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Recommendations for extension and re-calibration of an existing sand constitutive model taking into account varying non-plastic fines content

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ABSTRACT

Experimental findings have revealed that up to a certain transitional threshold, adding non-plastic silt to coarse soils like sands leads to the increase in susceptibility of liquefaction. In silty sands, silt grains fill voids between the coarse constituent, but do not actively participate in stress transmitting microstructure. To consider the partial participation of fines in load bearing structure, an equivalent intergranular void ratio is suggested. The proposed empirical relationship, takes into account the combined influence of fines content, soil gradation, and the average shape of coarse and fine constituents. An equivalent intergranular state parameter is employed in the model formulation to define soil state uniquely. Moreover, recent experimental studies indicate that the consequences of initial anisotropy on the mechanical behavior of silty sands are mitigated with the increase in fines content. To consider this phenomenon, vector magnitude, a measurable index of anisotropy, is related to fines content. Then, proper constitutive equations are introduced to modify plastic hardening modulus and critical state line in loading paths involving rotation of principal stress axes. The simulative capability of the model is evaluated by direct comparison of its predictions with experimental data of triaxial and hollow cylindrical cells reported by four research teams.

1. Introduction

Uniformly graded loose saturated sands exhibit pore water pressure build up, sizable loss of shear strength, and large shear deformations when subjected to undrained shear. Liquefaction is a technical term usually attributed to the above-mentioned phenomena. For many years, the liquefaction induced events were thought to be only related to clean sands. As a result, the majority of past experimental studies were dedicated to clean sands [3,17,27,50,63,66,75]. However, according to a comprehensive review by Yamamuro and Lade [71], the majority of the documented historic cases of liquefaction induced catastrophic incidents have occurred in natural and man made deposits of silty sands. Unexpectedly, subsequent inspections revealed that dense sands containing large amounts of non-plastic fines (e.g., non-plastic silts) are very prone to flow liquefaction because of the incomplete participation of fines in load transmitting microstructure (e.g., [1,15,31,48,59,70]). For these reasons, the question of non-plastic fines influence on the liquefaction susceptibility of granular soils has received increasing attention in the last two decades (e.g., [1,15,21,31–33,35,36,39,46,47,52,56,59,69,70,73,77] among others). Recent studies have indicated that adding non-plastic fines to coarse granular structures leads to a rise in liquefaction susceptibility up to a transitional threshold fines content generally in vicinity of 25–40% by weight of solid phase. Further increase in fines yields the rise in resistance against liquefaction (e.g., [37,46,59,77]).

Initial fabric also has a strong weight on the mechanical behavior of clean sands (e.g., [62,63,74,75]). On the subject of sand–silt mixtures, recent studies have reported that initial fabric effects decrease with the rise in fines content (e.g., [1,7,44,45,55]).

Muir Wood [28–30] was among the first who addressed the profound engineering influence of erosion-induced movement/relocation of fines within the structure of coarse granular soils. WAC Bennett Dam in British Columbia is an earthfill dam with a core formed of broadly graded non-plastic silty sand that was completed in 1968. In 1996, two sinkholes were found in the dam. Analysis of data provides evidence to support the hypothesis of the slow movement of fines from the core into the downstream. The migration of fines leads to time-dependent changes in the local permeability and shear strength of different dam zones. As a result, taking into account the influence of the movement of fines on the

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Nomenclature

(Bold faced symbols are used for tensor quantities.)

$\mathbf{1}$	second order identity tensor
a	fitting parameter for Eq. (4)
A	anisotropic state parameter (Eqs. (13) and (15))
A_c, A_e	anisotropic state parameter values under the compression and extension modes of triaxial
b	intermediate principal stress ratio $\{=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)\}$
c	$=M_e/M_c$ {see $g(\theta,c)$}
C_u	uniformity coefficient
D	Dilatancy (Eqs. (21) and (33))
D_{10}	effective size of host sand
d_{50}	mean size of fines
$\mathbf{e}$	deviator part of strain tensor
e	global void ratio
e^*	intergranular void ratio (Eq. (3))
e_{cs}	critical state void ratio
e_{max}, e_{min}	maximum and minimum void ratios
e_{sk}	skeleton void ratio (Eq. (2))
f_1, f_2	fitting constants for Eqs. (12) and (20)
$f(\boldsymbol{\sigma}, \boldsymbol{\alpha})$	yield surface (Eq. (25))
$\mathbf{F}$	second order fabric tensor (Eq. (14))
FC	fines content
FC_{th}	threshold fines content (Eq. (1))
$F(e)$	void ratio function (Eq. (17))
G	elastic shear modulus (see Section 4.4)
G_0	fitting constant for Eq. (17)
$g(\theta$,c)	interpolation function $(=2c/[(1+c)-(1-c)\cos 3\theta]$
H_0, H_A	see Eqs. (20) and (34)
H_{0c}, H_{0e}	values of H_0 under the compression and extension modes of triaxial
$H(e)$	void ratio function (Eq. (34))
K	elastic bulk modulus (Eq. (27))
K_p	plastic hardening modulus (Eq. (34))
$\mathbf{L}$	normal to yield surface (Eq. (29))
m	a model parameter (Eq. (25))
M_c, M_e	slopes of critical state lines in q–p plane under the compression and extension modes of triaxial
n	fitting constant for Eq. (17)
$\mathbf{n}$	deviator part of $\mathbf{L}$ (Eqs. (29) and (30))
n^b, n^d	fitting constants for Eq. (32)
N	$=\mathbf{n}:\mathbf{r}$ (Eq. (30))
p	mean principal effective stress
p_{in}	initial values of mean principal effective stress
p_{ref}	reference pressure (=101 kPa)
q	deviator stress
r	roundness ratio $(=R_c/R_f)$
$\mathbf{r}$	shear stress ratio tensor $(=\mathbf{s}/p)$
R_c, R_f	average roundness values of coarse and fines constituents
$\overline{R}$	average roundness of soil
$\mathbf{s}$	deviator part of effective stress tensor
$\boldsymbol{\alpha}$	back stress ratio tensor
$\boldsymbol{\alpha}^b$, $\boldsymbol{\alpha}^c$, $\boldsymbol{\alpha}^d$	back stress ratios corresponding to bounding surface, critical state surface, and dilatancy surface (Eq. (32))
β	fines influence factor (Eqs. (3) and (4))
β_0	fitting parameter for Eq. (4)
Δ	vector magnitude (Eq. (14))
Δ_c, Δ_f	vector magnitudes of clean coarse and fines constituents
$\boldsymbol{\varepsilon}$, $\boldsymbol{\varepsilon}^e$, $\boldsymbol{\varepsilon}^p$	total, elastic, and plastic strain tensors
ε_1, ε_3	major and minor strains
θ	Lode angle
λ	fitting constants for Eq. (11)
$\dot{\Lambda}$	loading index
ν	Poisson's ratio (Eq. (27))
ξ	fitting constants for Eq. (11)
$\boldsymbol{\sigma}$	effective stress tensor $(=\mathbf{s}+p\mathbf{1})$
σ_1, σ_2, σ_3	major, intermediate, and minor principal effective stress components
ω_1, ω_2	fitting constants for Eq. (19)
ϕ_{cs}	critical state friction angle
χ	particle size ratio $(=D_{10}/d_{50})$
ψ	state parameter (Eq. (9))
ψ^*	intergranular state parameter (Eq. (10))

mechanical response of dam requires an elaborated coupled analysis for seepage and fines transport combined with a constitutive model for simulation of the mechanical behavior of soil taking into account varying fines content (Muir Wood and Maeda [30]). The existing state-of-the-art sand constitutive models are utterly formulated for modeling of clean sands. In such models, soil behavior is greatly dependent on sand state measured with respect to a unique critical/steady state line [11,12,23-25,35]. This hypothesis works reasonably well for clean sands; however, its application for sands containing considerable fractions of fines is troublesome (e.g., [31,59,70]). Yamamuro and Lade [71] was the first who suggested a constitutive model for silty sands. However, the need for recalibration of yield function and model parameters for different fines contents, densities, and stress levels limit the model applicability in practice. Recently, Chang and Yin [6] introduced micromechanical constitutive models for simulation of the mechanical behavior of sand–silt mixtures.

This study focuses on establishing a unified critical state compatible framework for constitutive modeling of both clean and silty sands. The proposed method is generic and can be applied to other existing frameworks. The conventional elastoplastic models of granular soils consist of the following ingredients: constitutive equations describing the elastic behavior, plastic flow rule and stress–dilation constitutive equations, and constitutive equations for the plastic hardening response. Furthermore, the recent constitutive models are usually state-dependent and can take into account the influence of soil anisotropy on stiffness, dilation, and strength [11,12,23-25,35]. As a result, critical state line, state parameter, and fabric tensor are usually introduced in their formulations. Throughout the paper, a comprehensive literature review regarding the influence of adding non-plastic fines on each of the above ingredients is presented first. For each element, relevant new/modified constitutive equations with the possibility of smooth transition from the clean state (zero fines content) to the threshold fines content are presented. Then, the new/modified elements are implemented within the general formulation of the bounding surface plasticity platform of Dafalias et al. [12] that is a pure phenomenological constitutive model. According to Hegel (1724–1804), phenomenology is an approach to philosophy that begins with an exploration of phenomena (i.e., what presents itself to us in conscious experience) as a means to finally grasp the absolute, logical, ontological and metaphysical spirit that is behind the phenomena. Similar to the approach of Dafalias et al. [12] in establishment of the original platform, a phenomenological view is considered here in modification/suggestion of constitutive equations taking into account the influence of non-plastic fines