Closure to "Generalized Equation for Soil Shrinkage Curve" by Pan Chen and Ning Lu

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We thank the discussers for the opportunity to clarify their understanding of the generalized soil shrinkage curve equation and to provide further comments on the adsorption shrinkage expression suggested by the discussers. Their discussion consists of three parts: general comments on the generalized equation for soil shrinkage curve, request for further clarifications of four issues related to the generalized soil shrinkage equation, and a suggestion of a simpler expression for the adsorption shrinkage with some detailed evaluation. Our comments will follow the sequence of the discussion as follows.

Assessment of the Generalized Equations

The discussers assess that "The proposed shrinkage curve is made up of a capillary regime and an adsorption regime separated by the maximum adsorption moisture ratio ... Eqs. (2) and (3) in the original paper [for adsorption and capillary] are independent ..." The understanding of the generalized soil shrinkage curve equation consisting of capillary and adsorption soil water retention mechanisms is correct, but inaccurate in two nontrivial aspects. First, the generalized soil shrinkage curve in Eqs. (1)–(3) does not separate the two mechanisms by the maximum adsorption moisture ratio as understood by the discussers. In the generalized soil shrinkage curve, soil shrinkage under both mechanisms can coexist or overlap. Second, the shrinkages in void ratio due to both mechanisms are dependent because, the void ratio due to the capillary mechanism [Eq. (3)] depends on the void ratio due to the adsorption mechanism [Eq. (2)] under the constraint of the total void ratio [Eq. (1)].

Four Requested Points of Clarifications

The first point is an assessment that the generalized equation seems only able to represent certain types of shrinkage classified by Peng and Horn (2013) (i.e., Types E and F), and not other types (i.e., Types A and D). We clarify here that the generalized equation can represent all of these types of shrinkage classified by Peng and Horn (2013). Further explanations on the basis and nature of Peng and Horn's (2013) classification are needed here. Based on soil shrinkage curves of more than 270 soils, Peng and Horn defined four phases of soil shrinkage [structural (I), normal or basic (II), residual (III), and zero (IV)] from the fully saturated state to completely dry state (Fig. 1). As shown in the original paper, Type A (I + II + III + IV) is shown in Fig. 2(c), Type B (I + II + III) is in Fig. 2(b), Type C (I + II) is in Fig. 3(a), Type D (II) is in Fig. 4, Type E (II + III) is in Fig. 2(a), and Type F (II + III + IV) is in Fig. 5. Furthermore, the results from Peng and Horn (2013) show that the traditional definition on the soil shrinkage curve with these four phases is not always reliable. Thus, the proposed equation in the original paper is an excellent replacement, providing a simple and general description on the soil shrinkage behavior.

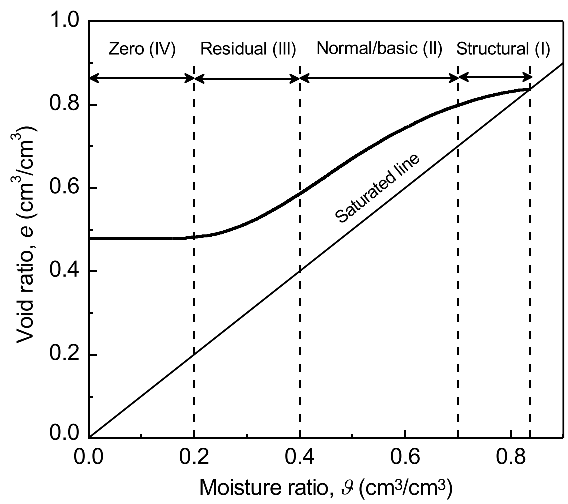

Fig. 1. Commonly conceptualized soil shrinkage curve. (Adapted from Peng and Horn 2013.)

The second clarification regards the validity of the volume expansion behavior shown in the data for the soil shrinkage test of Georgia kaolinite reported in a previously published article by Lu and Dong (2017). The pattern of slight swelling as the Georgia kaolinite specimen approaches the completely dry state is unmistakably a real behavior; it has been reported independently by several other investigators (Vesga 2009; Akin and Likos 2017). Such behavior would lead to a negative soil shrinkage rate that is counterintuitive, but can be physically explained (Vesga 2009; Lu and Dong 2017).

The third clarification regards the number of parameters obtained through curve fitting of the experimental data. The discussers assess that six parameters including the saturated void ratio defining Eqs. (1)–(3) were fitted. They further pointed out that the saturated void ratio does not need to be fitted. We clarify that we did not determine the saturated void ratio by fitting because this is a known property. These should be, but were not, clearly specified in Tables 2–4 of the original paper.

The fourth clarification regards if the demonstrated linkages between the two key parameters, namely, shrinkage rate c and maximum adsorption moisture ratio θ_{amax}^{SSC}, and other soil fundamental properties, i.e., specific surface area (SSA), cation exchange capacity (CEC), and clay-size content (CSC), are intended for postulation or for application. We clarify here that the demonstrated linkages serve for both purposes; it shows that the key parameters defined in the generalized soil shrinkage curve equation has clear physical meaning and physical roots, and in the case when SSA, CEC, and CSC are available, good estimations of these soil shrinkage parameters can be made.

Suggested Simpler Expression for Shrinkage due to Adsorption

The suggested Eqs. (1*a*) and (1*b*), as demonstrated through various cases in Table 4 and Fig. 2 of the discussion, perform equally well as the generalized soil shrinkage equation, being statistically equivalent and visually virtually identical. However, the simpler equations suggested by the discussers suffer several physical, mathematical, and practical drawbacks as follows.

Physically, directly portraying the shrinkage rate c as a function of the maximum adsorption moisture ratio θ_{amax}^{SSC} in the suggested Eq. (1*a*) precludes other possible controlling factors of shrinkage rate such as the strength of adsorption. As conceptualized in Lu (2016) and Lu and Dong (2017), the maximum adsorption moisture ratio is more controlled by the total amount of clay, not necessarily by the strength of adsorption. For example, a soil containing montmorillonite can provide a high shrinkage rate c, but not the maximum adsorption moisture ratio; the latter is more controlled by the fraction of montmorillonite in the soil. Thus, parameter c defined in the generalized soil shrinkage model remains more general in physical representation than the suggested one. Mathematically, the proposed equation creates a corner on the soil shrinkage curve at the moisture ratio equal to the maximum adsorption moisture ratio, so the soil shrinkage curve becomes nonsmooth. The generalized soil shrinkage curve ensures a mathematical smoothness in transition between capillary and adsorption regimes. Practically, the proposed equation adds one more parameter—void ratio at the zero moisture content, which makes the model more complicated rather than simpler.

In summary, the proposed expression of the adsorption shrinkage by the discussers performs statistically equally well as the generalized soil shrinkage curve in fitting the experimental data of a variety of soils, but suffers physical, mathematical, and practical drawbacks. The generalized soil shrinkage curve equation, as assessed by the discussers, describes all soil shrinkage behavior over the full range of soil moisture content including the commonly overlooked nonzero shrinkage rate in clay soil in the low soil moisture content range, and challenges the widely accepted notion of a shrinkage limit by explicitly considering soil-water retention mechanisms of adsorption and capillarity.

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