Ocean Engineering 160 (2018) 105–118

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Experimental study on soil response and wave attenuation in a silt bed

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ARTICLE INFO

Keywords:
Liquefaction
Wave attenuation
Excess pore pressure
Silt bed
Water waves

ABSTRACT

When ocean waves propagate over porous seabed, they cause variations of the pore pressure within seabed, leading to the possible wave attenuation and soil liquefaction. In order to advance and improve our understanding of the process of wave-induced seabed liquefaction and its impact on wave propagation, systematical experiments are carried out in a wave flume with a soil basin filled with silt. Both the pore pressures and water surface elevations are measured simultaneously, while the seabed liquefaction is videotaped using a high-speed camera. Laboratory measurements show that the pore pressure in surface layer mainly oscillates over time, while the wave period averaged pore pressure has little change. In the deep layer, however, the wave period averaged value of the pore pressure builds up dramatically. The results show that the wave height decreases rapidly along the direction of wave propagation when seabed liquefaction occurs. Such a wave attenuation is greatly enhanced when the liquefaction depth further increases. The experiments also demonstrate that the conditions (wave height and wave period) of incident waves have significant impacts on the wave-induced pore pressures, liquefaction depth and wave attenuation in a silt bed.

1. Introduction

When wave-induced pressure exerts on the surface of the highly saturated seabed, the pore pressure within the seabed will vary with time and the cyclic changing shear stress will occur due to wave loading. The emergence of the excess pore pressure results in an instant variation of effective stresses. Such effective stresses and their corresponding soil strength will decrease when the excess pore pressure increases. Under certain conditions, the effective stresses vanish and the soil behaviors as a viscous fluid, which has no resistance to any shear loading. This phenomenon is the so-called Liquefaction (Sassa and Sekiguchi, 2001). This situation is frequently encountered in the marine environment with potential serious catastrophic consequences. For example, liquefaction induced by the wave-seabed interactions may result in an incline of offshore oil platform and serious subsidence of breakwaters. This demonstrates that the wave-seabed interactions have considerable impacts on the foundation stability of offshore infrastructures.

As ocean waves propagate over a seabed, the soil deformation will dissipate part of wave energy. The displacement of soil particles in soil layer increases significantly once the soil is liquefied. As such, the specific Coulomb friction loss (Yamamoto and Takahashi, 1985) increases rapidly and the wave height attenuates accordingly. This phenomenon has been studied since 1958 (Gade, 1958; Mathew et al., 1995), demonstrating that it is important to consider the impacts of seabed liquefaction on accurate wave prediction.

Due to its practical importance and theoretical interest, the mechanism of wave-seabed interactions has been theoretically and numerically investigated in the past several decades. For example, various models considering the porous seabed as a poro-elastic material were developed for this purpose (Biot, 1941; Yamamoto et al., 1978; Hsu and Jeng, 1994; Zhang et al., 2011, 2012; Lin et al., 2016; Sui et al., 2016). Although the build-up of the pore pressure due to contractive soil behavior was out of the scope of the above models, these models provide reasonable results if the plastic deformation of seabed was negligible. These studies show that the excess pore pressure fluctuates around a constant value and the period-averaged excess pore pressure almost remains the same.

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https://doi.org/10.1016/j.oceaneng.2018.04.027
Received 12 August 2017; Received in revised form 26 November 2017; Accepted 8 April 2018

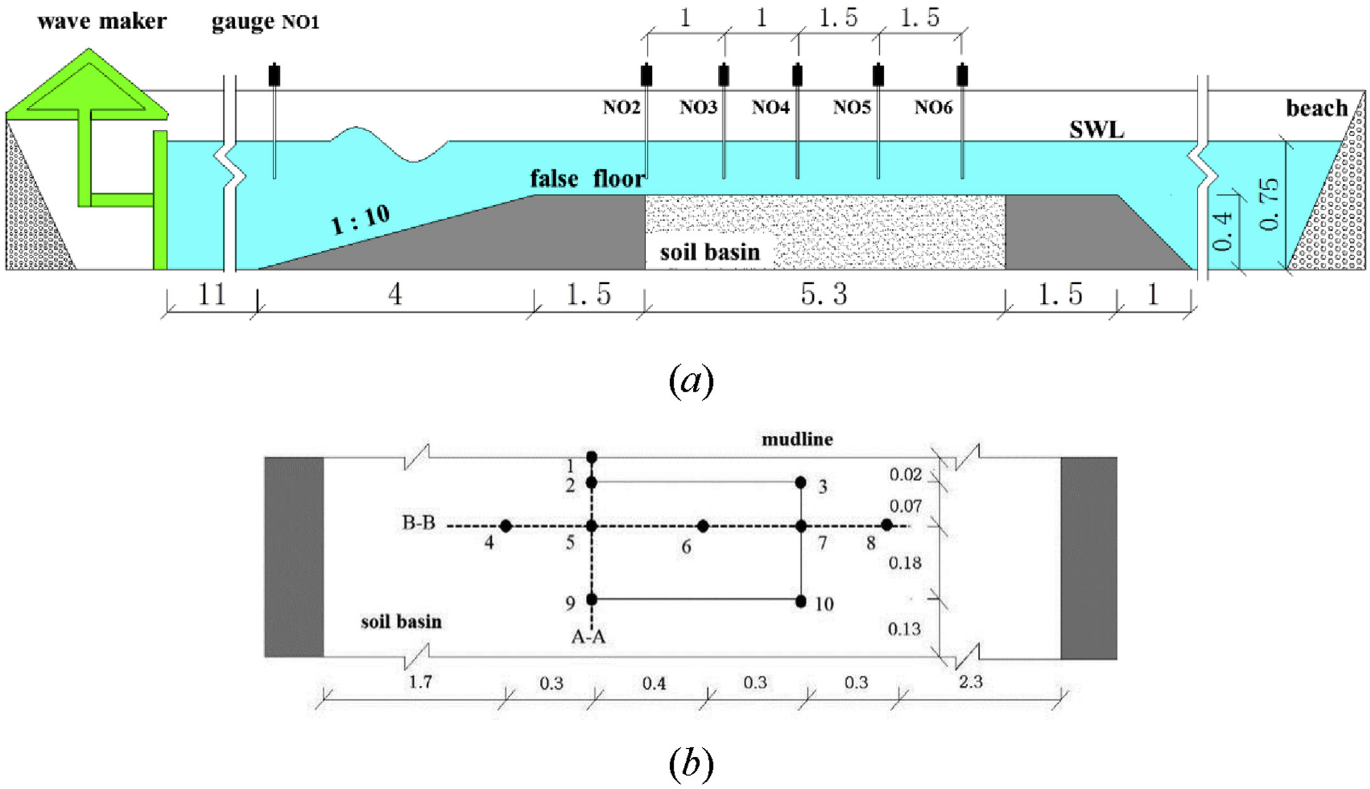

Fig. 1. (a) The experiment setup; (b) pore pressure transducers position drawing (unit: m).

Table 1
Summary of soil properties of the test sediment.

Parameter	Symbol	Value
Mean grain size	d_{50}	0.042 mm
Specific weight of sediment grains	γ_s	26.1 kN/m^3
Total specific weight of sediment	γ_t	19.8 kN/m^3
Maximum void ratio	e_{max}	1.10
Minimum void ratio	e_{min}	0.42
Void ratio	e	0.58
Relative density	D_r	0.76
Porosity	n	0.37
Coefficient of permeability	k_s	3.5×10^{-9} m/s
Submerged specific gravity	γ'	9.99 kN/m^3

Momentary liquefaction may occur under certain wave conditions when the amplitude of excess pore pressure exceeds the initial effective stress (Sumer and Fredsøe, 2002). However, for the cohesive seabed (such as, silt or clay) with low permeability (Tzang et al., 2009), the wave-induced plastic deformation cannot be neglected (Sekiguchi et al., 1995). In these situations, the seabed response becomes highly nonlinear and the residual pore pressure is generated. Meanwhile, the propagation velocity of the shear waves becomes comparable to that of the water wave. If the shear stress ratio is sufficiently large that the wave-induced residual pore pressure exceeds the initial vertical effective stress, the residual liquefaction will occur. On this occasion, the porous elasto-plastic theories considering the importance of contractive soil behavior under wave loading are needed (Sassa and Sekiguchi, 2001; Miyamoto et al., 2004; Jeng and Ou, 2010; Liao et al., 2015).

Laboratory experiment is another common approach to investigate the soil response to the wave action. The primary experimental studies mainly include the water flume experiments (Tzang and Ou, 2006; Sumer et al., 2010; Zhang et al., 2016) and cylinder experiments (Zen and Yamazaki, 1990; Liu et al., 2015), which generally focus on the seabed instability induced by liquefaction. However, it is worth of pointing out that the cylinder experiments only consider the excess pore pressure induced by macroscopic compression, while the water flume experiments investigate the excess pore pressure evolution characteristics under both the compression and shearing actions. The exception is the study of Sekiguchi et al. (1995), in which a centrifugal wave tests have been used to investigate the excitation of the excess pore pressure within the seabed as well as the seabed liquefaction under wave action. In centrifuge experiments, because the centrifugal acceleration is much larger than the gravitational acceleration, it can correctly represent the stress level at the field tests in the small-scale centrifuge wave tests. Some other studies indicate that sediment transportation is closely related to the seabed liquefaction (Tzang et al., 2009; Jia et al., 2014). The suspended sediment concentration near the mud-line increases substantially once the soil liquefied. The soil will experience a compaction process after liquefaction and the residual pore pressure will dissipate gradually. As a result, ripples will be formed on the bed, when the compaction process is completed (Miyamoto et al., 2004; Sumer et al., 2006).

As to waves, when seabed is liquefied, the velocity field near water-soil interface changes (Tzang et al., 2011) in which the horizontal velocity component decreases while the vertical velocity component significantly increases almost synchronously during the build-up stage of pore pressure. In front of breakwater, seawalls, and large caisson structures, standing waves will occur and the possible liquefaction induced by these standing waves is particularly investigated by Sassa and Sekiguchi (1999) and Wang et al. (2014). Compared to progressive wave, standing wave induced liquefaction exhibits some different features. For example, the pore pressure builds up rapidly near the node and subsequently the pore water spreads out towards the antinodes (Kirca et al., 2013). In addition, standing wave has a significant impact on the stability of coastal and offshore structures.

Although a substantial amount of knowledge has been gained on