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ScienceDirect

Soils and Foundations xxx (2018) xxx–xxx

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Modeling the static liquefaction of unsaturated sand containing gas bubbles

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Received 15 December 2016; received in revised form 8 October 2017; accepted 18 October 2017

Abstract

As a modification of the deviatoric hardening plasticity model, a material state-dependent model was proposed to simulate the response of unsaturated sand containing gas bubbles under undrained triaxial conditions. Affected by the compressibility of gas, the stress paths under undrained conditions approach the drained response of sand when the initial degree of saturation is low. Upon an increase in the degree of saturation, the stress path gradually approaches the saturated undrained response. According to the prediction based on the second-order work criterion, static liquefaction occurs in loose sand, but not in dense sand. Increases in the degree of saturation and the initial gas pressure reduce the stress ratio at the instability points. The instability line obtained by connecting those instability points in the p-q space is nonlinear, and its slope depends on the initial void ratio, the initial degree of saturation, the initial gas pressure, and the confining stress. After comparing the experimental results in the literature with the theoretical prediction, the proposed model was shown to precisely predict the onset of the static liquefaction of unsaturated sand containing gas bubbles.

Keywords: Static liquefaction; Unsaturated sand; Gas pressure; Material state; Second-order work criterion

1. Introduction

Due to biogenic or petrogenic processes (Floodgate and Judd, 1992), oceanic soil often contains a large amount of dissolved gases, (e.g., carbon dioxide, hydrogen sulfide, ethane, and methane). The dissociation of the gas pushes against the soil skeleton and creates gas-filled voids. In unsaturated soil, the gas often exists in discrete bubble form, while in fully saturated soil, it is entrapped (Pietruszczak and Pande, 1996). Due to the high compressibility of gas, the existence of gas bubbles affects the engineering properties of soil (Grozic et al., 1999). Furthermore, the dissociation of methane hydrates decreases the effective stress as well as the shear strength of soil (Xu and Germanovich, 2006; Wu and Grozic, 2008).

The mechanical behavior of soil can be significantly affected by the presence of free gas (Christian and Cranston, 1997; Fourie et al., 2001; Amaratunga and Grozic, 2009). The responses of unsaturated soil containing discrete gas bubbles in undrained and drained triaxial tests were bounded by the saturated drained and undrained responses (Vega-Posada et al., 2014). The shear strength of dense sand is reduced by the presence of free gas, and the mobilized shear strength depends on the type of gas, the amount of gas, and the magnitude of the pore-water pressure (Rad et al., 1994). To describe the constitutive behavior of unsaturated soil, a suitable description of

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Peer review under responsibility of The Japanese Geotechnical Society.

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https://doi.org/10.1016/j.sandf.2017.11.008

Please cite this article in press as: Lü, X. et al., Modeling the static liquefaction of unsaturated sand containing gas bubbles, Soils Found. (2018), https://doi.org/10.1016/j.sandf.2017.11.008

Nomenclature

A	material parameter
A_d	material parameter of stress-dilatancy
B	Biot's coefficient
B_g, B_w	strain concentration parameters
D^{e}_{ijkl}, $\mathbf{D}^\mathrm{e}$	elasto-plastic modulus tensors
D^{p}_{ijkl}, $\mathbf{D}^\mathrm{p}$	plastic modulus tensors
D^{ep}_{ijkl}, $\mathbf{D}^\mathrm{ep}$	elasto-plastic modulus tensors
$(\mathbf{D}^\mathrm{ep})_\mathrm{sys}$	symmetric part of elasto-plastic modulus tensor
d^2w	second-order work
$d\boldsymbol{\sigma}'$	effective stress increment
$d\boldsymbol{\varepsilon}$	strain increment
E	elastic modulus
e	void ratio
e_0	initial void ratio
e_c	void ratio at critical state
e_{ij}	deviatoric strain
F	yield function
G	pressure-dependent shear modulus
G_0	shear modulus constant
H_p	hardening modulus
h	Henry's constant
J_2	second stress invariant
J_3	third stress invariant
K	bulk elastic modulus
$\bar{K}$	elastic bulk modulus of solid matrix
K_g	bulk modulus of gas
K_s	intrinsic bulk modulus
K_w	water bulk modulus
L	total perimeter of air-water menisci
M	stress ratio
M_cs	stress ratio at critical state
M_d	dilatancy stress ratio
M_f	peak stress ratio
M_is	stress ratio at onset of static liquefaction
n	soil porosity
n_b	peak stress ratio parameter
n_d	dilatancy parameter
p	mean stress
p_α	liquid/gas pressure
p_at	atmospheric pressure
Q	plastic potential function
q	equivalent shear stress
R	radius of gas bubble
S_α	liquid/gas degree of saturation
S_s	internal solid surface area
s_ij	effective deviatoric stress
S_r	degree of saturation
S_{r0}	degree of saturation at initial state
T	surface tension force
T_n	normal component of surface tension force
u_g	excess gas pressure above the atmospheric pressure
u_{g0}	initial value of excess gas pressure
u_gw	average pore fluid pressure in voids
u_w	pore water pressure
V_a	volume of free gas
V_d	volume of dissolved gas
V_s	volume of soil particle
V_w	volume of water
V_g	volume of gas
V_v	volume of void
β	influence factor on surface tension
δ_{ij}	Kronecker's delta
ε_a	axial strain
ε_r	radial strain
φ	friction angle
σ'_a	axial effective stress
σ_c	initial confining stress
σ_{ij}	stress tensor
ε_{ij}	strain tensor
ε^p_s	equivalent plastic shear strain
ε_v	volumetric strain
$\dot{\lambda}$	plastic multiplier
λ_c	material parameter determining critical state line
v	Poisson's ratio
Ψ	material state parameter
θ_σ	Lode angle

effective stress must be proposed. In multi-phase porous media, the effective stress can be obtained by the continuum principle of thermodynamics (Borja and Koliji, 2009). Wheeler (1988) proposed a conceptual model, which consists of a matrix of saturated soil surrounding isolated gas-filled cavities, to calibrate the behavior of unsaturated soil containing large gas bubbles. Taking into account the compressibility and solubility of pore gas and liquids, Grozic et al. (2005) proposed a constitutive model for gassy sand (identical to unsaturated soil containing discrete gas bubbles) based on an existing model. However, this model cannot predict slight increases in the effective mean normal stress observed at the initial stage of undrained triaxial tests. Sultan and Garziglia (2014) presented a constitutive model for gassy soil based on the Cam-Clay model.

Static liquefaction is typical instability found in loose granular materials. It has been studied experimentally (Lade and Pradel, 1990; Doanh et al., 1997; Chu and Wanatowski, 2008; Wei and Yang, 2014), theoretically (Borja, 2006; Andrade, 2009; Buscarnera and Whittle, 2013; Lu et al., 2014; Sadrekarimi, 2014; Lu and Huang, 2015), and numerically (Mohammadnejad and Andrade,

Please cite this article in press as: Lü, X. et al., Modeling the static liquefaction of unsaturated sand containing gas bubbles, Soils Found. (2018), https://doi.org/10.1016/j.sandf.2017.11.008