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Effects of wave-induced seabed liquefaction on sediment re-suspension in the Yellow River Delta

Yonggang Jia [a,b], Liping Zhang [a], Jiewen Zheng [a,c,*], Xiaolei Liu [a], Dong-Sheng Jeng [d], Hongxian Shan [a,b]

[a] Environmental Geotechnical Engineering Institute, Ocean University of China, Qingdao 266100, China
[b] Key Laboratory of Marine Environment & Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China
[c] Key Laboratory of State Oceanic Administration for Marine Sedimentology and Environmental Geology, The First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China
[d] Griffith School of Engineering, Griffith University Gold Coast Campus, Queensland, QLD 4222, Australia

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ABSTRACT

This paper presented the results of wave flume experiments for the process of a silty sediment bed responded to wave action. Silty sediment was sampled from modern Yellow River Delta. In coastal areas, seabed liquefaction and sediment re-suspension were the most significant hydrodynamic processes the seabed sediment presented under wave action. However, few studies have focused on the internal response of sediment under wave action with regard to its role in liquefaction and sediment re-suspension. In this study, four wave height scenarios (5 cm, 7 cm, 10 cm and 18 cm) were tested. Results indicated that the movements of the suspended sediments were dominated by the re-suspension of surface sediment erosion at the initial stage of wave action, whereas the suspended sediments were transported from the internal seabed sediment upward due to wave-induced liquefaction and seepage at a later stage. The observations confirmed that waves enhanced sediment re-suspension by liquefying the soil bed through excess pore pressure accumulations, not simply by excess shear stress.

1. Introduction

The flow path in the Yellow River tail has experienced significant shifting over the last one hundred and fifty years. The dynamic marine processes in the region such as waves, tides and currents have interacted with the sediments through re-consolidation, re-suspension and transportation and reshaped the subaqueous delta, which contains a high silt content and experiences rapid deposition. It has been reported that waves played a crucial role in sediment transformation. For example, wave dynamic loading was found to disengage fine-grained sediment from the seabed skeleton (Bennett, 1977; Bennett and Faris, 1979). The sediment was transported upward under hydrodynamics (Shan et al., 2004), which led to the suspension of the silty sediment (Tzang et al., 2009) and further transportation to the surrounding waters (Obhrai et al., 2002; Dohmen-Janssen and Hanes, 2005). The horizontal wave shear stress and cyclic loads of vertical pressures have been recognised as two key factors dominating each state transition of the silty sediment during wave action (Zheng et al., 2011). The specific combination of the two forces may cause some variation in the seabed sediment re-suspension process, especially in the near-shore seabed.

In the process of wave-induced seabed sediment suspension, one of main concerns has been the effects of wave shear stress on the onset of the movements of the silty seabed surface sediments (Wright et al., 2001; Miles et al., 2002; Wang, 2003; Hoque et al., 2010; Jia et al., 2011). Among these studies, Wright et al. (2001) reported that a significant amount of the seabed sediment re-suspension during storm events was attributed to friction shearing stress increases at the seabed surface, caused by the elevated currents and wave orbital speed. Through field observations, Wang (2003) found that suspended sediment concentrations (SSC) suddenly increased when wave shear stress exceeded the sediment critical shear stress. Hoque et al. (2010) reported that SSC and sediment fluxes were substantially higher in spring tidal cycles compared to neap tidal cycles. Kong and Zhu (2008) reported from their observations on wave flume experiments, that SSC increased with water depth under wave action, and that the increases were greater under regular and irregular wave action than those under the current. Later, Pang et al. (2011) further established a linear relationship between the vertical concentration and relative water depth.

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* Corresponding author at: The First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China. Tel.: +86 18669837297; fax: +86 532 66782102.
E-mail address: jiewen@fio.org.cn (J. Zheng).

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The sediment of the Yellow River Delta can be rapidly consolidated and an over-consolidated hard shell may be formed within the surface sediment 1–2 days after deposition, which led to the shear strength of the seabed sediments generally increasing to several kilopascals (Jia et al., 2007). Using numerical simulations, Gao and Jia (2003) concluded that the magnitudes of the shear stresses under the combined wave and current loading were only several pascals at the soil bed surface. From a comparison of the two values, it seemed difficult for the wave/current to erode and re-suspend the seabed sediments. However, the stiff sediment may be quickly liquefied resulting in its strength to rapidly decreasing, even under slight vibrations (Shan et al., 2006). We hypothesise that cyclic wave loading may lead to an increase in accumulative pore pressure and a decrease in effective stress, which may result in a reduction of the seabed's critical shear stress until the sediment is fully liquefied, and subsequently soil bed sediment re-suspends under an altered, liquefied sediment condition. In other words, the liquefaction may play an important role in the soil bed sediment re-suspension process.

The phenomenon of the wave-induced accumulated pore pressure and the resultant soil bed liquefaction has been studied by numerous researchers. Foda and Tzang (1994) found that silt-bed was liquefied after a sudden increase in pore pressure under wave action. Using flume experiments, de Wit and Kranenburg (1997) established the pore pressure threshold at which soft soil liquefaction will occur. Through one-dimensional experimental studies, Zen and Yamazaki (1990, 1991) and suggested that the mechanism of the wave-induced seabed liquefaction was dominated by excess pore pressure redistributions, which were caused by wave damping and phase lags. Sumer et al. (2004, 2006, 2012) concluded that the silty sediment is liquefied when the “accumulated” excess pore pressure reaches its maximum value. Feng (1992) reported that the liquefaction depth was positively correlated to wave height and reversely correlated to consolidation time.

Among the aforementioned studies, the characteristics of wave-induced sediment re-suspensions, and the mechanism of liquefaction were particularly acknowledged. However, only a few studies have focused on the internal responses of sediment under wave action with regard to its role in sediment re-suspension. Wave-induced pore-pressure accumulation in the liquefied cohesive sediments was found to enhance bed erosion and suspension (Maa and Mehta, 1987; Aldridge and Rees, 1997). Fluidisation and its subsequent upward fluid propagation caused the cohesive sediment particles to separate, and essentially affected the fluvial erosional strength of sediments (Zheng et al., 2013). Thus, liquefaction plays an important role in re-suspension. Foda and Tzang (1994) initially observed that the phenomenon of sediment transportation and suspension was much more spectacular over fluidised beds than in unfluidised beds under the action of non-breaking waves. Tzang (1998) observed in alaboratory flume that the silt seabed formed a liquid surface layer after a short time and produced suspended materials. More recently, Tzang and Ou (2006) and Tzang et al. (2009) further explored some parameters inside fluidisation beds for the SSC and mechanism of sediment suspension, and found that the SSC occurs several wave cycles after the occurrence of the fluidisation response. Therefore, the effect of wave-induced liquefaction in silt sediment on the re-suspension feature and component is critical to understanding the mechanism of sediment re-suspension. However, to date this aspect has not been investigated experimentally. The objectives of this study are to use fine-grained sediment from the Yellow River Delta, exploring the relationships between wave-induced residual liquefaction in silt sediment and the seabed sediment re-suspension, and quantifying the contribution of silt bed fluidised responses to the quantity of re-suspended sediment.

2. Methodology

2.1. Experiment design and materials

The tests were conducted in a wave flume at the Geotechnical Laboratory, Ocean University of China. The experiment set-up is depicted in Fig. 1. The flume was 14 m $(L) \times 0.7$ m $(H) \times 0.5$ m (W) in size, equipped with a piston-type wave generator atone end and a 1:4 dissipating gravel beach at the other. The dissipation system is one of the most important parts of the wave flume used in this experiment, and the new generated monochromatic waves can be considered regular wave group parading in the direct of paddle wave-maker when the front waves reach the dissipation system and disappear during the test running-period. As shown in Fig. 1, three pore pressure transducers (20 mm in diameter and 60 mm in length) were deployed at different depths along the central site of the soil tank. Before the pore pressure transducers were embedded in the soil bed they were soaked in water for 24 h with continuous shaking to ensure gas removal. A TURB335IR-type nephelometer (WTW-Munich, Germany) and XR-420 turbidimeter (Rbr Ltd.-Ottawa, Canada) were used to measure the turbidity of the water during the flume test. The relationship between turbidity and the SSC was predetermined by an indoor test. The turbidity values measured during the flume tests were then converted to SSC, which was used to quantify the sediment re-suspension.

Artificially produced seawater with salinity of 35% was used in the tests. The soil samples were taken from the Diaokou Course Coast at the Yellow River Delta. The silt soil had a clay content between 13.6–16.7% with d_{50} values of 0.036–0.042 mm.

2.2. Quantification of soil liquefaction

2.2.1. Parameterisation of the onset of liquefaction

The effective stress was found to decrease when pore pressure built up in the saturated silt during cyclic wave loading for sediments with poor permeability. Furthermore, as the total stress remained constant during the wave action process, the excess pore pressure increased continually (Zen and Yamazaki, 1991; Foda and Tzang, 1994; Sumer et al., 2006, 2012). If excess pore pressure is defined as Δu, liquefaction then occurs when Δu reaches the maximum excess pore pressure Δu_{max} (McDougal et al., 1989). That is, the quantity Δu_{max} may be set equal to the initial mean normal effective stress σ'_0 (Sumer et al., 2006; Kirca et al., 2012). This consideration for the experimental conditions in the original testswas similar to Sumer's (Sumer et al., 2006), it can be expressed as

$$\Delta u_{max} = \sigma'_0 = \gamma' d(1+2K_0)/3 \tag{1}$$

where K_0 is the ratio between the horizontal and vertical effective stresses, i.e. $K_0 = \sigma'_h/\sigma'_v$, which is not a constant value for silt, so $K_0 = 0.5$ is used as an average value. Substituting $K_0 = 0.5$ into Eq. (1), $\Delta u_{max} = \sigma'_0 = 2\gamma' d/3$ was obtained, where d is the thickness of the overlaying soil; and $\gamma'(=\gamma_s - \gamma_\omega)$ is the submerged unit weight, which is assumed to be constant throughout the whole process, 7.9 kN m^{-3} in this experiment.

According to Eq. (1), when the wave-generated maximum pore pressure Δu_{max} equals the effective self-weight stress $(2\gamma' d/3)$ of the overlaying soil $(2\gamma' d/3)$, the soil at the corresponding depth is in a critical state of liquefaction. As mentioned by Sumer et al. (2012), when the accumulated period-averaged pore pressure reaches the initial mean normal effective stress at the corresponding depth, it will liquefy. When $\Delta u < 2\gamma' d/3$, the soil at the depth remains stable, and the degree of stability can be expressed by the ratio of $3\Delta u/2\gamma' d$. On the other hand, when $\Delta u > 2\gamma' d/3$, liquefaction will occur.