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Research Paper

An elasto-plastic damage model for argillaceous geomaterials

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A B S T R A C T

The aim of this paper is to present a new elastoplastic damage model for unsaturated porous media. The proposed model within the context of poromechanics is intended for constitutive modelling of geomaterials which show two (irreversible) dissipative aspects involving plastic flow and damage. Independent stress state variables, namely net stress and suction, are adopted as stress variables of the model. Barcelona Basic Model is extended to a non-isothermal formulation and is coupled to a damage formulation using damage dependent yield surface and damaged stress variables. The stress state variables are transformed into the damaged state through the definition of effective damaged suction and effective damaged net stress in the framework of Continuum Damage Mechanics (CDM). Damage effects on intrinsic permeability and transfer laws are also taken into consideration. The model has been implemented in Θ-STOCK Code and predictive capabilities of the model have been evaluated against experimental results from the literature. The model is validated by comparing the numerical results with experimental results of argillites and results of an elastodamage model. The proposed model is also shown to give satisfactory simulation results which match the experimental data from a heating test on bentonite samples.

1. Introduction

Nonlinearity of behaviour of geomaterials was traditionally attributed to slippage and dislocation of particles of porous media skeleton and was therefore modelled using mere elastoplastic models. Based on this hypothesis, many models have been developed for geomaterials (Alonso et al., 1990; Gallipoli et al., 2003; Wheeler et al., 2003; Shuku et al., 2012; Xiong et al., 2014 among others) and they have widely been employed either for research or for practical engineering purposes. After a long period of neglect, recently there has been increasing interest in the modelling of damage in geotechnical engineering and some damage models have been introduced in this context. However, it is often reported that a considerable range of geomaterials exhibit two dissipative mechanisms.

The experimental results from triaxial tests performed by Chiarelli (2000) have shown two basic phenomena on the overall mechanical responses of the sedimentary rocks (Chiarelli et al., 2003). Irreversible strains essentially related to plastic deformation by clay sheet sliding which is associated with a progressive damage (Alba et al., 2009; Zheng et al., 2014). Accordingly both of these dissipative aspects should be taken into account; therefore an elastoplastic damage model is required for constitutive modelling of such geomaterials.

For constitutive modelling of multi-phase unsaturated porous medium, complex aspects of governing mechanisms should be adequately accounted for. In such media, mechanical response (plastic flow and fracturing) combined with suction (capillary) effects and water retention characteristics should be taken into consideration, which undoubtedly induce complex poromechanical couplings. The model dedicated to this class of materials should be capable of addressing such effects in a sufficiently rigorous manner. The adoption of stress state variables is the first step and an essential prerequisite for a suitable formulation of such models. Hence, a chronological development of stress variables for modelling of unsaturated porous media is briefly reviewed in the sequel to summarize the principal ideas (e.g. independent and combined stresses) to adopt most appropriate ones.

The difficulty was early realized in 1950s and 1960. During this period, concentrated researches were carried out to investigate unsaturated soils behaviour and a large effort was made to interpret the experimental observations by use of extension of Terzaghi's Effective stress to the unsaturated state. Bishop's effective stress (Bishop, 1959) was one of the well-known definitions which clearly failed to justify unsaturated soils behaviour, particularly, in the case of volumetric behaviour.

Development of effective stress expressions for unsaturated soils, therefore, came inevitably under criticism and the notion of adoption of two stress variables emerged in the geotechnical literature (e.g. Coleman, 1962; Bishop and Blight, 1963; Blight, 1967). Matyas and Radhakrishna (1968) followed this framework and proposed their state surfaces for degree of saturation and void ratio. The state surfaces were originally introduced to explain the hydro-mechanical behaviour of unsaturated soils and are typically accompanied with nonlinear elasticity problems (Gatmiri and Delage, 1997; Gatmiri et al., 1997).

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Nomenclature

C_0	material parameter
C_1	material parameter
C_a	material parameter
C_{PW}	water specific heat capacity
C_{PV}	vapour specific heat capacity
C_{Pa}	gas specific heat capacity
e	void ratio
F_p	plastic yield surface
F_d	damage yield surface
g	material parameter
H	Henry's coefficient
h_{fg}	latent heat of vaporization
$\boldsymbol{Id}$	identity matrix
$\boldsymbol{K_{int}^{tot}}$	intrinsic permeability tensor
K_{rt}	relative thermal permeability
K_{rc}	relative capillary permeability
M	slope of critical state line
n	porosity
p	mean net stress
$\hat{p}$	damaged effective mean net stress
p_{geo}	geostatic stress
p_{ref}	reference stress
p_s	intercept of plastic yield surface
$\hat{p}_s$	damaged counterpart of p_s
Q	total heat flow
q	deviatoric stress
$\hat{q}$	damaged deviatoric stress
s	matric suction
$\hat{s}$	damaged effective suction
G	Gibbs free energy
r	material parameter
S_r, S_w	liquid degree of saturation
T	temperature
t, t'	time
u_a	air pressure
u_w	water pressure
α_0^*, α_1	material parameter
α_2, α_3	material parameter
α_a	material parameter
α_w	material parameter
β	material parameter
β_1	material parameter
β_2	material parameter
κ_i	conventional unloading-reloading compression index
κ_s	elastic stiffness parameter for suction changes
γ_H	plastic compressibility modulus
γ_T	material parameter for thermal evolution
γ_w	unit weight of water
γ_{vap}	unit weight of water
$\boldsymbol{\varepsilon}$	strain tensor
ε_v^p	plastic volumetric strain
η_{air}	dynamic viscosity of air
η_w	dynamic viscosity of water
θ, θ_w	water content
ρ_a	density of air
ρ_{vap}	density of vapour
ρ_w	density of water
$\lambda(s)$	suction-dependent slope of virgin consolidation line
λ_{equ}	thermal conductivity (Fourier heat diffusion coefficient of unsaturated mixture)
Ω	scalar damage variable
$\boldsymbol{\Omega}$	tensorial damage variable
$\boldsymbol{\sigma}$	Cauchy stress tensor
$\boldsymbol{\sigma}'$	effective stress
$\boldsymbol{\sigma}''$	net stress
$\hat{\boldsymbol{\sigma}}''$	damaged effective net stress
Φ	volumetric bulk heat content

Fredlund and Morgenstern (1977) proposed a set of stress state variables for unsaturated soils. They presented the results of null tests supporting their choice and indicated that any couple of variables among $(\boldsymbol{\sigma} - u_a)$, $(\boldsymbol{\sigma} - u_w)$ and $(u_a - u_w)$ can be employed as stress state variables for modelling of unsaturated soils behaviour.

Alonso et al. (1990) pioneered elastoplastic constitutive modelling of unsaturated soils by their celebrated model which was later referred as Barcelona Basic Model (BBM). BBM uses two independent stress variables, net stress (the total stress in excess of pore air pressure) and the suction (the pore air pressure in excess of pore water pressure), as a basis for its formulation.

In recent decades there has been a renewal of interest in justification and application of pseudo-effective stress definitions for unsaturated porous media. For instance, Khalili and Khabbaz (1998) demonstrated supporting evidence for the validity of Bishop's effective stress expression. They proposed a relationship between the effective stress parameter χ and the suction ratio (ratio of suction over the air entry value). Some authors (e.g. Hutter et al., 1999) made attempts to validate Bishop's effective stress by making use of averaging methods and mixture theories. Sheng et al. (2003a) used the term '*Constitutive stress*' for the Eq. (1) as a state variable:

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \boldsymbol{m}\varphi(S_r)u_w \tag{1}$$

where $\mathbf{m}$ is the column vector with 1 at normal stress entries and 0 at shear stress entries, $\varphi(S_r)$ is the constitutive stress parameter that depends on the degree of saturation S_r or the suction, and u_w is the pore water pressure. To eliminate the need for a material parameter for the constitutive stress function, this function is set to either $\varphi = S_r$ or $\varphi = \sqrt{S_r}$ in the problems analyzed by Sheng et al. (2003b).

The resurgence of the models based on Bishop-type effective stress in recent years is accompanied with realization of the fact that two stress variables are required for modelling of an unsaturated soil medium. Indeed, as Jommi (2000) pointed out "in fact, no single stress variable has ever been found which, substituted for effective stress, allows for a description of all the aspects of the mechanical behaviour of a given soil in the unsaturated range." As a result in such models, the suction is used as a hardening variable or a stress variable along with the other variable. Accordingly, Laloui and Nuth (2009) and Nuth and Laloui (2008) proposed the following set of stresses for the modelling of unsaturated soils and referred to them as the '*generalised stresses*' for unsaturated soils in which Bishop's stress and suction are respectively conjugated to strain and degree of saturation.

$$\begin{array}{l}\boldsymbol{\sigma}'_{Bishop} \leftrightarrow \boldsymbol{\varepsilon} \\ s \leftrightarrow S_r\end{array} \tag{2}$$

Overall, the complex stress variables (e.g. Bishop's effective stress) are dependent on material states and therefore are not straightforwardly controllable in conventional laboratory testing procedures. It is not feasible to develop an entirely new constitutive relationship in terms of these variables, unless an existing framework is used (Sheng et al., 2008). In the models which make use of the Bishop's effective stress with the parameter $\chi = S_r$, the inherent hydro-mechanical coupling is greatly dependent on the water retention relation used in the model. This entails utilizing sophisticated water retention models. Consequently the water retention properties of unsaturated medium should be specifically determined and it may necessitate the use of hysteretic water retention models in addition to mechanical formulation.

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