Modelling the plastic response of dilative and compacting soils with suffusion

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Thread

1. Introduction: modelling strategy
2. A plasticity model accounting for suffusive behaviour
   - Model formulation
   - The case of dense dilative soils
   - The case of loose compactive soils
3. Conclusions and outlook

Is a Cam-Clay based model able to capture suffusion effects ?

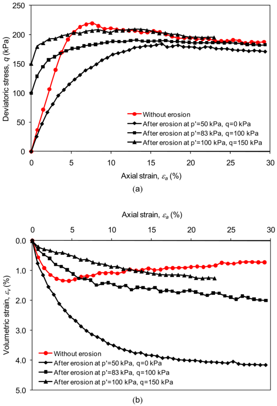
What to model ?

Suffusion may have different mechanical implications, depending on the soil initial properties.

Features for dense/dilative soils

i) Switching behaviour from dense to loose
ii) Vanishing of the strenght peak
iii) (Induced strain)

(Observations from Chang and Zhang [2011])



After Chang and Zhang [2011]

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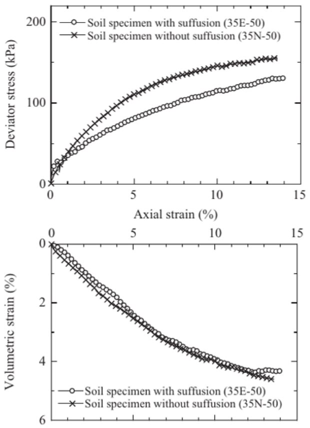

After Ke and Takahashi 2014 [2014]

Features for loose/contractive soils

i) Preserved loose behaviour

ii) Residual strength reduction

iii) (Induced strains)

(Observations from Ke and Takahashi [2014])

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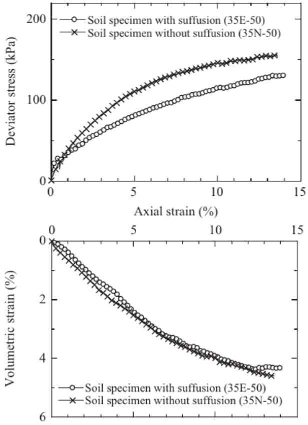

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Features for loose/contractive soils

i) Preserved loose behaviour
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(Observations from Ke and Takahashi [2014])

Modelling strategy

i) Classical elasto-plasticity theory
ii) Extend an existing model (e.g. Cam-Clay based)
iii) Keep it as simple as possible
iv) Evaluate its abilities

Kinematics of a suffusive porous medium

Hypothesis : grains are incompressible

Classical porous medium:
Volume changes = porosity variations

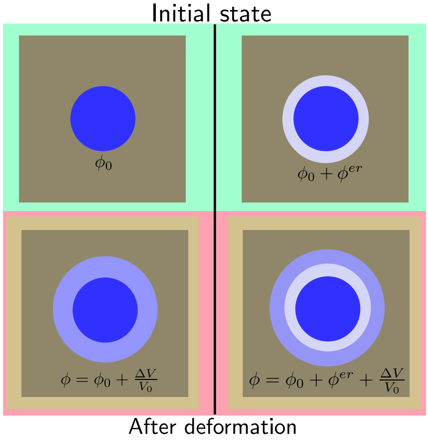
$$\frac{\Delta V}{V_0} = \phi - \phi_0$$

Accounting suffusion

According Zhang et al., [2010]:
Suffusion = modification of the reference state (before deformation).

Suffusive porous medium : $$\frac{\Delta V}{V_0} = \phi - \underbrace{(\phi_0 + \phi^{er})}_{\text{reference}}$$

ϕ^{er} : porosity generated by suffusion



The parent model: "Sinfonietta-Classica" (R. Nova [1988])

Loading surface and plastic potential

$$f\left(\boldsymbol{\sigma}', p_c\right) = 3\beta\,(z-3)\ln\frac{p'}{p_c} + \frac{9}{4}(z-1)\frac{q^2}{p'^2} + z\frac{\det \mathbf{s}'}{p'^3}$$

$$g\left(\boldsymbol{\sigma}', p_g\right) = 9\,(z-3)\ln\frac{p'}{p_g} + \frac{9}{4}(z-1)\frac{q^2}{p'^2} + z\frac{\det \mathbf{s}'}{p'^3}$$

The plastic flow

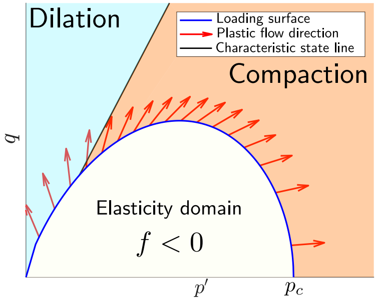
Non associative flow rule : $\dot{\varepsilon}^p_{ij} = \dot{\lambda}\,\dfrac{\partial g}{\partial \sigma'_{ij}}$

The hardening law

$$\dot{p}_c = \frac{p_c}{\beta_p}\left(-\dot{\varepsilon}^p_v + \varkappa\left\|\dot{\varepsilon}^p_d\right\|\right)$$

i) β_p : plastic compliance

ii) $\varkappa$: deviatoric hardening (typical for medium/dense sands)



Loading surface and plastic flow direction (Cambridge plane)

Improving the parent model (1/2) : hardening law

Notation

ϕ^{ir}: irreversible porosity

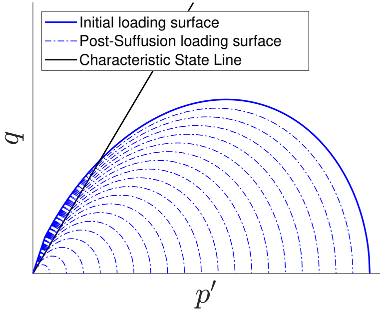
Rephrasing and improvement

Without suffusion : $\dot{\varepsilon}_v^p = \dot{\phi}^{ir}$

$$\dot{p}_c = \frac{p_c}{\beta_p}\left(-\dot{\phi}^{ir} + \varkappa\dot{\bar{\epsilon}}^p\right)$$

With suffusion : $\dot{\phi}^{ir} = \dot{\varepsilon}_v^p + \dot{\phi}^{er}$

$$\boxed{\dot{p}_c = \frac{p_c}{\beta_p}\left(-\dot{\varepsilon}_v^p - \dot{\phi}^{er} + \varkappa\dot{\bar{\epsilon}}^p\right)}$$



Shrinking of the elasticity domain

Consequences

i) $\dot{\phi}^{er} > 0 \Rightarrow \dot{p}_c < 0$: the elasticity domain shrinks

ii) If dense sand: the peak strenght vanishes

iii) Transition in the behaviour: dense $\rightarrow$ loose

iv) Plastic strains develops while suffusion occurs

Improving the parent model (2/2) : hardening law

From dense to loose

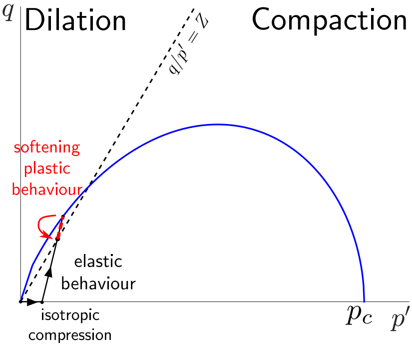
i) Drained triaxial loading (CD)

ii) Comparison with/without suffusion

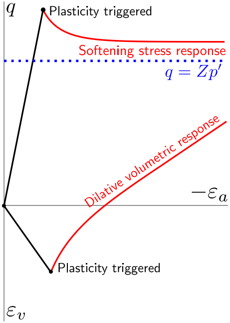
The behaviour typology depends on the stress state

i) if $q/p' < Z$: Contractive behaviour

ii) if $q/p' > Z$: Dilative behaviour



Loading path, without suffusion



Stress strain behaviour, without suffusion

From dense to loose

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ii) Comparison with/without suffusion

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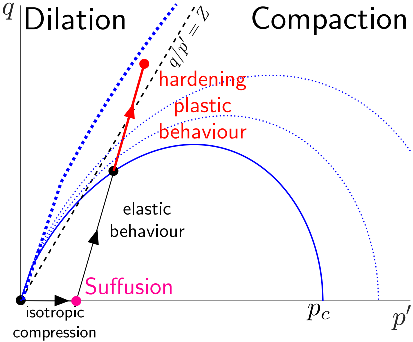
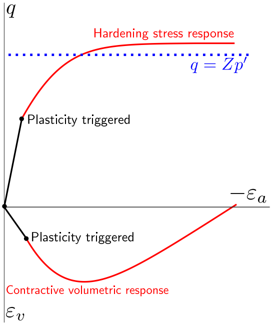


Loading path, with suffusion



Stress strain behaviour, with suffusion

Test program

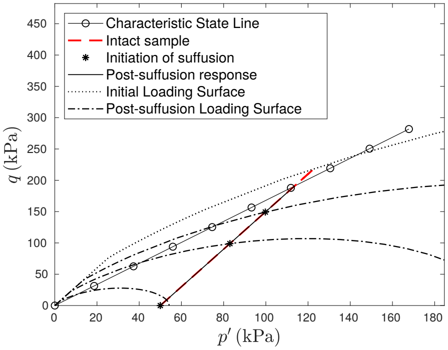
1) Strain driven loading toward a given q'_p
2) Suffusion-like loading :

$$\phi^{er} : \quad 0 \xrightarrow{+d\phi^{er},\ d\boldsymbol{\sigma}' = \mathbf{0}} \phi^{er}_{max}$$

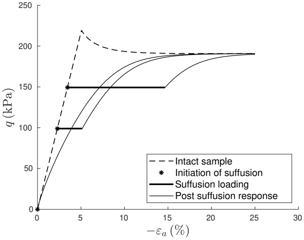
3) Strain driven loading
4) Mechanical failure

Parameters (calibrated with respect to Chang and Zhang [2011])

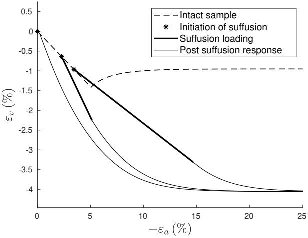
$E = 4.34\,\mathrm{MPa}$, $\nu = 0.36$, $p_{c0} = 720\,\mathrm{kPa}$, $\beta = 1.2$, $\beta_p = 0.012$, $\varkappa = 0$



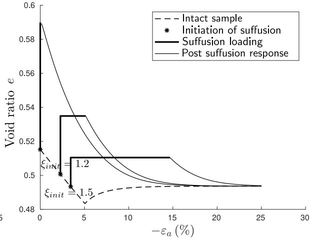
Drained triaxial compression loading path



Stress response



Volumetric response (1)



Volumetric response (2)

Model abilities

i) The peak strenght vanishes

ii) Dense $\rightarrow$ Loose

iii) Plastic strains develops while suffusion occurs

iv) Critical state is not affected

v) Experimental behaviour is qualitatively captured

The case of the loose sands : characteristic state parametrization

Characteristic state

$$\frac{q}{p'} = \frac{6 \sin \varphi}{3 - \sin \varphi} \Rightarrow \dot{\varepsilon}_v^p = 0$$

Porosity parametrization

$$\varphi\left(\phi^{er}\right) = \frac{1}{2}\varphi_{er}\left(1 + \tanh\left(\frac{1}{l}\left(\phi^{er} - A\phi^{er}_{max}\right)\right)\right) + \frac{1}{2}\varphi_i\left(1 + \tanh\left(\frac{1}{l}\left(A\phi^{er}_{max} - \phi^{er}\right)\right)\right) \quad (1)$$

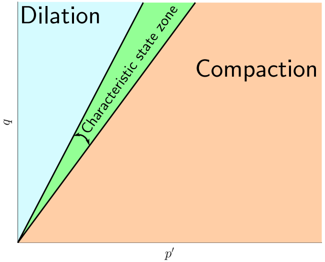
- $A\phi^{er}_{max}$: porosity threshold
- l : transition bandwidth

Consequences

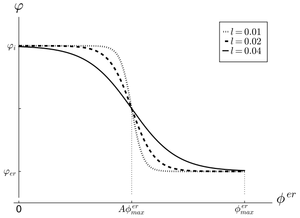
i) Characteristic state *zone*

ii) Transition from contractive to ↔ dilative

iii) Reduction of residual strenght



Characteristic state *zone*



Evolving characteristic state friction angle

Simulations : loose gap-graded under drained triaxial compression (1/2)

Programme d'essai

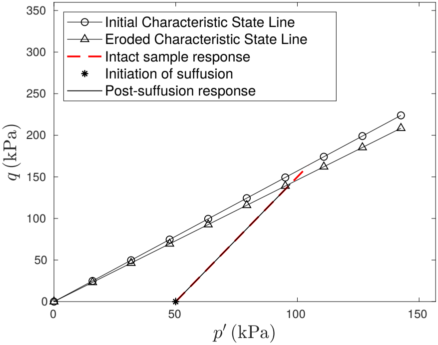
1) Suffusion-like loading :

$$\phi^{er} : \quad 0 \xrightarrow{+\Delta\phi^{er},\ \Delta\boldsymbol{\sigma}' = \mathbf{0}} \phi^{er}_{max}$$

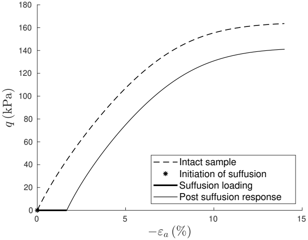
2) Strain driven loading
3) Mechanical failure

Parameters (calibrated with respect to Ke and Takahashi [2014])

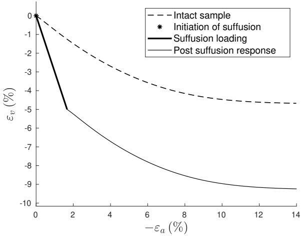
$E = 3.46\,\mathrm{MPa}$, $\nu = 0.25$, $p_{c0} = 50\,\mathrm{kPa}$, $\beta = 1.2$, $\beta_p = 0.01$, $\varkappa = 0$,



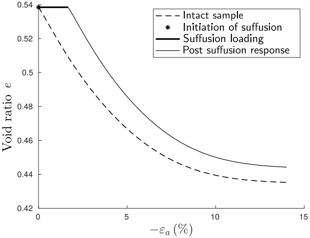
Drained triaxial compression loading path



Réponse contrainte déformation



Réponse volumique (1)



Réponse volumique (2)

Model abilities

i) Loose behaviour is preserved

ii) Critical state changes

iii) Experimental behaviour is qualitatively captured

Conclusions and outlook

Model technical advantages

1) Simple Cam-Clay based model with few new parameters (0 or 5)
2) Suffusion induced porosity is naturally introduced as hardening variable
4) Calibration against *exp. data* is possible. (see for details Nova, (1988))

Model abilities

1) Strenght peak desapearance
2) Eventual residual strenght reduction
3) Change in the volumetric behaviour
4) Suffusion induced strains

Outlook

1) *Poro*-elastoplastic modelling
2) *Proper model calibration with respect to laboratory test (triaxial apparatus, oedo-permeameter)*
3) Consider the effect of suffusion induced heterogeneities (master thesis starting in feb/march 2021)

Thank you for your attention

References

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