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Effect of Clay Content on the Sediment Suspension Over Liquefied Sand-Clay Mixed Bed Under Waves

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Abstract: In this study, a series of laboratory experiments on the response of sand-clay seabed under progressive waves were carried out to investigate the process of sediment suspension over a liquefied seabed. The sand-clay beds with various clay content (CC) ranging from 0 to 15% were tested for a specific wave condition. The excess pore water pressure (EPP), suspended sediment concentration (SSC) and elevation of mixed beds were recorded for each test. The experimental results indicated that seabed with a certain amount CC was easier to liquefy compared with pure sandy bed. The SSC of liquefied sand-clay bed is bigger than that of non-liquefied mixed bed. The SSC above sand-clay bed is smaller than that of sandy bed, but the erosion depth of mixed bed is bigger than that of sandy bed.

Keywords: sediment suspension; clay content; erosion; pore water pressure; cohesion; waves

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1. Introduction

Ocean waves play a crucial role in sediment transformation. Sediment particles on the seabed surface would be suspended by wave actions. Mehta and Lee studied the threshold condition of cohesionless and cohesive sediment incipient motion [1]. They pointed out that grains on bed surface were moved by shear and normal forces. The hydrodynamic forces include the lifting force, the drag force and buoyant weight were considered in cohesionless sediment and the cohesive force should be added in cohesive sediment. Also, fine particles within bed would be disengaged from seabed skeleton by cyclic loadings, and then transported upward to the water by seepage flows when excess pore water pressure (EPP) was accumulated enough (would cause seabed liquefaction). Tzang et al. executed a series of flume experiments with monochromatic waves to investigate the relationship between sediment suspension and liquefaction of sandy bed [2]. The observed suspended sediment concentration (SSC) was relatively significant above a liquefied bed compared with those above non-liquefied bed. Obvious development of SSC usually occurred after the bed was liquefied to its deepest depth. The variation of SSC was closely related to the accumulation and oscillation of EPP. Cheng et al. analyzed the influence of seepage force caused by EPP accumulation on sediment incipient motion through theoretical calculation and flume experiments [3]. It was found that seepage force in low permeability fine sand bed is far greater than the effective gravity. The sediment on seabed surface was suspended when the seepage force was upward. Jia et al. carried out wave flume experiments with silty sediment obtained from the Yellow River Delta to clarify the interaction between seabed liquefaction and sediment re-suspension [4]. It was pointed out that the re-suspension of sand presented two-stage characters. The initial re-suspended sediment increment was caused by bed shear stress and erosion of surface sediment under the wave action. The later re-suspended increment (slowly) was related to the accumulation and oscillation of EPP.

Despite there are many researches on sediment suspension above the sandy or silty bed under wave actions, few studies focus on sand-clay bed. In natural environments, both coasts and estuaries exist mixture which dominated by sands but with various amount of clay. Artificial clay-sand mixtures were also considered in geotechnical and environmental engineering for using as hydraulic barriers [5]. Some researches have indicated that erosion resistance of a bed increases with increasing CC added to sand due to the cohesive effect of the clay in binding the sand matrix together [6,7]. Kamphuis and Hall observed the erosion processes of silty clay by unidirectional current and revealed that the size of particles eroded from the bed decreased with sand content [6]. Mitchener and Torfs described the results related to wave/current-induced erosion of sand-mud mixture based on both laboratory and field measurements [7]. Predictive models for characterizing the erosion behavior of mixed sediments were proposed. It was found that adding sand to mud, or vice versa, increased the erosion resistance and reduced the erosion rates when the critical shear stress for erosion was exceeded. The value for the erosion shear stress of homogeneously mixed beds occurs at a maximum in the region 30 to 50% sand by weight. The most significant effect on erosion resistance occurred when adding small percentage of mud by weight to sand. The mode of erosion also changes from cohesionless to cohesive behavior at low mud contents added to sand, with a transition occurring in the region 3% to 15% mud by weight.

According to the aforementioned studies, the suspended sediment above sand-clay seabed under current and wave actions was investigated. However, no researcher paid attention to the effect of liquefaction on the sediment suspension of sand-clay seabed. Therefore, wave flume experiments were executed by mixing sand with different CC from 0 to 15% in this study. The SSC and corresponding EPP were measured by OBS 3+ sensor and pore water pressure sensor. Experimental phenomena were recorded with 2K camera to analyze the movement of sediment suspension. Elevation of mixed beds at specific time point were counted by the screen shots of experimental video.

2. Methods

2.1. Flume Experiments

This study adopts flume experiments to clarify the variation of sediment suspension over sand-clay bed under waves. The experiments were conducted in a wave flume, 80.0 m long, 0.5 m wide and 1.5 m high, with a trench filled with mixed sand-clay seabed (Figure 1). To figure out the influence of CC on sediment suspension, hydrodynamic conditions were kept same for all tests. The water depth was 0.45 m, the wave height was 0.14 m and the wave period was 1.6 s.

As shown in Figure 1, three wave gauges were set above the seabed to measure the water elevation. The OBS 3+ turbidity sensor (Campbell Scientific, Inc, UT, USA) was set at 0.2 m downstream the front edge of the trench and 0.035 m above the bed surface to record SSC. The pore-water pressure sensor was located 0.23 m below the seabed surface in the middle of the trench to analyze the lifting force caused by EPP. Soil samples used for experiments were made indoor, by mixing natural sand and commercial kaolin with the determined content ratios. Preparation of the sand-clay mixtures and procedures of experiments can refer to Zhang et al. [8].

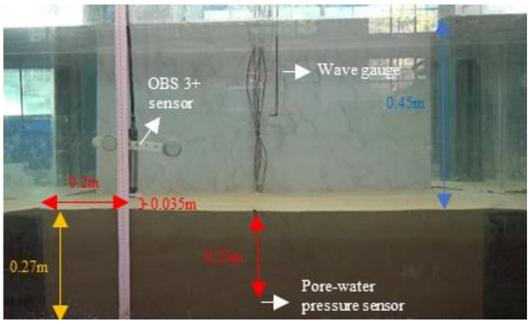

Figure 1. Soil trench at wave flume.

2.2. Calibration of OBS 3+ Sensor

The OBS 3+ sensor is a submersible, turbidity sensor that measure suspended soils and turbidity for assessment of sediment transport. The dry-sediment calibration method was used in this study. For application in different soil samples, the OBS sensor was first calibrated with a set-up utilizing electromagnetic mixer. The calibration was carried out by the following steps. Firstly, 9 L water was added into a bucket. Then, a known quantity of well-mixed dry soil sample (with a determined ratio of sand and clay) was dispersed into the bucket and was suspended in the water by mixer stirring. Meanwhile, OBS signal changes induced by increased SSC were recorded by the connected computer. This process was repeated with known increments of soil sample and the OBS signal were recorded and time-averaged accordingly.

2.3. Parameters of Soil Property

The particle size distribution of sand and clay was obtained by the Mastersizer 3000 laser particle size analyzer. The d_{50} of soils were 0.16 mm (sand) and 0.009 mm (clay). The friction angle of sand (31 degrees, obtained by direct shear test) was used here to calculate the critical mean normal effective stress (σ_0) for judging the liquefaction state of the mixed bed. The σ_0 was calculated by Equation (1), where γ' is the submerged specific weight of mixed bed, z is the distance from bed surface to the sensor, and φ is the friction angle. The detailed calculation was shown in Zhang et al. [8]. The densities of mixed soil samples were 1.83 g/cm^3 (sand), 1.78 g/cm^3 (CC2.4), 1.75 g/cm^3 (CC4.9), 1.74 g/cm^3 (CC7.7), 1.72 g/cm^3 (CC9.9) and 1.69 g/cm^3 (CC14.2) respectively.

$$\sigma_0 = \gamma' z \frac{1+2(1-\sin\varphi)}{3} \tag{1}$$

2.4. Measurement of Seabed Erosion

Seabed surface was not flat in most of experimental time. Ripples were formed on non-liquefied sandy bed under waves. Surface of liquefied clayey bed would oscillate with waves. Only non-liquefied mixed bed remained unchanged. Thus, the seabed elevation at a specific time was obtained by averaging the measured value of marked points from screenshots. For example, the image in Figure 2 is the seabed profile at t = 30 s of CC2.4. The proportion between the picture and the actual situation is obtained through the pink ruler left side. All elevation of red points were measure form the screenshot and converted to the actual value by the proportion. The elevation of CC2.4 at t = 30 s was calculated by averaging actual values of red points. Seabed erosion was studied by the variation of seabed elevation with different time points.

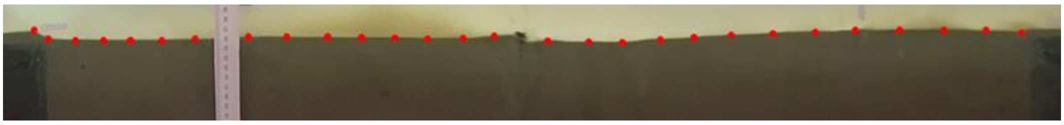

Figure 2. Seabed profile of CC2.4 (t = 30s).

3. Results and Discussion

In order to clarify the relationship between sand-clay seabed liquefaction and sediment suspension, it is necessary to understand the EPP and SSC response of sand-clay bed. Table 1 gives the EPP and SSC response of mixed beds under wave actions, where P_{acc} is the accumulation of EPP. It can be seen that P_{acc} in mixed beds is significantly higher than that in sandy bed, but the SSC of mixed bed is less than that of sandy bed. P_{acc} and SSC of sand-clay beds decreased with the increase of CC. Previous studies indicated that P_{acc} would significantly improve the SSC of liquefied seabed and SSC would develop when the bed was liquefied to its deepest depth [2–4]. Mixed seabeds with 2.4% to 7.7% in this study were liquefied under waves, but the measured SSC were less than non-liquefied sandy bed, as shown in Table 1. Therefore, this section will analyze the causes of experimental phenomena from two aspects: the sediment incipient motion and the seabed erosion.

Table 1. Seabed response under waves.

CC (%)	P_{acc} (kPa)	σ_0 (kPa)	SSC (g/L)
0	0.067	1.226	6.629
2.4	1.705	1.154	5.879
4.9	1.544	1.118	2.651
7.7	1.519	1.096	1.952
9.9	0.928	1.065	1.033
14.2	0.622	1.023	0.32

3.1. Sediment Incipient Motion

Forces on sediment particle of sand-clay bed are shown in Figure 3, where u is the velocity of water particle under waves, D is the diameter of sand particle, F_D is the drag force, F_f is the friction force, F_L is the lifting force, W is the weight of sand particle and F_c is the cohesive strength among particles. The influence of CC on D is ignored in this section. F_D is related to wave elements and water depth which are constant in this study. Therefore, the incipient motion of sediment is related to the vertical forces which determine the F_f. F_v is defined as the resultant force of vertical forces by Equation (2). F_L and W can be calculated by Equations (3) and (4). F_c of sand-clay mixtures with different CC were investigated by Dafalla with direct shear tests [5]. The cohesive stresses were 5.20 kPa, 8.83 kPa and 14.72 kPa corresponding to CC5, CC10 and CC15. According to results of Dafalla, F_v of the sediment particle on mixed seabed with different CC can be calculated and results are shown in Table 2. In order to calculate the F_v, F_L and W are converted into the force on per unit area. It can be seen that particles on the seabed surface with 2.4% and 4.9% CC were easy to suspend to the water, particles on the seabed surface with 9.9% and 14.2% CC were hard to move, and F_v of CC7.7 is similar to that of sandy bed.

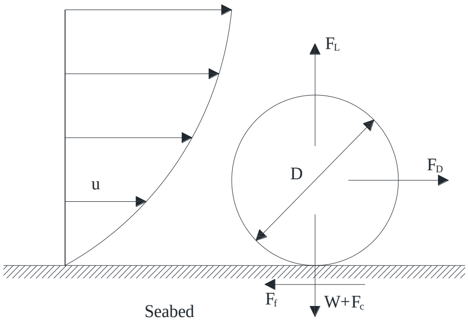

Figure 3. Forces on sediment particle of the sand-clay seabed.

$$F_v = F_L - W - F_c \tag{2}$$

$$F_L = \frac{\pi D^2}{4}\frac{P_{acc}}{z} \tag{3}$$

$$W = \frac{g\pi D^3}{6}\gamma' \tag{4}$$

Table 2. Vertical forces on the sediment particle.

CC (%)	F_L (kPa)	F_c (kPa)	W (kPa)	F_v (kPa)
0	0.29	0	1.91	−1.62
2.4	7.41	2.35	1.86	3.2
4.9	6.71	4.73	1.83	0.15
7.7	6.60	7.11	1.82	−2.33
9.9	4.03	9.49	1.80	−7.26
14.2	2.71	13.58	1.77	−12.64

3.2. Erosion of Mixed Seabed

With the measurement of seabed elevation (like Figure 2), it was found that the elevation of mixed with more than 7.7% CC (non-liquefied mixed bed, such as CC9.9 and CC14.2) kept still as shown in Figure 4. Points with different colors were the elevation of seabed surface at different time points, such as red means t = 70 s, yellow means t = 200 s and so on. Thus, erosion of seabed with 0 to 7.7% CC was discussed in this part.

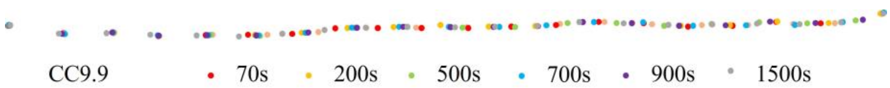

Figure 4. Elevation of CC9.9 bed at different time points.

Variation of SSC and seabed erosion was shown in Figure 5. It can be seen that the average erosion depth of liquefied mixed bed is significant deeper than that of non-liquefied sandy bed, although the near bed SSC of sandy bed is higher than that of mixed bed. The net upward gradient generated by EPP accumulation in the liquefied bed, which made more fine particles on bed surface or within bed suspended to the water compared with sandy bed. But the cohesive force by clay made particles moved near the bed. The sensor measured SSC in this study was set 3.5 cm above the bed and it was set 1cm above bed in Tzang's study. As a result, high density suspended sediment near bed surface was not detected by the OBS sensor over the liquefied bed.

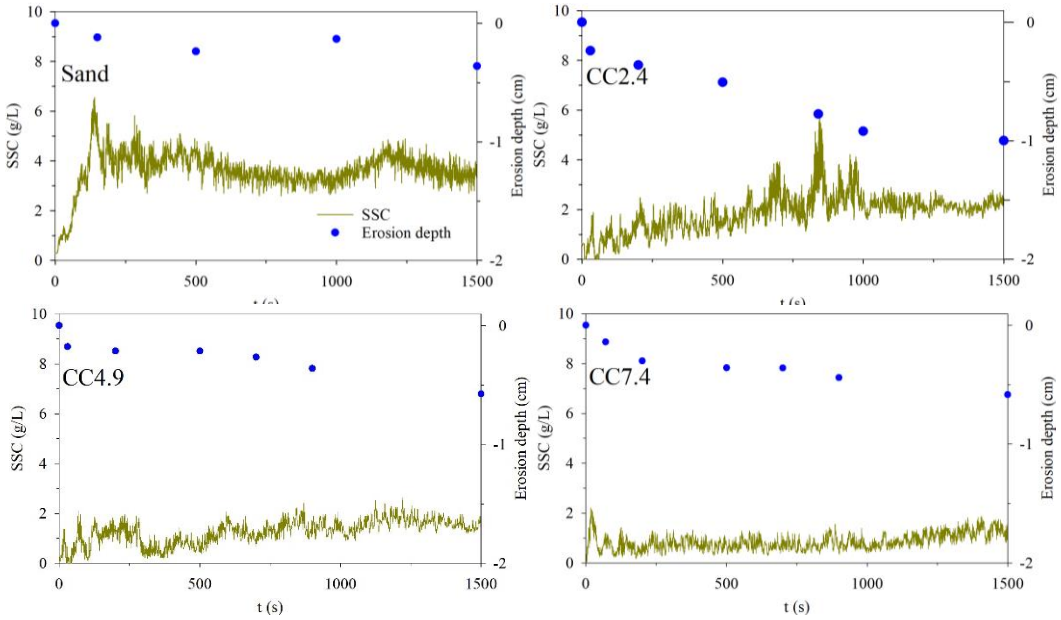

Figure 5. Variation of SSC and seabed elevation.

4. Conclusions

The effect of CC on sediment suspension over sand-clay bed was investigated by wave flume experiments in this study. The primary conclusions are as follow: (1) The sediment incipient motion of mixed bed was mainly influenced by the cohesive force and lifting force in this study. Particles on the mixed bed with less than 5% CC were easy to suspend due to the high lifting force, and particles were hard to move when CC is more than 5% due to the cohesive force; (2) The SSC above the mixed bed decreased with the increase of CC due to the decrease of EPP accumulation within the mixed bed; (3) The elevation of non-liquefied mixed beds (CC9.9–14.2) were almost unchanged under waves due to the high cohesive strength among particles. The erosion of liquefied beds (CC2.4–7.7) were bigger than that of sandy bed, because the accumulation of EPP made more sediments suspended to the water.

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