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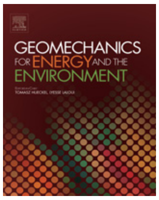

Physical modeling of shrink–swell cycles and cracking in a clayey vadose zone

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HIGHLIGHTS

- Crack origin far from the soil surface in a clayey vadose zone is addressed.
- Soil structure, layer size, loading, water content range, and cycling are caught.
- Clay, intra-aggregate matrix, soil without and with cracks are studied.
- Primary and scanning shrinkage and swelling curves are derived.
- Crack volume hysteresis for steady shrink–swell cycles is predicted.

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ABSTRACT

Physical understanding of the *crack* origin and quantitative physical prediction of the *crack* volume variation *far* from the clay soil surface are necessary to protect the underlying aquifers from pollutants. The *basis* of this work is an available physical model for predicting the shrink–swell curves in the maximum water content range (the primary curves) and crack volume variation in the range. The *objective* of the work is to generalize this model to the conditions of the deep layer of a clayey vadose zone with the *overburden* pressure, *multiple* shrinkage–swelling, and variation of water content in a *small* range. We aim to show that the scanning shrinkage and swelling curves, and steady shrink–swell cycles existing in such conditions, lead to the occurrence of cracks and a hysteretic crack volume. The *generalization* is based on the transition to the increasingly complex soil medium from the contributive clay, through the intra-aggregate matrix and aggregated soil with no cracking, to the soil with cracks. The *results* indicate the single-valued physical links between the scanning shrink–swell cycles and crack volume variation of the four soil media on the one hand, and primary shrinkage and swelling curves of the media on the other hand. The predicted cycles and crack volume hysteresis can be expressed through the *physical properties* and *conditions* of the soil at a given depth. The available observations of the cracks and crack volume variation in the clayey vadose zone give strong qualitative experimental *evidence* in favor of the feasibility of the model.

1. Introduction

Shrinkage cracks occurring close to the soil surface owing to the vertical water content gradient are known.[1,2] Their characteristics cannot explain the origin and volume variation of the cracks that are directly or indirectly observed at sufficiently large depths of a clayey vadose zone[3,4] (among others). Such cracks can essentially increase the hydraulic conductivity of the clayey vadose zone. The physical understanding of the origin of such cracks and quantitative physical prediction of the crack volume variation are important to protect the underly-

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ing aquifers from different pollutants. The physical understanding and prediction should take into account the major *specific limitations* existing in a clay soil at large depths: (i) *overburden* action at a given depth; (ii) *limited* and frequently *small* range of water content variation (compared to the maximum range); and (iii) *multifold* drainage-wetting alternation. The works that consider the explanation and prediction of shrink–swell cycling and accompanying cracking in a clayey vadose zone, based on the physical characteristics of soil texture and structure (with no fitting) and local hydrological characteristics, are absent. The contemporary approaches that combine the microphysics of water–vapor–solid interactions with different variants of transition to a clay soil continuum based on conservation laws and thermodynamics (see[5] among others), essentially consider a clay paste with no crack occurrence as well as no inter- and intra-aggregate structure leading to soil cracking at shrink–swell processes. The known approach to overburden effects in swelling soils[6] (for previous references see[6]) and subsequent discussion (see[7] among others) are based on the equilibrium thermodynamics and the shrinkage curve slope as a function of water content and applied load, with the use of some form of fitted shrinkage curve in the maximum water content range. The physical description (i.e., with no fitting) of overburden effects in connection with soil structure effects as well as cracking, swelling, and multifold drainage-wetting in an arbitrary range of water content are beyond the scope of this approach. The same relates to a recent work[8] that modifies the approach[6] using still another form of the fitted shrinkage curve. It should be noted that available approaches to soil cracking, based on either a physical description (e.g.,[9]) or using a number of empirical dependences (e.g.,[10]), only relate to shrinkage in the *maximum* water content range *close* to the soil surface or in *small* samples, that is, with no effects of overburden, swelling, and multifold shrink–swell cycling in a small water content range. A natural *background* for the development that accounts for the above limitations in a clay soil of large depths should include some description of the shrink–swell curves and crack volume variation during a *single* drainage-wetting cycle in the *maximum* range of water content and *without* soil loading. Such a description was recently suggested and experimentally validated.[11] The *objective* of the present work is to *extend* the approach[11] accounting for overburden, arbitrary water content range, and multifold drainage-wetting cycles, and keeping the *physical* character of the approach. The methodology[11] is based on the recently suggested inter- and intra-aggregate structure of inorganic soils[12–14] (Fig. 1) and successive consideration of the increasingly complex soil media: clay (paste), intra-aggregate soil matrix (including clay, silt, sand, and lacunar pores), aggregated soil without cracks (small samples), and aggregated soil with cracks (soil layer). The key point is also a link between the swelling curves of these soil media as well as between the swelling and shrinkage curves for each of the media. First, we *extend* the shrinkage–swelling of *contributive clay* to conditions of *overburden* pressure and *multifold* drainage-wetting with *small* variations of water content (Section 2). Then, we *extend* the results to be found for *clay* to the case of the *intra-aggregate matrix* (Section 3) and *aggregated soil* without and with *cracks* (Section 4). Section 5 sums the theoretical results. In Sections 6 and 7 we analyze the limited available data on shrinkage under loading to check the major model aspects.

2. Modeling shrinkage and swelling of a pure clay

2.1. Modeling clay shrinkage and swelling with no loading

2.1.1. Available modeling of primary shrinkage and swelling curves with no loading

We will refer to the shrinkage and swelling curves of a clay paste in the *maximum* possible range of water content as *primary* curves. The expressions of the primary shrinkage, $v(\zeta)$ and swelling, $\hat{v}(\zeta)$ curves of clay in *relative* coordinates (Fig. 2, curves 1 and 2; v and $\hat{v}$ are the ratios of the clay volume at shrinkage and swelling to its maximum in the solid state, i.e., at the liquid limit; ζ is the ratio of the clay water content to its maximum in the solid state) have been derived and experimentally validated[11] (for previous references see[11]). The derivation was based on the smallness of a number of values as $\zeta_n - \zeta_z \ll 1$, $v_n - v_z \ll 1$, $\zeta_h \cong 0.5 < 1$, $v_h - v_z \ll 1$ (Fig. 2; the (ζ_z, v_z), (ζ_n, v_n), and (ζ_h, v_h) points correspond to the clay shrinkage limit, air-entry point, and maximum swelling point, respectively). The $v(\zeta)$ curve (Fig. 2) consists of two linear parts in the $0 \le \zeta \le \zeta_z$ and $\zeta_n \le \zeta \le \zeta_h$ ranges and a square part in the $\zeta_z \le \zeta \le \zeta_n$ range. $\hat{v}(\zeta)$ is presented by one square line (Fig. 2). Note also the porosity, $P(v(\zeta))$ and the maximum and minimum *internal* sizes, $r_m(v(\zeta))$ and $r_o(v(\zeta))$, respectively, of clay matrix pores at primary shrinkage (excluding pore wall thickness) as well as the corresponding values at primary swelling, $\hat{P}(\zeta) = P(\hat{v}(\zeta))$, $\hat{r}_m(\zeta) = r_m(\hat{v}(\zeta))$, and $\hat{r}_o(\zeta) = r_o(\hat{v}(\zeta))$.[11] The two physical clay parameters, v_s (ratio of clay solid volume to clay volume at the liquid limit) and v_z determine $v(\zeta)$ and $\hat{v}(\zeta)$[11] (for experimental estimating v_s and v_z see[12]; note that $v_h = v_s + (1 - v_s)\zeta_h \cong 0.5(1 + v_s)$[11]). The coordinates (ζ, v) or $(\zeta, \hat{v})$ give the *customary* $(\bar{w}, V)$ or $(\bar{w}, \hat{V})$ (the specific volume V or $\hat{V}$ vs. gravimetric water content, $\bar{w}$ of the clay) by $V = v/(v_s\rho_s)$, $\hat{V} = \hat{v}/(v_s\rho_s)$, and $\bar{w} = ((1 - v_s)/v_s)(\rho_w/\rho_s)\zeta$ (ρ_s and ρ_w are clay solid and water density).

2.1.2. Extension to scanning swelling and shrinkage curves of clay with no loading

The swelling curve, $\underline{\hat{v}}(\zeta, \zeta_o)$ (Fig. 2, curve 3) that starts at a point $(\zeta_o, v(\zeta_o))$ of the primary shrinkage curve, $v(\zeta)$ (Fig. 2, curve 1) will be referred to as the *scanning swelling* curve. The shrinkage curve, $\underline{v}(\zeta, \zeta_o)$ (Fig. 3, curve 3) that starts at a point $(\zeta_o, \hat{v}(\zeta_o))$ of the primary swelling curve, $\hat{v}(\zeta)$ (Fig. 3, curve 2) will be referred to as the *scanning shrinkage* curve. The possible initial ζ_o values are $0 < \zeta_o < \zeta_h$ (Figs. 2 and 3). Only one pair of scanning swelling and shrinkage curves passes through any point of the (ζ, v) plane between the primary shrink–swell curves (Figs. 2 and 3). The analytical expressions for the *scanning swelling* curves (Fig. 2, curve 3) flow out of: (i) the available primary swelling curve (Section 2.1.1); (ii) the same smallness