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Modelling water retention and volume change behaviours of unsaturated soils in non-isothermal conditions

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ABSTRACT

This study presents a simple approach to modelling the effect of temperature on the soil–water retention curves (SWRCs) of deformable soils and takes into consideration the following two aspects: (1) the effect of temperature on the liquid–gas interfacial tension and (2) temperature-induced deformation of the soil skeleton. The first aspect, the temperature effect, can be modelled using an equation proposed by Grant and Salehzadeh [18], but the second aspect is generally neglected in the literature. To quantify the thermo-hydro-mechanical (THM) deformation of unsaturated soils (i.e., the second aspect mentioned above), a simple volume change equation, referred to as the non-isothermal SFG volumetric equation, is proposed on the basis of the original SFG framework [37]. A three-dimensional THM yield surface in the space of net mean stress, suction and temperature is presented here. The proposed volume change equation is integrated into the non-isothermal SWRC by means of a simple hydro-mechanical coupling law [38]. The performance of the non-isothermal SFG volumetric equation and the non-isothermal SWRC equation is investigated through several numerical examples. A number of experimental results reported in the literature are employed to confirm the validity of the proposed non-isothermal SFG volume change equation and the non-isothermal SWRC equation.

1. Introduction

The water retention behaviour of a soil is usually described by a soil–water retention curve (SWRC, also referred to as a water retention curve, WRC, or a soil–water characteristic curve, SWCC), which is defined as the relationship between the degree of saturation (S_r) (or the effective degree of saturation, S_e) and the matric suction (s) (or soil–water potential, ψ). It is usually obtained by drying or wetting a soil sample under a constant stress while monitoring the water released from or absorbed by the specimen and the total volume change of the specimen. Since the beginning of the 20th century, a great many analytical and empirical SWRC equations have been proposed to model the soil–water retention behaviour of soils (e.g., [16,7,23,47,15], etc.). SWRCs are known to be affected by a number of factors, such as the pore size and pore shape distribution, the specific surface area, the particle size distribution, the chemo-physical properties of the soil phases, the soil density and the temperature (e.g., [1,8,29,2,10], etc.). These factors can be classified into two groups: *internal* and *external* factors. The internal factors are those related to the soil type, such as the particle size distribution, the pore size and pore shape distribution, the specific surface area, and the chemo-physical properties of the soil phases. In theory, the effects of the internal factors should be incorporated into the parameters of SWRC equations because most of the SWRC equations are phenomenological in nature. The external factors are those related to the external or environmental conditions surrounding the soil, which can usually vary over a range of values. Typical examples of external factors are stress and temperature. For example, the density of a soil can vary due to the external stress states and stress history. Temperature can also change significantly, due to natural and artificial environmental conditions. In practice, it is difficult to justify treating samples of a given soil with different densities or at different temperatures as entirely different soils for modelling purposes. That is, the SWRC is only characteristic for a given soil at a specific density and at a specific temperature, and its variation with external factors should be modelled.

The study of the effects of external factors on the hydraulic properties of unsaturated soils has attracted much attention. Various approaches have been proposed to model the effects of volume change or stress variation on soil–water retention behaviour (e.g., [24,48,40,22,38]). For example, Sheng and Zhou [38] proposed an incremental relationship between the degree of saturation (S_r)

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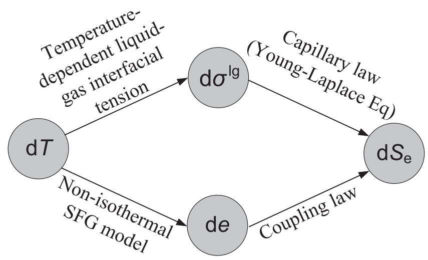

Fig. 1. Scheme to model thermal effects on SWRCs of deformable soils.

and the void ratio (e) based on the fact that most SWRCs are obtained under constant stress rather than constant volume. Zhou et al. [53] modified this incremental relationship to model the effect of initial density on soil–water retention behaviour. On the other hand, the study of thermal effects on SWRCs is relatively limited. The issue of the thermal effect on the hydraulic properties of a soil was perhaps first raised in the area of soil science by Richards and Neal [27], who observed that the capillary pressure in a soil decreases in the morning as the soil is warmed. The seminal work by Philip and de Vries [25] reported that temperature has a substantial effect on liquid–gas interfacial tension (σ^{lg}), which decreases linearly with increasing temperature. Grant and Salehzadeh [18] calibrated the parameters in the equation by Philip and de Vries and incorporated it into van Genuchten's widely used equation [47] to obtain a temperature-dependent SWRC equation (referred to herein as Grant and Salehzadeh's model). This equation has been widely adopted and discussed in the literature (e.g., [35,29,3,49]).

The recent productivity of the research into external effects on soil–water retention behaviour can perhaps be attributed to the rapidly growing demand for modelling the thermo-hydro-mechanical behaviour of soils with more accuracy. The description of the interactions among the stress field, suction field, saturation field and temperature field is becoming more significant in modern geotechnical problems. A typical example of these problems is related to the disposal of high-level nuclear wastes. Soils surrounding nuclear waste disposal sites are exposed to increasing temperatures and partially saturated conditions for long periods of time. Some shallow buried geothermal conveyance pipelines and high-voltage cables continuously heat the surrounding unsaturated soils and alter the hydraulic and mechanical behaviour of the soils. Therefore, the combined effects of temperature and partial saturation on the mechanical and hydraulic properties of soils need to be investigated to ensure the safety of both geotechnical structures and the surrounding environments. In the past decade, several models have been proposed to interpret the constitutive behaviour of unsaturated soils with varying temperatures (e.g., [28,49,14], etc.). To reproduce the hydraulic behaviour and further the hydro-mechanical coupling under different temperatures in the constitutive relations, a non-isothermal SWRC model proposed by Grant and Salehzadeh [18] has been widely adopted to describe the dependency of SWRCs on temperature (e.g., [28,29,49], etc.). Grant and Salehzadeh's model is also used to describe the effect of temperature on the permeability coefficients of unsaturated soils [29].

However, in Grant and Salehzadeh's model, soil is assumed to be undeformable, and the deformation caused by temperature variation (i.e., temperature-induced density variation) is neglected. Recently, some researchers (e.g., [31,14,33,34]) realised that the effects of temperature-induced density variation on soil–water retention behaviour could not be neglected. François and Laloui [14] proposed a constitutive model (ACMEG-TS) to describe the thermo-hydro-mechanical behaviour of unsaturated soils. In this model, a non-isothermal SWRC equation is embedded into the proposed constitutive model. The air entry value (s_e) is assumed to be a function of both temperature and plastic volumetric strain. As such, the air entry value must enter into the SWRC equation explicitly, which is not consistent with some widely used SWRC equations, such as van Genuchten's equation [47] and Fredlund and Xing's equation [15], in which the air entry value is not explicitly used. Salager et al. [33] presented a theoretical approach to modelling the effect of temperature on the water retention behaviour of deformable soils. The proposed approach is based on the general law linking the variation in suction with water content, temperature, and void ratio. As noted by the authors themselves, some functions (e.g., the suction change due to a change in void ratio) employed in this general approach are not conveniently determined by laboratory experiments.

In this study, an alternative approach to describing thermal effects on SWRCs for deformable soils is presented. The thermal effect (dT) is separated into two parts: the effect on the liquid–gas interfacial tension ($\partial\sigma^{lg}/\partial T$) and the effect on the thermal deformation ($\partial e/\partial T$), both of which affect the soil–water retention behaviour (dS_e), as shown in Fig. 1. The thermal deformation ($\partial e/\partial T$) is quantified by the proposed volume change equation (i.e., the non-isothermal SFG model). The non-isothermal SFG model is then integrated into the proposed SWRC equation via the coupling method presented in Sheng and Zhou [38]. This study is organised as follows. The first part of the paper addresses the quantification of thermal effects on SWRCs and proposes a new equation for the saturation variation caused by temperature change, which involves the temperature-induced volume change and the hydraulic response coupled with it. In the second part of the paper, a non-isothermal SFG volumetric model based on the SFG framework [37] is proposed to quantify the temperature-induced volume change under an arbitrary suction and net stress. The third part of the paper presents a numerical study of the proposed non-isothermal SWRC equation into which the non-isothermal SFG volume change equation is embedded. In the final part of the paper, the proposed non-isothermal SFG volumetric model and non-isothermal SWRC equation are validated against experimental data.

2. Interpreting thermal effects on water retention behaviour

2.1. Saturation variation for undeformable soil due to temperature change

The effective degree of saturation (S_e) of a soil under a given suction can be theoretically derived based on the normalised cumulative distribution function of soil pores, $F(r)$, which ranges between 0 and 1. $F(r)$ stands for the fraction of the volume of pores that are greater than an arbitrary pore radius (r) to the total volume of pores. $F(r)$ can be integrated from the renormalised pore size distribution function, $\bar{f}(r)$, by assuming that the pore network of a soil has a simple geometric configuration. It should be noted that $\bar{f}(r)$ does not include the micropores whose pore water cannot be desorbed by drying. If pores greater than an arbitrary pore radius are dewatered by applying a matric suction, the effective degree of saturation is given by

$$S_e = 1 - F(r) = 1 - \int_r^{r_{max}} \bar{f}(r)\,dr \tag{1}$$

where r is an arbitrary pore radius. The key relationship to connect the normalised cumulative distribution function of soil pores with the soil–water retention behaviour is the capillary law (i.e., the Young–Laplace equation in Fig. 1), which can be expressed as follows:

$$s = \frac{2\sigma^{lg}\cos\theta}{r} = \frac{2\sigma^{lg}}{r} \tag{2}$$