced by a surface solitary wave where the bed was characterized as Bingham-plastic mud. A semi-analytical approach was developed to analyze the motions inside the mud bed under the surface solitary wave loading. Soltanpour et al. (1999) simulated the various features of wave-mud interaction on fine-grained shore profiles including wave height attenuation, wave-induced mud mass transport, and gravity-driven flow of fluid mud and the reconfiguration of profile shape. A two-dimensional mud beach deformation model was presented considering the transport of fluid mud under continued wave action and downward gravity force.

In parallel with the theoretical development, efforts have also been made to perform laboratory experiments to validate and extend the analytical and numerical models. The analytical solutions of Liu & Orfila's (2004) for the boundary-layer flows under a transient long water wave, including the solitary wave, have been validated by a set of particle image velocimetry (PIV) experiments (Liu, Park & Cowen 2007a). Liu et al. (2006) studied the characteristics of the laminar bottom boundary layer under a solitary wave and the theoretical results were compared with their conducted laboratory experiments. The theoretical framework was based on perturbation analysis of Liu and Orfila (2004). They extended the boundary layer solution from linear to fully nonlinear that only possible to be solved numerically. Measuring the time history of velocity profiles in the bottom boundary layer, they also presented a set of PIV based laboratory data. Using the perturbation approach of Liu & Orfila (2004), Liu and Chan (2007) derived a set of Boussinesq-type equations for transient long waves with the effects of a viscous muddy seabed. In their derivation, three major assumptions were made: (i) the mud bed is characterized as a viscous fluid and its viscosity is several orders-of-magnitude higher than that of the water; (ii) the thickness of the mud bed is much less than the characteristic wavelength; and (iii) the displacement of the water–mud interface are negligible. Park et al. (2008) presented laboratory data for the solitary wave-induced flows in a viscous muddy bed and validated the results by theory of Liu and Chan (2007). They compared the analytical solutions of Liu and Chan (2007) with the conducted laboratory results of PIV experiments. Hsu et al. (2013) investigated the wave attenuation over a kaolinite layer through both laboratory experiments and numerical modeling. The measured time-dependent velocity profiles in the fluid mud revealed that the shear rate under wave loading is highly phase dependent.

In order to evaluate the complicated aspects of solitary wave over a soft layer of fluid mud, series of wave flume laboratory experiments of wave-mud interaction with different wave characteristics were conducted in this study, using commercial kaolinite with a homogeneous concentration distribution as the mud bed. In addition to the wave energy damping, the instantaneous particle velocities were also measured to define the time-dependent velocity profiles in the fluid mud layer and the resultant mass transport under the solitary wave action.

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 piston-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 with the thickness of 0.11 m. The flume was then slowly filled with tap water, up to the total depth of 0.34 m, in order to avoid disturbing the mud layer.

The velocity field in the mud layer should be carefully determined for better understanding of complex interaction of fluid mud layer and overlaying water wave. Measuring the time-dependent velocity profiles in highly turbid water, with an concentration of O(100) g/L, requires special devices as optical instruments are probably not applicable here. The accurate measuring device of Electromagnetic Current Meter (ECM, ACM2-RS), which has been proved to be applicable in both the clear water and highly concentrated fluid mud (400 kg/m^3), was adopted for this research. ECMs were fixed at the preselected locations ($z = 0.02$, 0.05, 0.085, 0.12, and 0.15 m above the bed), where the first three sensors were used to capture the particle velocities in the fluid mud layer, and the latter two were installed in the water layer to measure the particle velocities near water-mud interface and above that level (Fig. 2).

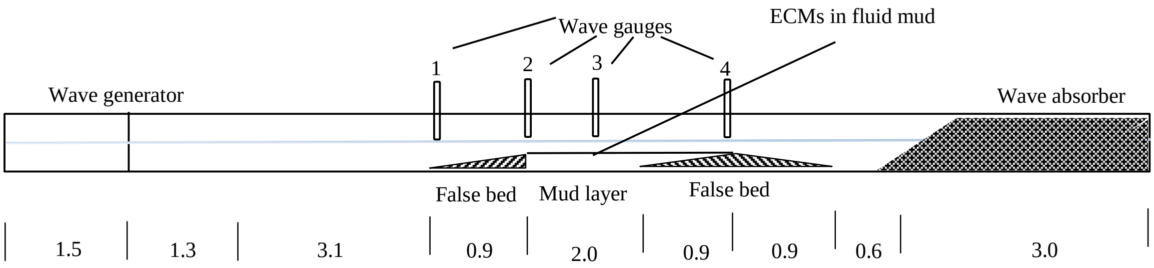


Fig. 1 Sketch of the wave flume experimental setup (dimensions in m)

Fig 2. (a) A side view of the measuring devices and mud layer dimensions (b) A view of the setup of ECMs at the wave flume (c) Mud section

Different wave characteristics were considered to examine the wave effects on time series of particle velocities in both layers of water and fluid mud. In order to capture the wave evolution over the mudddy bed, four wave gauges were applied along the wave flume (Fig. 1). Table 1 presents the experimental conditions of applying solitary waves and water content ratios of fluid mud. The ratios of wave heights to water depths (*H/h*), as a representative of the nonlinearity of the wave, are also presented.

Table 1. Summary of test conditions

Case	*H* (cm)	*h* (cm)	*d* (cm)	*H/h*	Water content ratio (%)
1a	1.5	24	11	0.0625	135
1b	1.5	24	11	0.0625	135
1c	1.5	24	11	0.0625	135
1d	1.5	24	11	0.0625	135
2a	2.5	24	11	0.1	135
2b	2.5	24	11	0.1	135
2c	2.5	24	11	0.1	135
2d	2.5	24	11	0.1	135
3a	3.5	24	11	0.145	135
3b	3.5	24	11	0.145	135
3c	3.5	24	11	0.145	135
3d	3.5	24	11	0.145	135
4a	6	24	11	0.25	135
4b	6	24	11	0.25	135
4c	6	24	11	0.25	135
4d	6	24	11	0.25	135
5a	7	24	11	0.292	135
5b	7	24	11	0.292	135
5c	7	24	11	0.292	135
5d	7	24	11	0.292	135
1aa	2.5	24	11	0.1	150
1bb	2.5	24	11	0.1	150
1cc	2.5	24	11	0.1	150
1dd	2.5	24	11	0.1	150
2aa	8	24	11	0.33	150
2bb	8	24	11	0.33	150
2cc	8	24	11	0.33	150
3aa	9	24	11	0.375	150
3cc	9	24	11	0.375	150
4bb	5	24	11	0.208	150

3 RESULTS AND DISCUSSION

The conducted laboratory tests on wave energy dissipation over mud bed and the instantaneous velocities in fluid mud layer provide a comprehensive data set to study the complex responses of nonlinear solitary wave-mud interaction.

3.1 Water particle velocities

Figure 3 shows three test cases of time series of particle velocities in water layer at two different vertical positions. It is observed that the measured velocities follow the free water surface of solitary waves. A smaller trough is observed in front of the crest of the main wave, which might be generated due to the nonlinearity of the wave (high values of *H*/*h*) and wave steepness. Similar responses are observed in water particle velocities.

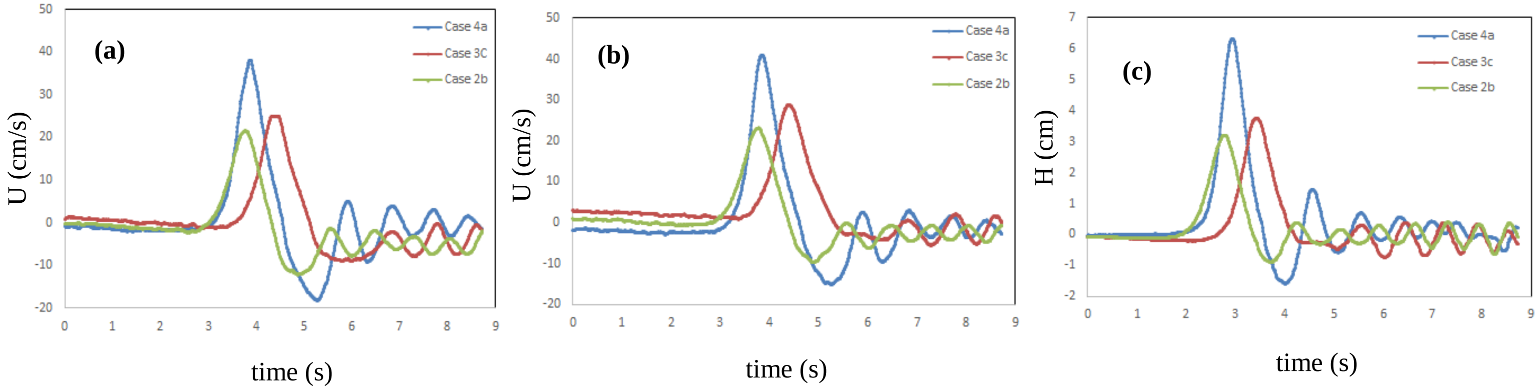


Fig 3. Time series of particle velocities in water layer at *z*=12.4 cm (a), *z*=13.6 cm (b) and free water surfaces (gauge 4), (c) for three test cases, 4a, 3c,and 2b

3.2 Velocity field in the mud layer

Figure 4 provides examples of time series of particle velocities in mud layer at three vertical positions of *z*=0.02 m, 0.05 m and 0.085 m above the fixed bottom. It is observed that the measured velocities follow the free water surface of applying solitary waves. However, a time shift is also observed between the measured velocities in fluid mud layer in comparison to the water layer.

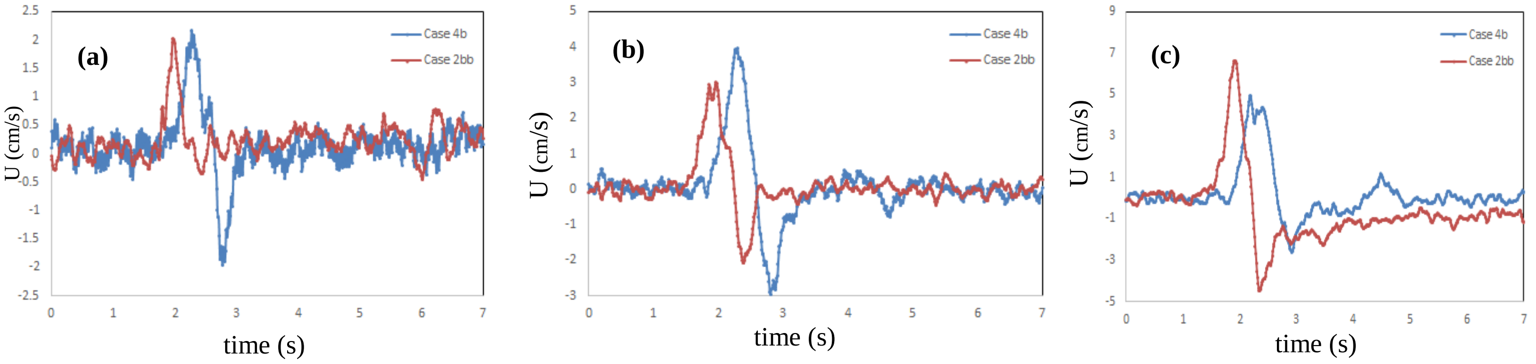


Fig 4. Time series of velocities in mud layer at *z*=0.02 cm (a), *z*=0.05 cm (b) *z*=0.085 cm (c) for two different cases, case 4b and case 2bb

Figure 5 present the measured velocity profiles in mud layer (cases 4b, 3d) at different phases, including the peak. As it is observed, the velocity profile gets negative values after passing the main positive velocity phase. This is due to negative secondly waves generated by the movement of wave generator after the main positive solitary wave. Also reflection of waves from the end of the flume gave influences. Going deeper in the mud layer, the greater gets the negative values of the mud particle velocity. This may be due to gravitational forces induced by the mud layer slope, which is created by the mud mass transport.

The negative values due to the secondary part of the solitary wave are much greater in the mud layer in comparison to the overlying water layer. This may be because of the limited length of mud section, which results to the induced gravitational forces by the generated mud slope at water-mud interface.

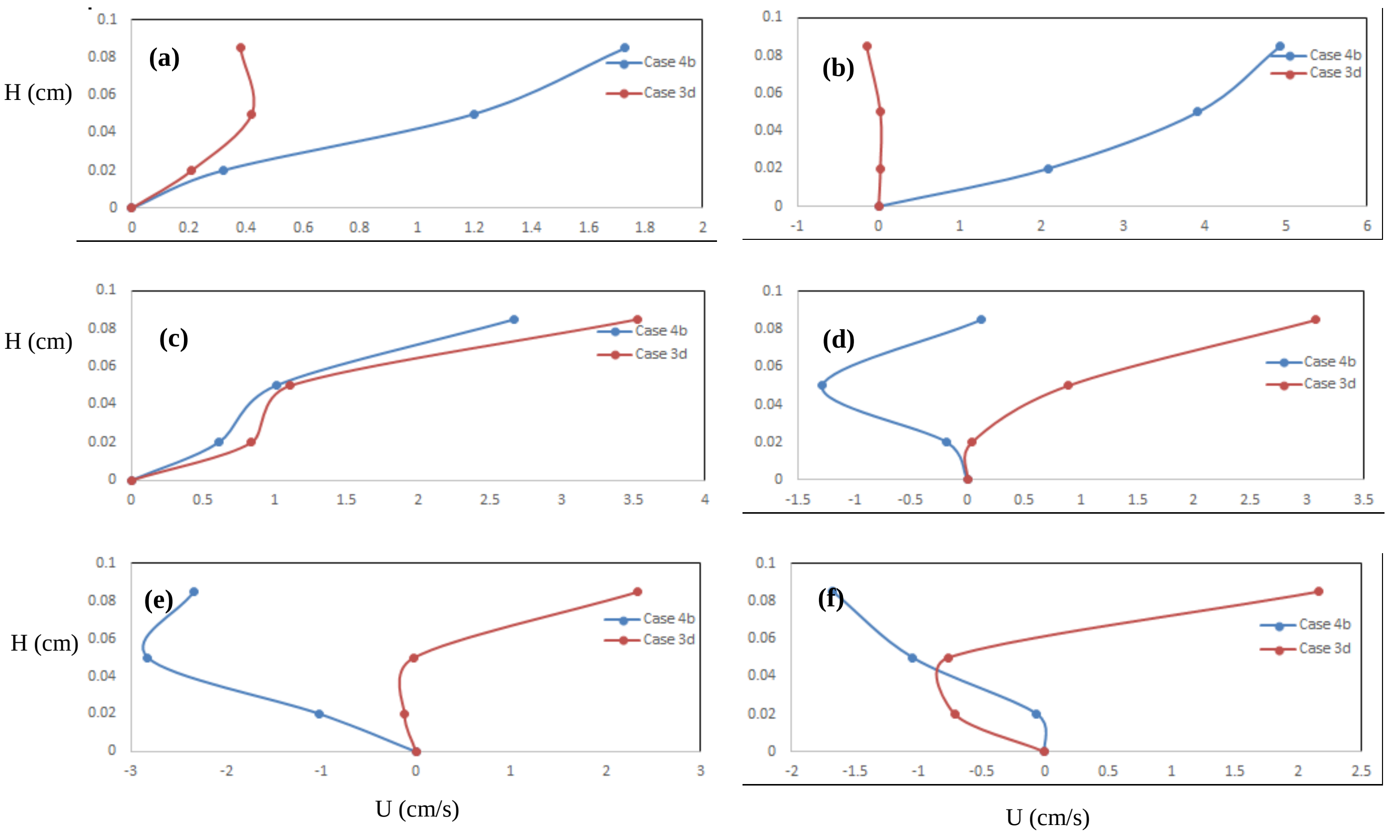
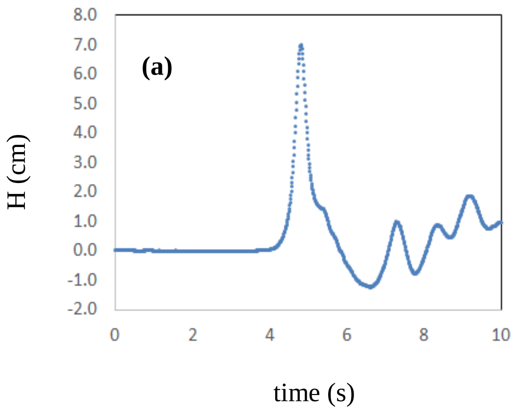


Fig 5. Velocity profiles in mud layer (cases 4b and 3d), at different times (*t*=2, 2.31, 2.53, 2.65, 2.69, 2.87, and 3 s), (a-f)

The different values observed through the velocity particles provided by figure 5, is due to a time shift which occurs between the measured velocities in the mud layer in comparison to the water particle velocities. Figure 6 presents an example of the time shift of the velocity time series in mud layer, compared to the overlying water layer (case 4a). The measured time shifts were presented in Table 2. Also, the free surface evolution is presented by figure 6, which the water particle velocity follows.



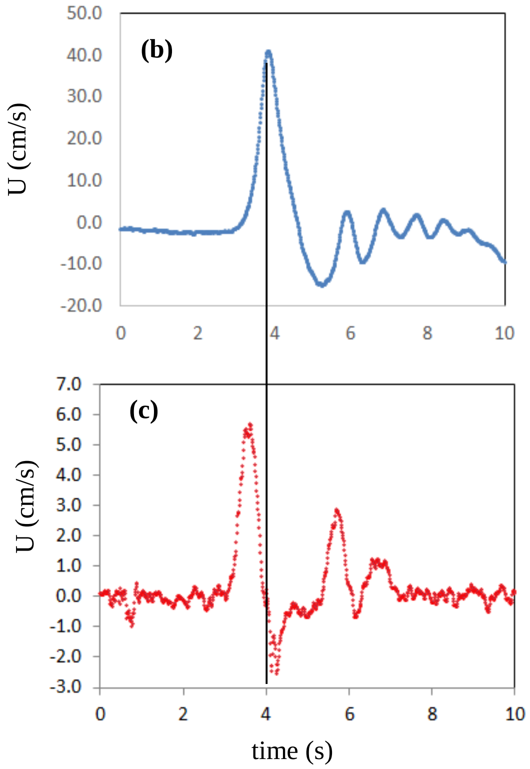


Fig 6. An example of time shifts between water surface elevation (a), velocities in water layer (b), and mud layer (c) (case 4a)

Table 2. Measured time shifts between velocities in water layer and mud layer

Case	Time shift (s)
4a	0.16
4b	0.32
4c	0.44
4d	0.38
3a	0.31
3b	0.23
3c	0.20
3d	0.35
2b	0.27
2d	0.38
5a	0.13
5c	0.27

3.3 Wave dissipation

Using the measured water surface at gauges 2 and 3 (Fig. 1), figure 7 shows an example of wave dissipation on mud section. Table 3 offers the measured incident and attenuated wave heights and the corresponding attenuation rates of different test cases.

$$Attenuation\ rate = \frac{Incident\ wave\ height - attenuated\ wave\ height}{Incident\ wave\ height} (\%) \tag{1}$$

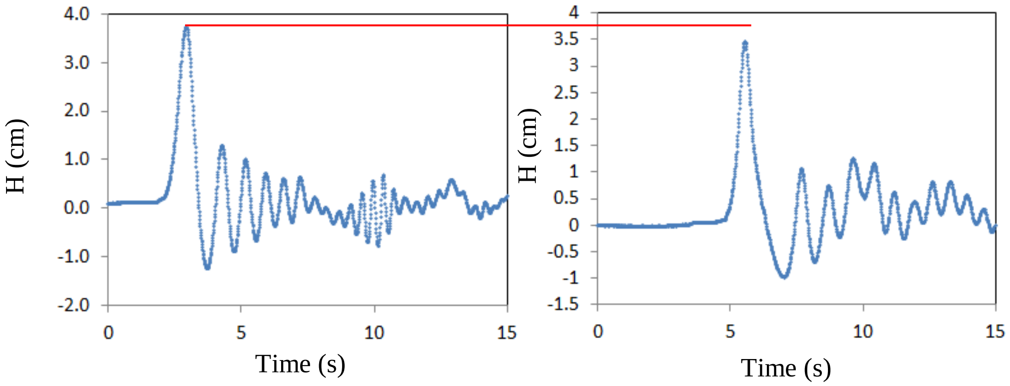


Fig 7. An example of incident wave (gauge 2) and attenuated wave (gauge 3) on mud layer (case 2a).

Table 3. Wave attenuation rates of test cases

case	Incident wave	Attenuated wave	Attenuation rate (%)
2a	3.72	3.46	6.9
1a	2.55	2.36	7.45
1b	2.33	2.18	6.43
1aa	4.04	3.3	18.3
1bb	3.54	3.09	12.7
1cc	3.46	2.96	14.4
1dd	3.27	2.74	16.2

4 Summary and Conclusion

The concurrent measurements of surface wave damping and particle velocities in the water and mud layers were provided to study the responses of mud under various solitary wave loadings, as well as the resulting wave dissipation. An experimental investigation of the wave transformation and the induced fluid particle motions in a mud layer and the overlying water layer is provided. It was observed that the attenuation rates slightly increase by the increase of overlaying wave heights. Experimental analyses of the flow in the fluid mud bed, which is driven by the pressure gradient induced of the solitary wave, were also discussed. A considerable falling down of water surface level is observed in measurements, which are followed by the time series of particle velocities in both water and mud layers. The negative values of the particle velocities in mud layer are larger, in comparisons to the water layer velocities that might be resulted due to the induced gravitational forces by the mud slope at water-mud interface.

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