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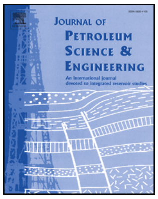

Wetting collapse analysis on partially saturated oil chalks by a modified cam clay model based on effective stress

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ABSTRACT

This paper presents an interpretation of wetting collapse in partially saturated oil chalks subjected to water flooding. For this purpose, two competitive mechanisms, namely, compressive plastic strains and elastic swelling, have been analyzed through a modified Cam Clay model based on effective stress. The resulting simulation shows that, mechanical behaviors of oil chalks upon wetting have been captured with good accuracy. The interpretation detects the possibility of wetting compaction/swelling for oil chalks under different stress states, emphasis is also placed on specific conditions for the occurrence of wetting collapse. Inspections on effective stress and preconsolidation stress paths show that, the distance between two streams plays the main role on the magnitude of accumulated compressive plastic strain. Since wetting process generally leads to two competitive deformation, elastic swelling due to the diminution of suction and additional plastic flow due to the diminution of plastic yield stress (contraction of yield surface), the plastic compaction would outweigh elastic swelling if a threshold value of suction can be achieved.

1. Introduction

Wetting collapse of partially saturated, highly-porous oil chalks, have been concerned in fields of mining and petroleum engineering. Typical examples reported in these fields are, instability of underground quarry subject to long term wetting-drying cycle (De Gennaro et al., 2005; Duperret et al., 2005; Sedki et al., 2002; Sorgi and Gennaro, 2011), collapse of chalk filled embankment upon water flooding (Clayton, 1980; Ingoldby, 1979; Parsons, 1981; Rat and Schaeffner, 1989), remarkable subsidence of seabed and eventual undersea earthquake due to enhanced oil/gas recovery (Collin et al., 2002; De Gennaro et al., 2004; Delage et al., 1996; Maury et al., 1996; PASACHALK2, 2004). Although, it is accepted that, the collapse of chalk filled embankment and seabed settlement in oil/gas field is the compaction of chalks subjected to water weakening and overburden pressure (De Gennaro et al., 2004), the mechanism or the origin of wetting induced compaction is still an open filed for research.

It is note that, two main competitive deformation mechanisms can be identified during wetting process, elastic swelling due to the reduction of suction and corresponding plastic flow due to the decreasing plastic yield stress (contraction of yield surface). For this reason, both experimental investigation (De Gennaro et al., 2006; Delage et al., 1996; Priol et al., 2006; Schroeder et al., 1998; Taibi et al., 2009; Wan et al., 2013) and theoretical analysis (Bell et al., 1990; Brignoli and Sartori, 1993; Duperret et al., 2005; Jia et al., 2010; Ma, 2016; Papamichos et al., 1997; Talesnick et al., 2001) are carried out with the help of some concepts and approaches applied in unsaturated soil mechanics (De Gennaro et al., 2004; Ma, 2016; Wan et al., 2013). In line with well-developed frameworks in the community of unsaturated soils, constitutive models developed recently (Brignoli et al., 1994; Collin et al., 2002; Homand and Shao, 2000; Ma, 2016; Maury et al., 1996; Navarro et al., 2010; Papamichos et al., 1997; Piau and Maury, 1995; Taibi et al., 2009) sheds light on the mechanisms of water weakening and suction hardening effects in partially saturated oil chalks. Generally, two main approaches are classified: one is the analysis based on 'independent stress state concept (net stress and suction, being treated as independent state variables, or the so-called Barcelona concept)' (Alonso et al., 1990; Fredlund and Morgenstern, 1976, 1977; Sheng et al., 2008) and the other on effective stress approach (Bishop, 1959; Bishop and Donald, 1951; Khalili and Khabbaz, 1998; Loret and Khalili, 2002).

The 'independent stress state concept' although is able to capture some basic mechanical responses of unsaturated geo-materials, including plastic collapses upon wetting and stiffer mechanical responses upon drying (Collin et al., 2002; Homand and Shao, 2000; Maury et al., 1996; Navarro et al., 2010; Papamichos et al., 1997; Taibi et al., 2009). The main demerit of this approach has been discussed extensively; specifically, with an increasing suction in normally consolidated soils plastic volumetric change followed by an elastic response could not be captured (Fleureau et al., 1993). In addition, two plasticity models are

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prescribed for saturated and unsaturated states, which requires a considerable amount of laboratory testing to calibrate model parameters (Loret and Khalili, 2002). In contrast, the effective stress approach only require a single set of model parameters, this simplicity is significant because model parameters under partially saturated states would be the same as those applied in fully saturated state, except the air entry/expulsion values and suction hardening (Loret and Khalili, 2002). Thus, a unified, simple, yet effective framework can eliminate the demerits of time consuming and prohibitive cost in practical application marked by ‘independent stress state concept’ (Ma, 2016; Ramos da Silva et al., 2008; Schmitt et al., 1994; Van Eeckhout, 1976).

Although previous contribution centers on deformation of solid skeleton and variation of strength associated with saturation changes. Very few study describe the wetting induced two competitive deformation mechanisms explicitly, e.g. elastic response observed in the initial wetting stage, plastic contraction in the second stage, and elastic swelling in the last period of wetting process for partially saturated rocks under various stress conditions. For this reason, this paper aims to present an interpretation of wetting collapse in partially saturated oil chalks by a modified Cam Clay model (MCC) based on the effective stress approach. Detailed reasoning of the contraction of yield surface and the effective stress variation with decreasing suction have been presented, emphasis is also placed on specific conditions for the occurrence of wetting collapse.

Sign convention and notation: compression is defined to be positive and tension negative to keep the conventional simplicity in geomechanics. Tensor/matrix variables are denoted by bold symbols; $\sigma'_2 - \sigma'_2$ represents the deviatoric stress tensor and $\sigma'_1 - \sigma'_1$, where $\boldsymbol{\delta}$ is the identity vector. Triaxial notation ($p' - q$ plane) is applied, with effective mean stress being written as $p' = \frac{\sigma'_1 + 2\sigma'_3}{3p'} = \frac{\sigma'_1 + 2\sigma'_3}{3}$ and deviatoric stress $q = \sqrt{3J_2}$. The volumetric strain is expressed as $\varepsilon_p = \varepsilon_1 + 2\varepsilon_3 \varepsilon_p = \varepsilon_1 + 2\varepsilon_3$ and the deviatoric strain is taken $\varepsilon_q = \frac{2(\varepsilon_1 - \varepsilon_3)}{3\varepsilon_q} = \frac{2(\varepsilon_1 - \varepsilon_3)}{3}$, with $\varepsilon^{dev} = \varepsilon - \delta Tr(\varepsilon)/3$.

2. Theoretical background

2.1. Suction and wetting induced two main deformation mechanisms

Partially saturated chalks compose of three main phases: solids, a wetting fluid (normally water) and a non-wetting fluid (normally air/gas or other liquids such as oils in some oil filed), the stress state can be described by three main components: total stress ($\boldsymbol{\sigma}$), water pressure (p_w) and air pressure (p_a) (Loret and Khalili, 2000). The difference between air pressure and water pressure is defined as matrix suction: $S = P_a - P_w$, which is introduced to consider the contribution of surface tension at the interface between phases in partially saturated porous media. The net stress is expressed as the difference between total stress and air pressure: $\boldsymbol{\sigma}_{net} = \boldsymbol{\sigma} - P_a\boldsymbol{\delta}$. Thus, within the approach of effective stress, deformation in solid skeleton associated with variations in total stress, pore air pressure and pore water pressure is captured through a single set of stress, namely effective stress, defined by a general expression (Bishop, 1959)

$$\sigma' \equiv (\sigma - P_a\delta) + \chi(S)(P_a - P_w)\delta = \sigma_{net} + \chi(S)S\delta \tag{1}$$

where, $\chi(S)$ is the suction or saturation dependent parameter for effective stress. It is really apparent that the reduction in suction would lead to diminution in effective stress, corresponding to swelling in the wetting process. This process also can be regarded as the unloading procedure, its corresponding mechanical behavior is supposed to be elastic without the consideration of wetting weakening.

The other contribution of suction for partially saturated media is the hardening effect on yield surface within the effective stress space (or the size of yield surface), which normally expressed as a function of current stress state and a plastic hardening parameter

$$f(\sigma', p'_o(\varepsilon_p^p, S)) = 0 \tag{2}$$

in which, $p'_o(\varepsilon_p^p, S)$, controlling the size of the yield surface, is a plastic hardening parameter which depends on both the plastic volumetric strain and suction. Thus, it can be interpreted that the reduction in suction would lead to the diminution of yield surface, corresponding to plastic softening, or water weakening. Therefore, sustaining a constant net stress state, wetting process may result in a mechanical compaction owing to the deteriorate of material properties. This process is also called wetting collapse, which is associated with plastic behaviours of partially saturated geo-materials and their interaction between geosystems. Obviously, wetting induced compaction must serve as the main plastic driver for constitutive models.

Based on the discussion above, two main competitive deformation mechanisms can be identified for partially saturated porous media upon wetting, the elastic swelling due to diminution of effective stress and the plastic compaction owing to the reduction in plastic yield surface. Thus, the interpretation of wetting collapse must account for both two mechanisms; otherwise, the simulation produced by constitutive models may violate collapse experiments or subsidence field observations. In addition, the competition between elastic swelling and plastic compaction relies on both the reduction in effective stress and the deteriorate of material properties, thus, an appropriate definition of effective stress is pivotal for capturing the responses of elastic swelling, and a capable suction hardening law plays the key role in modelling the contraction of yield surface associated with plastic compaction. Moreover, collaborating the suggestion that wetting collapse must be interpreted as a plastic mechanism, the plastic driver applied in the constitutive framework should be as simple as possible, ensuring that the two main deformation mechanisms have been taken into account appropriately. Thus, a simple, yet effective elastic-plastic framework (modified cam clay), has been adopted in this paper, which is expressed in the effective stress space. Note that, other plastic drivers are also acceptable, the simple approach suggested here is to keep the analysis as simple as possible, with limited number of model parameters.

2.2. The occurrence condition of wetting collapse

The so called wetting collapse is characterised by large plastic compaction upon small changes in hydraulic conditions, suggesting that the structure of unsaturated media is metastable (Brink and Heymann, 2014; Mihalache and Buscarnera, 2015). Inspection of some filed observation and experimental work reveals that, the subsidence of oil chalk seabed and wetting compaction of some partially saturated porous medias normally takes places gradually, indicating a controllable process that can be verified through a continuum mechanical approach (Collin et al., 2002; Homand and Shao, 2000; Maury et al., 1996; Navarro et al., 2010; Papamichos et al., 1997; Taibi et al., 2009). In addition, if a sharp change in compressive strain occurred during wetting process, the loss of stability of deformation should also be verified through an appropriate model to figure out the threshold strength upon wetting. Thus, no matter the wetting induced compaction is stable or not, within the framework of continuum mechanics, elastic swelling due to unloading effect follows a basic loading law

$$\dot{\varepsilon}_p^e = L_e(\dot{\sigma}'(S)) \tag{3}$$

and plastic compaction due to the deteriorate in material properties follows

$$\dot{\varepsilon}_p^p = L_p(\dot{\sigma}'(S), p'_o(\varepsilon_p^p, S)) \tag{4}$$

Where,L represents loading function, subscript e and p indicate elastic and plastic loading, respectively. Therefore, the onset wetting compaction is satisfied if

$$\dot{\varepsilon}_p^e + \dot{\varepsilon}_p^p = L_{ep}(\dot{\sigma}'(S), p'_o(\varepsilon_p^p, S)) = 0 \tag{5}$$

which corresponding to a threshold suction S^*; and this process would