EFFECTS OF HORIZONTAL NON-HOMOGENEOUS SOIL PROPERTY ON LOCAL WAVE-INDUCED SOIL RESPONSE

Jinhai Zheng[12], Titi Sui[12], Chi Zhang[12] and Yakun Guo[3]

In this study, a numerical model for wave-induced horizontal non-homogeneous seabed response is developed. Two new coefficients are proposed to describe the influence degrees of horizontal non-homogeneous soil property. The effects of wave condition and adjacent soil properties on the local soil response are investigated. Numerical results show that the influence range of the horizontal non-homogeneous soil property increases with the increase of wave period, wave height and soil permeability, and increases with the decrease of soil air content.

Keywords: wave; soil response; horizontal; non-homogeneous.

INTRODUCTION

Wave-induced seabed response is an important factor to be considered in coastal engineering. When wave propagates over porous seabed, pore pressure is generated with fluctuation and attenuation in the vertical direction. Such fluctuation and attenuation may cause excessive pressure in the inner seabed, which is responsible for seabed instability. Many studies indicated that the damage of coastal structures may be mostly caused by wave-induced seabed response, rather than construction deficiencies (Smith and Gordon 1983).

A large number of studies on wave-induced seabed response have been carried out since 1970s. Based on Biot’s equations (QS equation), the analytical solutions for pore water pressure, soil stresses, soil displacements with an infinite seabed depth were given by Yamamoto et al. (1978) and Madsen (1978). Following their studies, Hsu and Jeng (1994) considered the seabed of finite depth under short crest wave system. Zienkiewicz (1980) proposed partly-dynamic (PD) and fully-dynamic equations (FD) to consider the acceleration effects of water and soil skeleton in porous media. The effect of inertia force on soil response was taken into account by Jeng and Cha (2003). Recently, Ulker (2009) extended their solutions under plane strain conditions and clarified the application range of the three different approximations (QS equation, PD equation and FD equation). However, these studies all assumed a uniform seabed property, while seabed is often non-homogeneous in the real world.

Generally speaking, seabed is usually non-homogeneous because of the long-time consolidation process under pure water pressure and its own gravity. Based on semi-analytical analysis, Yamamoto (1981) and Rahman et al. (1994) gave the solution of linear wave-induced seabed response in the general layered seabed. Jeng and Lin (1996) developed a finite element model to investigate the non-homogeneous soil response, in which the soil property continuously changes in the vertical direction. More recently, the dynamic response in the layered seabed was also studied under non-linear wave loading (Zhou et al. 2011) and wave-current loading (Wen and Wang 2013). In addition, due to the complex coastal dynamics (Zhang et al. 2011), the soil property may vary in the horizontal direction from near-shore area to offshore area (Edwards 2001; Abuodha 2003). To the authors’ knowledge, wave-induced seabed response with horizontal non-homogeneous soil property has not been explored.

In this study, the horizontal non-homogeneous seabed response under linear wave loading is considered. First we give an introduction to the numerical model formulation and validation. Then, two important coefficients named the horizontal impact factor and the horizontal impact factor curve are firstly proposed. Finally, the model is used to investigate effects of wave and soil parameters on the horizontal non-homogeneous soil response.

NEMERICAL MODEL

Based on the poro-elastic theory (Zienkiewicz et al. 1980), thse fully-dynamic model (FD equation) is used as the governing equations.

$$\sigma_{ij,j} + \rho g_i - \rho_f \ddot{w}_i - \rho \ddot{u}_i = 0 \qquad (1)$$

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[1] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, 1 Xikang Road, Nanjing, Jiangsu Province, 210098, China.

[2] College of Harbour, Coastal and Offshore Engineering, Hohai University, 1 Xikang Road, Nanjing, Jiangsu Province, 210098, China.

[3] School of Engineering, University of Aberdeen, Aberdeen, Scotland, AB24 3FX, UK.

$$-p_{,i} + \rho_f g_i - \frac{\rho_f g \dot{w}_i}{k_i} - \rho_f \ddot{u}_i - \frac{\rho_f \ddot{w}_i}{n} = 0 \tag{2}$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} + n\beta\dot{p} = 0 \tag{3}$$

In which σ_{ij} is the total stress, p is the pore water pressure, ρ is the total density of the porous medium, g is the acceleration due to gravity, u is the displacement of soil matrix, w is the average relative displacement of the fluid to the solid skeleton, k is permeability of porous medium, n is the porosity of the solid phase, β is the compressibility of pore fluid (=$1/K_w$+(1-S_r)/($\rho_f gh$), where K_w is the bulk modulus of water taken as 1.95×10^9 N/m^2, h is the water depth and S_r is the degree of saturation).

The total stresses are given in terms of the effective stress (σ'_{ij}) and pore water pressure (p):

$$\sigma_{ij} = \sigma'_{ij} - \delta_{ij} p \tag{4}$$

where δ_{ij} is the Kronecker delta denotation. According to the Hook's Law, the poro-elastic stress-strain relationship can be expressed as

$$\sigma'_{ij} = \lambda u_{i,i}\delta_{ij} + 2Gu_{i,j} \tag{5}$$

In which G is the shear modulus, λ is calculated by $\lambda=2G\mu/(1-2\mu)$ with μ being Poisson's ratio.

At the bottom and lateral boundaries of the seabed, where the material is assumed to be impermeable and rigid, the soil displacements and normal gradient of pore pressure are zero (u = 0 and $\partial p/\partial n$ =0). At the seabed surface, the water pressure for seabed model is given by linear wave theory (Eq. 6).

$$p = \rho g H \frac{\cosh K(z+h)\cos(Kx - 2\pi\cdot t/T)}{2\cosh Kh} \tag{6}$$

In which K is wave number ($K = 2\pi/L$, L is wave length), T is wave period, H is wave height.

MODEL VALIDATION

Tsui and Helfrich (1983) conducted a series of laboratory experiments to measure pore water pressure in deep soil. Two kinds of soil (loose soil and dense soil) are used as the porous media. Fig. 1 shows the comparison between measured and simulated pore water pressure, in which p_0 denotes the maximum water pressure at seabed surface. For both soils, pore water pressure has a slight decrease at the upper part of soil, following with a rapid decrease into the deeper region (0.6 h). In addition, more obvious attenuation of pore pressure can be found in the dense soil than in the loose soil. Analytical solution given by Jeng (2010) is also plotted here for comparison. As shown in Fig. 1, good agreements are found among experimental data (Tsui and Helfrich 1983), analytical solution (Jeng 2010) and simulated results in this study.

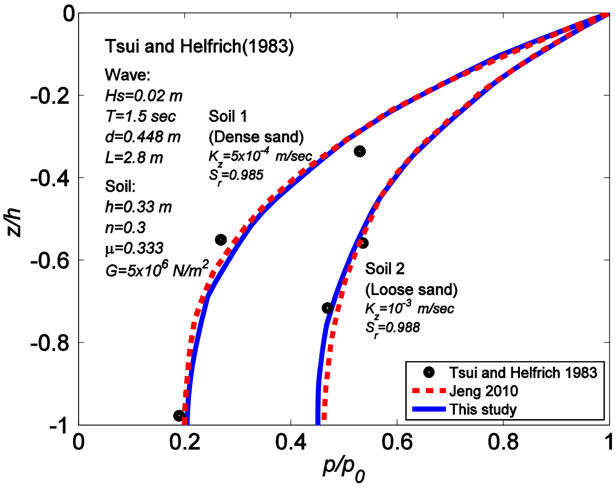

Figure 1: Comparison of simulated and measured (Tsui and Helfrich 1983) wave induced vertical dynamic pore water pressure distribution. Analytical solution by Jeng (2010) was included for comparison.

MODEL APPLICATION

In the present study, two kinds of soil (fine soil and coarse soil) are considered. Two test cases are designed. The first case considers the fine soil for the whole domain. The other case assumes the seabed as a combination of fine soil and coarse soil in the horizontal direction, as shown in Fig. 2. In the numerical simulation, we will change the coarse soil properties and wave parameters to investigate their effects on the fine soil response.

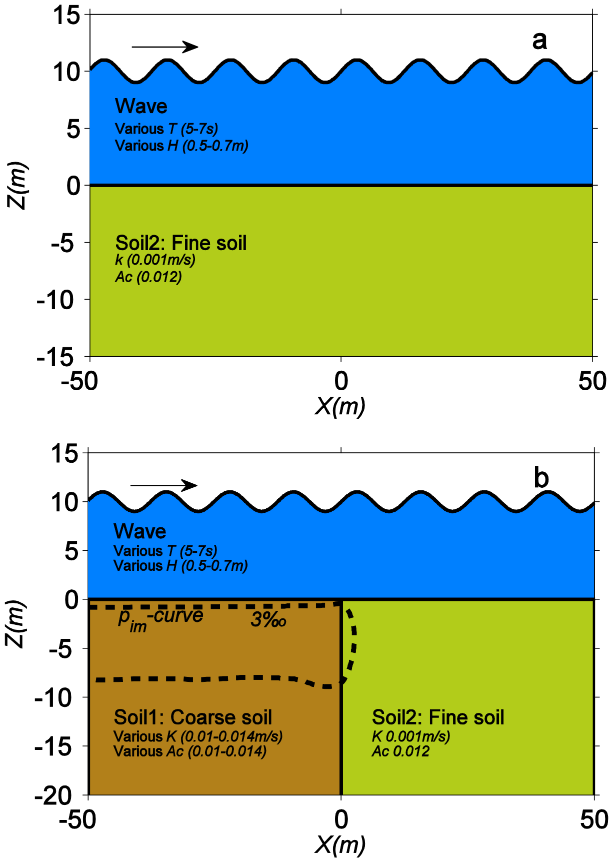

Figure 2: Model setup of this study. (a) Fine soil case. (b) Coarse-fine soil case and the definition of P_{im}-curve.

Definition of new coefficients

In order to parameterize the impact of adjacent coarse soil property on local fine soil response, two new coefficients are first proposed. They are the impact factor (P_{im}) and the impact factor curve ($p_{im}-curve$). P_{im} is defined as the maximum pore pressure difference due to variable soil property in the horizontal direction and is expressed by

$$p_{im} = Max\left(\frac{\left|p_{coarse/fine} - p_{fine}\right|}{\gamma_w}\right) \tag{7}$$

where γ_w is the unit weight of water ($\gamma_w = 9810$ N/m^3).

The second coefficient P_{im}-*curve* is defined as the curve when P_{im} reaches 3‰. As can be seen in Fig. 2b, $P_{im}-curve$ represents the influence range of the adjacent coarse soil property on the local fine soil response.

The effect of wave parameters on P_{im}-*curve*

When wave propagates above seabed, dynamic pore water pressure is generated inside the seabed. In this section, the effects of wave characteristics (wave period T, wave height H) on $P_{im}-curve$ are investigated. The soil parameters used are listed in Table 1.

Table 1. Parameters for coarse and fine soil

	k (m/s)	E (N/m^2)	S_r	μ	n
Coarse soil	1.0×10^{-2}	1.33×10^{7}	0.99	0.333	0.3
Fine soil	5.0×10^{-3}	1.33×10^{7}	0.988	0.333	0.3

Fig. 3a shows the effects of wave period T on P_{im}−*curve*. The range of P_{im}−curve increases as wave period T increases. This may be due to the fact that waves with larger T can transmit more wave energy into the deep soil. Similar phenomenon can be found in Fig. 3b that larger range of P_{im}−*curve* corresponds to the larger wave height H.

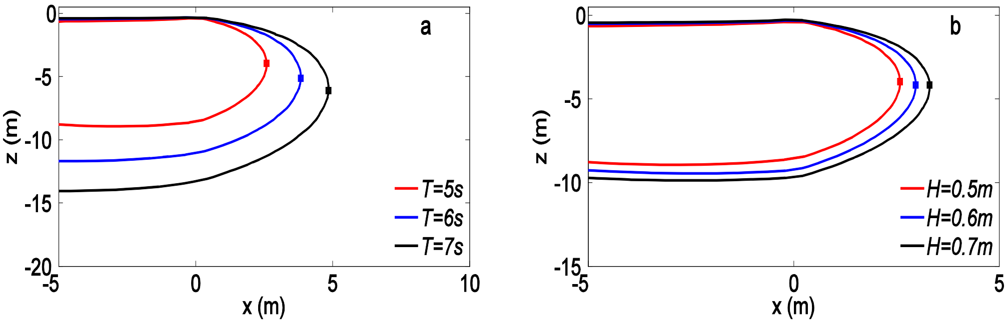

Figure 3: The effect of wave parameters on P_{im}-*curve*. (a) Wave period T (H = 0.5 m, h = 10 m). (b) Wave height H (T = 5 s, h = 10 m).

The effect of soil property on P_{im}-*curve*

In this section, soil parameters (soil permeability k, air content Ac) in the adjacent coarse soil are changed to investigate their influence on the local fine soil response. Wave parameters used are as follows: T = 5 s, H = 0.5 m, h = 10 m.

Fig. 4a illustrates the effect of soil permeability on P_{im}−*curve*. The range of P_{im}−*curve* increases as the soil permeability increases. In contrast, Fig. 4b shows that larger values of soil air content result in smaller ranges of P_{im}−*curve*. The reason is that less wave energy will be transmitted into seabed with the increasing air content.

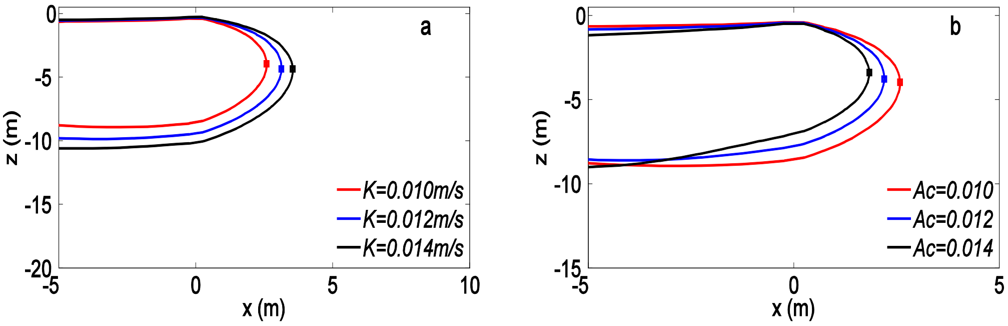

Figure 4: The effect of horizontal non-homogeneous soil property on P_{im}-*curve*. (a) Soil permeability k (Ac = 0.01). (b) Soil air content Ac (k = 0.01 m/s).

CONCLUSIONS

In this study, a numerical model is developed to investigate the effects of horizontal non-homogenous seabed property on the local wave-induced seabed response. In particular, the effects of the adjacent coarse soil property on the local fine soil response are studied. Some concluding remarks can be summarized as follows:

1. Two new coefficients P_{im}, $P_{im}-curve$ are first proposed to parameterize the influence of property change in the adjacent soil on the local soil response.
2. The influence range ($P_{im}-curve$) increases with the increase of wave period T, wave heights H and soil permeability k, and increases with the decrease of air content Ac.

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