

Critical trigger condition of seabed liquefaction under ocean waves

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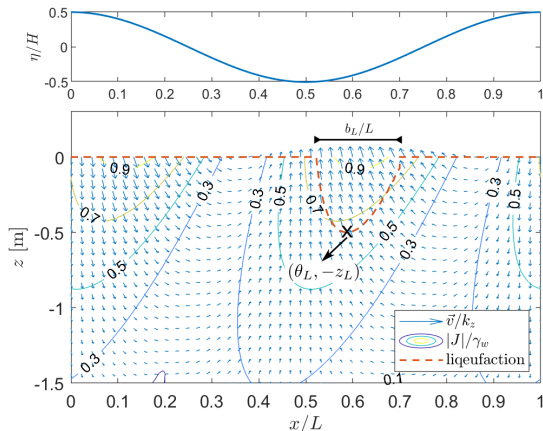
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Example of seabed liquefaction

Liquefaction occurs when the excess pore pressure u_e exceeds the overburden loading σ'_0 (Sumer and Fredsoe, 2002):

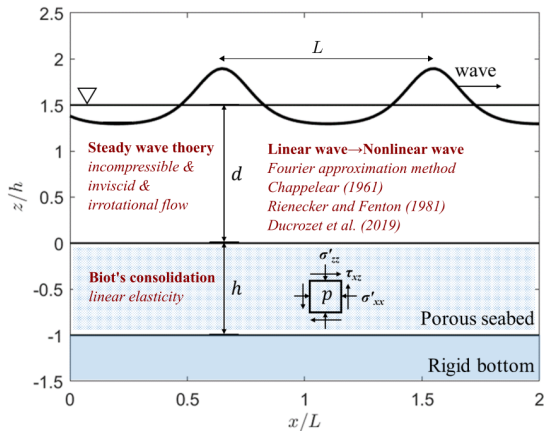
$$\sigma'_0 + u_e \geq 0 \quad (1)$$

where

$$u_e = -(p_b - p)$$

$$\sigma'_0 = \frac{1 + 2K_0}{3} \gamma' z$$

Wave-induced seabed response



Sketch of theoretical model

According to Zienkiewicz et al. (1980), the governing equations of Biot's consolidation theory considering with the inertia force of soil skeleton:

$$\sigma_{ij,j} + \rho g_i = \rho \ddot{u}_i \quad (2)$$

$$-p_{,i} + \rho_f g_i = \rho_f \ddot{u}_i + \frac{\gamma_w}{k_i} \dot{w}_i \quad (3)$$

$$-\frac{n}{K_f} \dot{p} = \dot{u}_{i,i} + \dot{w}_{i,i} \quad (4)$$

The harmonic solution of wave-induced seabed response $S(x, z, t)$ can refer to Hsu & Hung (2020):

$$S(x, z, t) = \text{Re} \left\{ \sum_{i=1}^6 C_i v_i e^{D_i z} e^{i(kx - \omega t)} \right\}$$

The steady wave theory in terms of potential function $\phi(X = x - ct, Z)$ can be referred by Fenton (1990):

$$\nabla^2 \phi = 0, (X, Z) \in D \quad (5)$$

$$(\phi_X - c)\eta_X - \phi_Z = 0, Z = \eta(X) \quad (6)$$

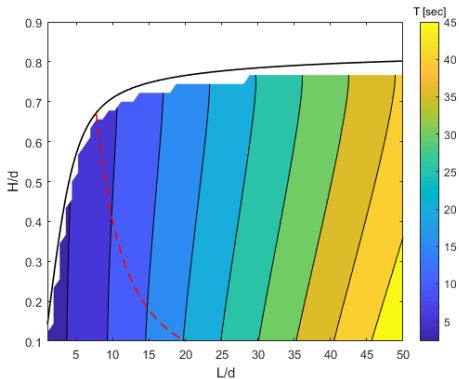
$$\frac{p}{\rho_f} + gZ + \frac{1}{2}\{(\phi_X - c)^2 + \phi_Z^2\} = R, Z = \eta(X) \quad (7)$$

$$\phi_Z = 0, Z = 0 \quad (8)$$

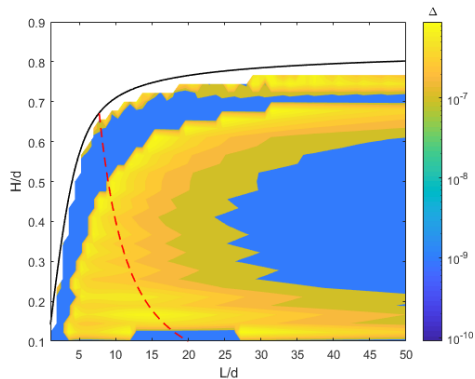
Perturbation is used to analytically solve this problem such as Stokes wave or cnoidal wave, and the linear wave solution is

$$\eta = \frac{H}{2} \cos(kx - \omega t)$$
$$\phi = \frac{H}{2} \frac{g}{\omega} \frac{\cosh kz}{\cosh kd} \sin(kx - \omega t)$$

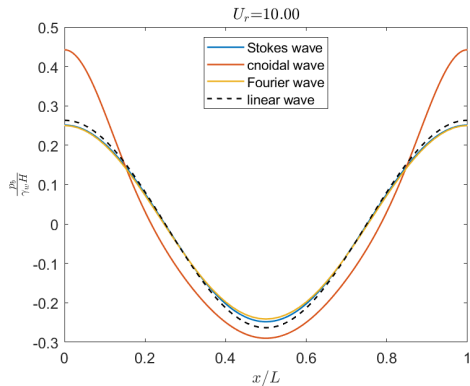
Based on Fourier approximation method (Fenton ,1999), the present algorithm adapted with automated refined space grids and iterative height steps has accurate prediction behind 98% breaking wave limit.



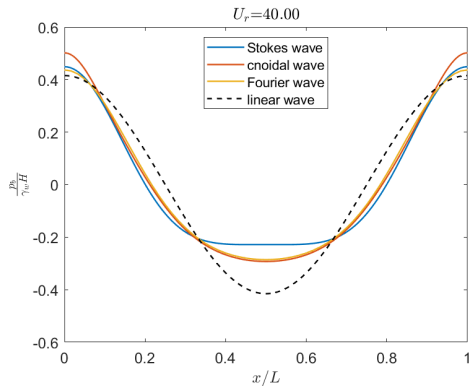
(a) calculated wave period



(b) convergence analysis



(a) $U_r = 10$

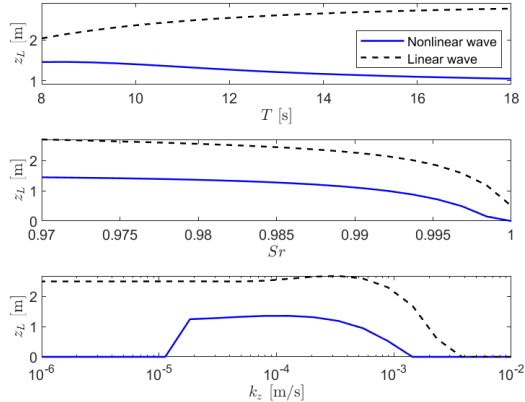


(b) $U_r = 40$

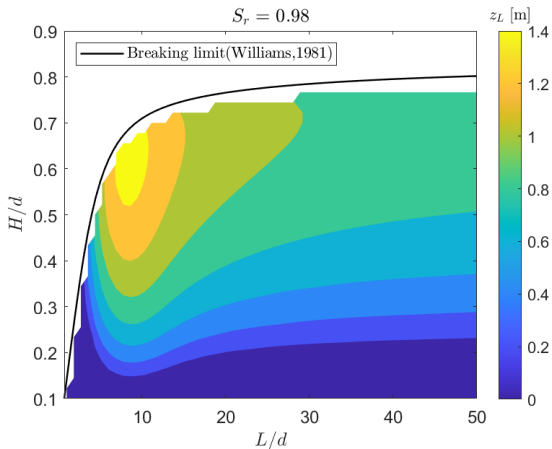
The present solution predicts well with Stokes wave for intermediate water wave and with cnoidal wave for shallow water wave.

Table 1: Seabed parameters and wave condition

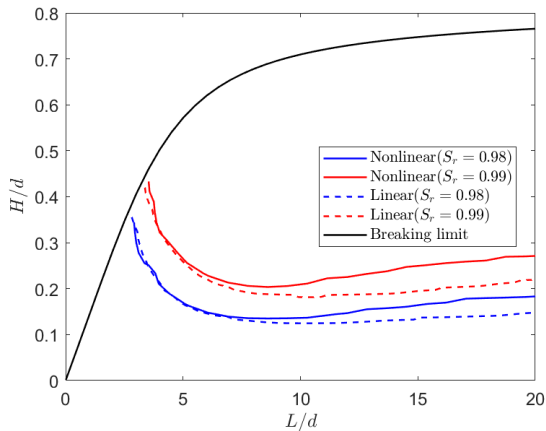
Parameter	Value	Unit
Density of soil particles, ρ_f	2700	kg/m ³
Bulk modulus of water, K_w	2×10^9	Pa
Shear modulus of soil, G	10^7	Pa
Hydraulic conductivity, k_z	10^{-4}	m/s
Poisson's ratio, μ	1/3	
Porosity, n	0.3	
Saturation, S_r	0.98	
Seabed thickness, h	22.65	m
Water depth, d	10	m
Wave height, H	6	m
Wavelength, L	113.24	m
Wave period, T	12	s



characteristics of seabed liquefaction:(a)wave period; (b)saturation; (c) hydraulic conductivity



maximum liquefaction depth for varied wave conditions ($d = 20[\text{m}]$)



critical trigger condition

Conclusion

1. No liquefaction happens for small wave height. In parametric study, a seabed liquefaction may happen only under the wave height is greater than 10% water depths ($\frac{H}{d} > 0.1$).
2. For an identical wave height, the wave in shallow water triggers liquefaction more easily than that in deep water.
3. The nonlinear effect of water wave attenuates seabed liquefaction.
4. For partially saturated soil, the seabed with less saturated soil has more possibility to trigger liquefaction.

Future work

- wave-current interaction/ seabed anisotropy/ soil cohesion

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