An Experimental Study on Surface Wave Modulation Due to Viscoelastic Bottom

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Abstract In the present study, we developed viscoelastic bottom layers of required rheological properties in the laboratory using a mixture of a polymer, polydimethylsiloxane with glycerol. The properties of the viscoelastic layers were quantified using oscillatory shear tests in a rheometer. Wave flume experiments with different viscoelastic bottom layers were then conducted under shallow water conditions. The synchronized time series data at seven locations along the direction of wave propagation were obtained using ultrasound sensors, which were used to determine the attenuation rate due to the presence of the bottom boundary. The results of the analysis showed that the attenuation rate of waves change with the variation of rheological property of bottom boundary, with the softer bottom attenuating the waves more significantly.

Keywords Viscoelastic bottom · Attenuation · Shallow water

1 Introduction

Increasing surface temperature and sea-level rise associated with global warming can reshape the shorelines around the globe by altering the climate-driven wave parameters including the wave height, wave period and wave direction [1]. A large portion of the muddy Indian coastline which is devoid of vegetation [2] can be

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susceptible to the changes in the direct wave action. This demands the need for a better understanding of the interaction of surface waves with the erodible seabed, including the muddy bottom.

Several theories have been developed with various approximations made for the soft mud bottom. A two-layer viscous model with inviscid water above viscid bottom mud layer was developed by Gade [3] for shallow water conditions. This two-layer viscous model was subsequently modified for shallow and intermediate waters by Dalrymple and Liu [4], with the verification effort using kerosene over sugar solution [3]. The elastic model for mud by Mallard and Dalrymple [5] assumed mud as an infinitely deep elastic bottom layer underlying water of finite depth. This model was later improved by Dawson [6] with the inclusion of soil inertia for bottom layer. Recent work on the wave interaction with a bottom elastic plate was performed by Mohapatra and Sahoo [7], assuming the bottom layer as thin Euler Bernoulli beam. Muds with high sediment concentrations exhibit both viscous and elastic properties [8], and the energy dissipation thus needs to be included in coastal wave modelling. A generalized viscoelastic model [9–11] was subsequently proposed, which considered both properties.

The linear viscoelastic model includes Voigt model and Maxwell model. The material testing of Kaolinite and mud in the laboratory by Maa [8] showed that Voigt model was suitable for soft mud. However, a substantial error was evident between the inversely calculated rheological properties from the experimental results and actual rheometric measurements by Soltanpour and Samsami [12] for multilayered viscoelastic models. The discrepancy drives the need for more detailed experimental studies for the verification of theoretical models and to identify possible missing factors. In other words, laboratory experiments need to be performed under controlled environment with similar viscoelastic conditions as in the theory. To the authors' knowledge, wave interaction experiments with a real homogeneous viscoelastic bottom have not been done so far. In this paper, we will describe a laboratory study using a precisely controlled real viscoelastic bottom to quantify its influence on the modification of surface waves. The objective is to obtain measurement to verify the related theories in the future. Noted that the scaling of the laboratory parameters with respect to specific field conditions is not considered.

2 Material Preparation and Experimental Setup

The 2.0 m long viscoelastic bottom boundary above the raised platform was made of glycerol-doped Polydimethylsiloxane (PDMS). PDMS was commercially available as Sylgard 184 Silicone Elastomer kit, consisted of a silicone oil base and curing agent/crosslinker. The specific gravity for PDMS was 1.02. Glycerol was added to increase the specific gravity of the bottom layer. The preparation procedures included the mixing of the three components (base, curing agent and glycerol) in required proportions, followed by degassing and curing. The fraction of glycerol added was

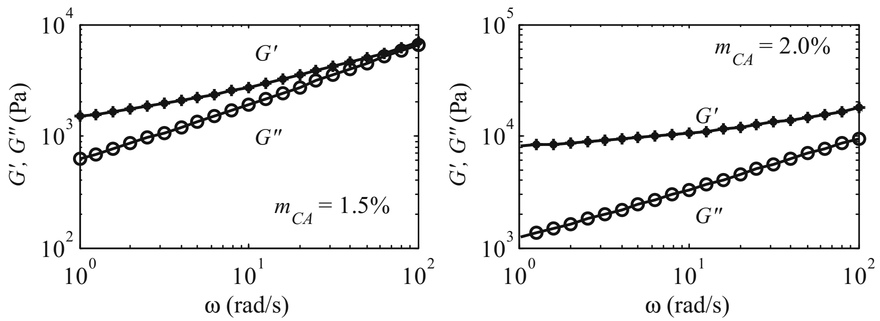

Fig. 1 Variation of viscoelastic properties with rotational frequency

calculated as $m_g(\%) = \frac{M_g}{M_g+M_b+M_{CA}} \times 100$, where M_g is the mass of glycerol, M_b is the mass of base and M_{CA} is the mass of curing agent. Similarly, the percentage of curing agent was calculated as, $m_{CA}(\%) = \frac{M_{CA}}{M_b+M_{CA}} \times 100$. For the present study, $m_g = 10\%$ while two fractions of curing agent were used ($m_{CA} = 1.5$ and 2.0%) to alter the properties of the bottom layer. The curing period for $m_{CA} = 1.5\%$ was 32 days and that for $m_{CA} = 2.0$ was 18 days, which was determined using rheological tests.

The rheological properties of the viscoelastic bottom were determined using small amplitude oscillatory shear tests in a rheometer (Anton Paar, MCR 302, Germany). Rheometry testing included two parts: (a) determination of linear viscoelastic regime (LVR) using frequency sweep analysis and (b) measurement of dynamic modulus of the material for the required frequency range within LVR. The dynamic modulus comprises of storage modulus (G') and loss modulus (G''), which represents the elasticity and viscosity of the material, respectively. Figure 1 shows the variation of G' and G'' with rotational frequency of rheometer (ω). Three samples were tested for each m_{CA} to check the repeatability. The stability of the material property was ensured by conducting the tests within two weeks after the curing period.

The G' and G'' values were obtained by equating the wave frequency (σ) to the rotational frequency of rheometer. Within the required range of frequency, G' was always greater than G'', with the dependence of G' on ω lesser compared to G''. Both G' and G'' increased with m_{CA}, and the rate of increase of G' was relatively larger than G''. The ratio G''/G' decreased with increase in m_{CA}.

The laboratory experiments were conducted in a wave flume (8.0 m long and 0.3 m wide), equipped with a piston-type wave generator, at the Environmental Process Modelling Centre (EPMC) Laboratory of Nanyang Environment and Water Resources Institute (NEWRI), Singapore. The wave flume was made of tempered transparent glass panels and was filled with fresh water up to a height, $d = 26.5 \times 10^{-2}$ m. The inclined mesh type beach (slope 1.0V:1.25H) was provided to dissipate the reflected wave energy.

The shallow water region was created with a raised platform, consisted of 2.0 m long horizontal section with slopes at both ends (see Fig. 2). The slope near the leading edge was 1.0V:1.8H whereas that near the trailing edge was 1.0V:1.0H. The

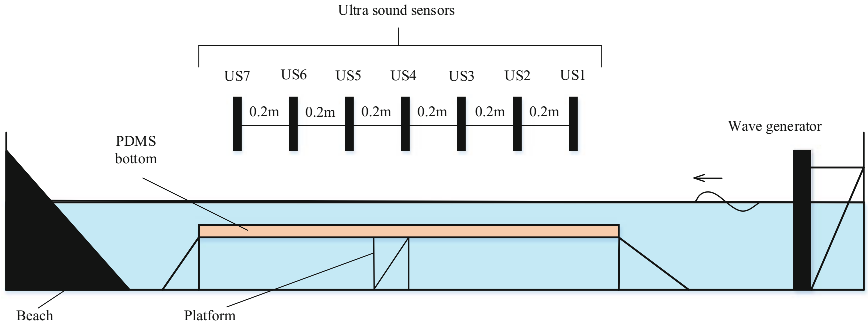

Fig. 2 Schematic diagram of experimental setup

Table 1 Test conditions and attenuation coefficients

T (s)	$k_o a$	α (rad/m)		
		m_{CA} (%)		Rigid bottom
		1.5	2.0	
0.6	0.08	0.28 ± 0.16	0.20 ± 0.13	0.14 ± 0.03
0.8	0.11	0.47 ± 0.22	0.37 ± 0.19	0.23 ± 0.06
1.0	0.11	0.39 ± 0.20	0.31 ± 0.18	0.19 ± 0.08

slopes enabled the gradual change of water depth from 26.5×10^{-2} to 8.0×10^{-2} m above the horizontal section of the platform. The 2.0 cm thick viscoelastic layer was laid over the horizontal section which then reduced the water depth to 6.0×10^{-2} m.

In the present study, regular monochromatic waves were generated. The test conditions are provided in Table 1. The surface wave displacement along the platform was determined using seven ultrasound sensors (US 325, General Acoustics), statically calibrated with different water depths. The synchronized surface displacement data from the ultrasound sensors were obtained using a data acquisition system (NI 9215), and the digitized data was collected using LABVIEW. The first sensor US1 was positioned at 0.2 m from the leading edge of the viscoelastic bottom. All other sensors were kept at 0.2 m interval as shown in Fig. 2. The position of the sensors, except US1, were shifted by 0.1 m once all the experiments with the initial position were done. Thus, for each test condition, displacement data at 13 locations were obtained.

3 Data Analysis and Discussion

The sampling rate of the ultrasound sensors was 50 Hz. It was increased to 200 Hz using the *PCHIP* function in MATLAB. Only the first three fully developed waves were considered in the analysis so that the results were free from beach refection. The

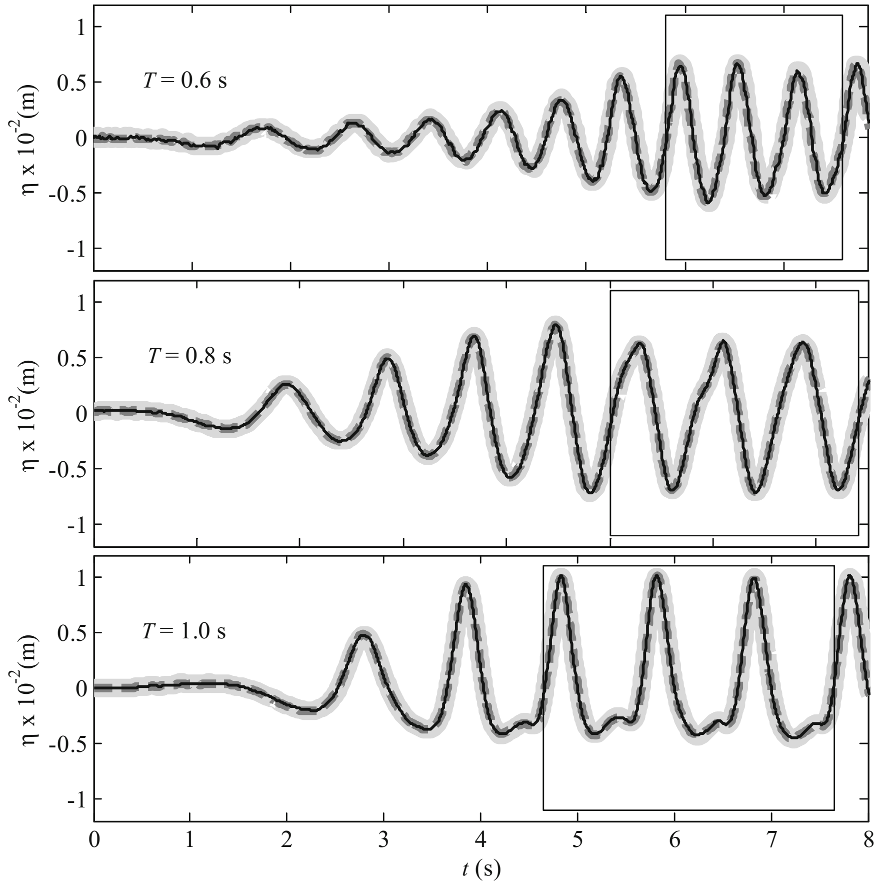

Fig. 3 Surface wave displacement (US4) for different wave periods, for $m_{CA} = 1.5\%$. The three fully developed waves considered are enclosed in the rectangle box, the repeatability of test was confirmed using three experiments of the same test conditions (light grey solid line, dark grey dashed line and black solid line)

repeatability of the wave experiments was verified by conducting each experiment three times, see Fig. 3.

Figure 4 shows the spectral analysis of the surface water displacement at different locations along the shallow water region with viscoelastic boundary. It is clearly visible that with an increase in wave period, a second peak corresponding to twice the input frequency to the wave generator ($\sigma = 2\pi/T$) became significant. The surface profile for $T = 0.6$ s was linear; with an increase in wave periods, the non-linearity became obvious (Fig. 3). For constant T, the height of the dominant peak increased from $m_{CA} = 1.5$ to 2% and then further increased for the rigid bottom case. For each constant T and fixed boundary condition, the wave height decreased along the distance of sensors from the leading edge of the viscoelastic bottom.

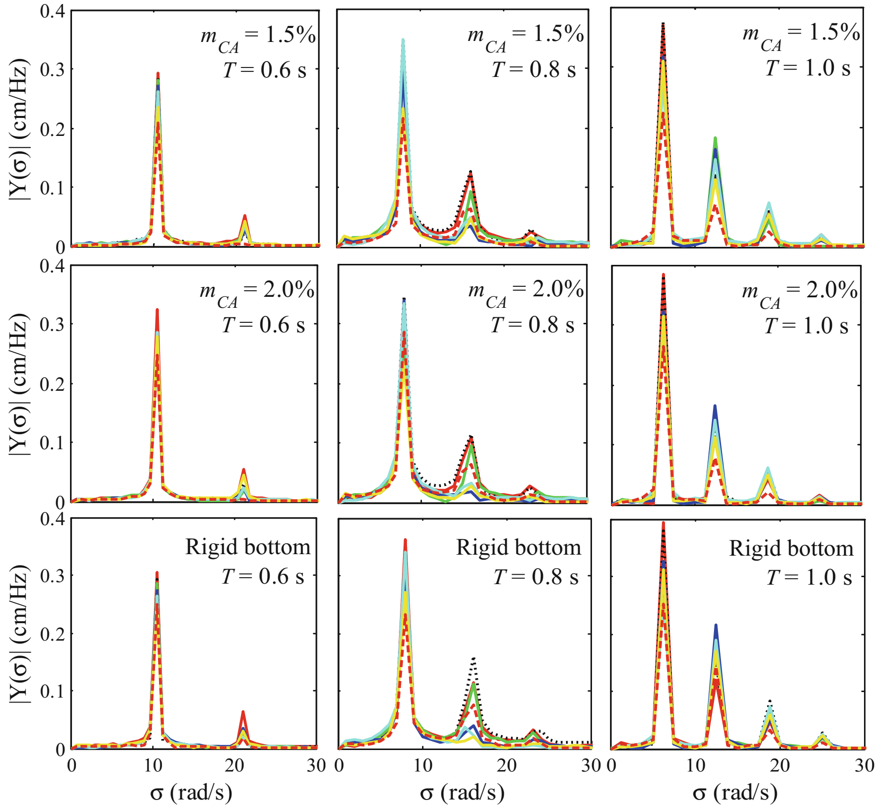

Fig. 4 Spectral analysis of the surface water displacement. The different colours indicate the different sensor positions; **a** red = 0.2 m, **b** black = 0.4 m, **c** green = 0.6 m, **d** blue = 0.8 m, **e** cyan = 1.0 m, **f** yellow = 1.2 m, and **c** dashed red = 1.4 m

The *findpeaks* function in MATLAB was used to identify the value of peaks from the surface displacement data. The attenuation of waves along the viscoelastic bottom was calculated by fitting the variation of wave height with an exponential curve as shown in Fig. 5. The exponential fitting equation is given by $H_x = H_o e^{-\alpha x}$, where H_x is the wave height at x distance from the leading edge, α is the attenuation coefficient and H_o is the wave height at $x = 0$. The attenuation coefficients obtained for the different cases are included in Table 1, which shows that the bottom boundary properties significantly influenced the decay of wave height. For all the wave periods considered, the cases with $m_{CA} = 1.5\%$ showed notably higher attenuation compared to $m_{CA} = 2\%$ and lower for the rigid bottom. The maximum wave attenuation was for $T = 0.8$ s and minimum for $T = 0.6$ s. The viscoelastic bottom thus led to the attenuation of wave height for shallow water cases, like soft mud [13].

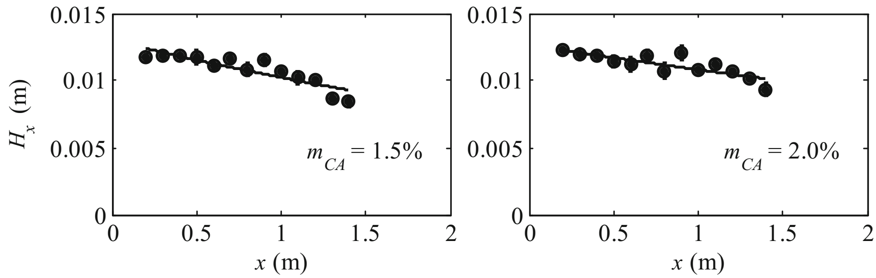

Fig. 5 Variation of wave height along the length of viscoelastic bottom ($T = 0.6$ s)

4 Conclusions

An experimental study was conducted to analyze the attenuation of surface waves due to the presence of the viscoelastic bottom under shallow water conditions. A novel method was developed to prepare a viscoelastic bottom layer in the laboratory using a polymer, Polydimethylsiloxane doped with glycerol. The wave experiments showed that the non-linear effects increased with wave period. The material property of the viscoelastic bottom G''/G' was found to be directly proportional to attenuation rate for a particular wave period.

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