Analysis of seabed instability using element free Galerkin method

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In recent years, wave-induced seabed responses have engrossed growing interests not only in coastal engineering but also in geotechnical engineering. This is because seabed instability may have caused the damage and destruction of some coastal and offshore installations, such as breakwaters, piers, pipelines and so on (Sumer et al., 2001; Jeng, 2003). Two types of seabed instability may occur in a sandy seabed: momentary liquefaction and shear failure. Waveinduced momentary liquefaction was reported in laboratory tests (Sekiguchi et al., 1995; Sassa and Sekiguchi, 1999, 2001) and in field observations (Zen and Yamazaki, 1990; Sakai et al., 1992). Computational results (Madsen, 1978; Yamamoto et al., 1978; Okusa, 1985; Hsu and Jeng, 1994; Jeng and Seymour, 1997; Jeng, 2001) also revealed the potential of momentary liquefaction. If momentary liquefaction occurs routinely in shallow waters, serious stability problems have to be confronted for the structures laid on a cohesionless seabed. Because momentary liquefaction and shear failure are directly related to the excess pore pressure and effective stresses within seabed sediments, prediction of seabed responses and evaluation of seabed instability have become important issues in coastal and ocean engineering.

Liquefaction and shear failure are produced by different mechanisms (Zen et al., 1998; Jeng, 2001). The liquefaction is a state that effective stress in any direction becomes zero. For example, quick sand or boiling is closely related to vertical seepage flow. When water wave propagates over a seabed, the fluctuation of water pressure exerts on the seabed surface, causing pore fluid in the seabed to flow out or into and producing frictional force on soil skeletons (this frictional force is called as seepage force). The wave train generates the fluctuation of pore water pressure, and thus the transient fluctuation of effective stress in soil masses. If the effective stress momentarily becomes zero, soil skeleton loses its structural strength and the seabed becomes momentarily liquefied. In addition, shear stresses in a seabed may be big enough to overcome its shear resistance, resulting in another type of seabed instability, shear failure. A shear failure refers to a state that stress level reaches to shear failure envelope which is usually described by Mohr–Coulomb criterion.

Wave-induced seabed response can be evaluated by Biot consolidation theory (Biot, 1941) and Verruijt's storage equation (Verruijt, 1969). Analytical and numerical methods have been employed to solve the Biot consolidation equation. Analytical solutions are usually available for those problems with simple boundary conditions. For example, Madsen (1978) investigated a hydraulically anisotropic and partially saturated seabed, whilst Yamamoto et al. (1978) studied an isotropic seabed with infinite thickness. Okusa (1985) used the compatibility equation under elastic conditions and reduced the sixth-order governing equation of Yamamoto et al. (1978) to a fourth-order differential linear equation. Yamamoto (1981) developed a semi-analytical solution for a nonhomogeneous layered porous seabed. Later, Hsu and Jeng (1994) and Jeng and Hsu (1996) further extended the framework to a finite-thickness seabed as well as a layered seabed (Hsu et al., 1995).

Several numerical algorithms were proposed to accumulate complex geometry and physical conditions. For example, Thomas (1989) developed a semi-analytical onedimensional finite element model to simulate the waveinduced stresses and pore water pressure. This method was later extended to 2D and 3D wave-seabed interaction problems (Jeng and Lin, 1996; Jeng, 2003). Gatmiri (1990) developed a simplified finite element model for an isotropic and saturated permeable seabed. Recently, a meshless EFGM model was developed for the analysis of transient wave-induced soil responses (Karim et al., 2002). In order to improve the computation efficiency, a radial PIM method (Wang and Liu, 2002a, b; Wang et al., 2002) was extended for wave-induced seabed responses by introducing repeatability conditions (Wang et al., 2004). This radial PIM considers not only sinusoidal waves but also other nonlinear waves such as solitary wave. These numerical meshless methods provide a useful tool for further analysis of seabed instability.

Seabed instability is a complicated topic in marine geotechnics (Poulos, 1988). Past studies have revealed that both soil characteristics and wave properties play a dominant role in the wave-induced seabed responses (Jeng, 2003). Some parameters are proposed to assess the potential of momentary liquefaction. For example, Sakai et al. (1992) proposed two parameters to justify the occurrence of liquefaction based on a boundary layer theory (Mei and Foda, 1981). They concluded that the maximum depth of liquefaction is about half the wave height for surf conditions. However, no single parameter is available to evaluate the momentary liquefaction. Furthermore, the parameters so far are obtained for a homogeneous porous seabed. Is it suitable for a nonhomogeneous seabed? Seabed is usually non-homogeneous and its shear modulus of seabed increases with soil depth such as Gibson soil (Jeng, 2003). This paper will also explore the effect of depth-variable modulus on seabed responses.

This paper proposes a non-dimensional parameter to study the most critical condition governing seabed instability due to momentary liquefaction. This single parameter includes both wave characteristics and seabed properties. Numerical examples are studied to verify its effectiveness through a meshless EFGM model as well as three criteria of liquefaction. It is noted that this EFGM model has been critically examined against available analytical and/or semianalytical methods (Karim et al., 2002). A parametric study, in the perspective of wave-induced soil instability, is carried out to examine the sensitivity of soil and wave properties on seabed responses. The shear failure in one-wave period is briefly discussed, too. The focus is mainly on the potential of wave-induced momentary liquefaction and liquefaction depth. This paper is organized as follows: The criteria of seabed instability, momentary liquefaction and shear failure, are first discussed in Section 2. Then Biot consolidation equation and its EFGM meshless method are briefly introduced in Section 3. A non-dimensional parameter which includes both soil and wave properties is proposed to identify the potential of momentary liquefaction in Section 4, and this parameter is validated with a finite-thickness seabed and three criteria for liquefaction in Section 5. Parametric study is carried out in Section 6. Parameters include wavelength, fluid compressibility or degree of saturation, soil permeability and Young's modulus, as well as variable shear modulus along depth. Mohr cycles of effective stress status within one wave period and shear failure mechanisms are discussed in Section 7. Finally, the conclusion and remarks are given.

Seabed instability under wave loading

Wave-induced momentary liquefaction and shear failure are caused by different mechanisms. When a sandy seabed is subjected to cyclic wave loading, the effective stresses and pore water pressure fluctuate with the propagation of waves. When the effective stress attains to some critical value, momentary liquefaction or shear failure may occur. This section will discuss the criteria of liquefaction and the shear failure.

Liquefaction

As discussed in the Introduction, liquefaction is a state where a soil loses its structural strength and behaves like a fluid, producing large deformation and the evolution of seabed such as ripples (Ourmieres and Chaplin, 2004).

Three criteria have been proposed in various reports to assess momentary liquefaction.

Criterion 1: Soil is liquefied when vertical effective stress becomes zero (Yamamoto, 1981): denotes the soil depth beneath seabed surface, in which g_s and g_w are the unit weights of soil and pore fluid, respectively. Eq. (1) indicates that liquefaction occurs when seepage force lifts above soil column and soil particles are no more in contact.

Criterion 2: Liquefaction occurs when wave-induced effective volumetric stress in soil becomes identical or larger than the initial in situ effective volumetric stress (Okusa, 1985; Tsai, 1995):

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