Measuring shrinkage of undisturbed soil peds

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First published in Soil Science Society of America Journal: 19 October 2021

https://doi.org/10.1002/saj2.20318

Core Ideas:

- We obtained a soil shrinkage curve from single volume and moisture measurements of 200 peds.
- The method avoids drawbacks of other techniques that disturb samples.
- Similar SSCs could be produced with as few as 20 undisturbed peds.

Abbreviations: SSC, soil shrinkage curve; COLE, coefficient of linear extensibility.

ABSTRACT

Methods to measure shrinkage curves typically either disturb natural aggregate structure or include difficult or slow volume measurement techniques. Additionally, most shrinkage curves are obtained by serial measurement of a few samples. We obtained shrinkage curves by collecting rapid, one-off measurements of volume and moisture content for each of 200 undisturbed peds extracted from a field soil, taking measurements as peds slowly dried in the laboratory. The large sample size increased robustness of the shrinkage curve parameter estimates to noise generated by this rapid measurement technique, but a much smaller sample would have resulted in similar parameter estimates.

1. INTRODUCTION

Expansion and contraction of soil volume with changes in soil moisture affect a range of properties such as soil strength, hydraulic behavior, and ecological relationships. Expansion is driven by repulsive forces arising when water becomes adsorbed between clay particles, a process that is relatively well understood for many clay minerals and affiliated cations (Sposito et al., 1999; Hensen & Smit, 2002). In contrast, shrinkage and swelling properties of natural soils are less predictable because of many factors such as interacting thermodynamic processes (Laird, 2006), mixed mineralogy, solutes, and the presence of organic matter. The latter can inhibit swelling when adsorbed to clay surfaces or flocculating particles (Yariv, 2002) but can also increase swelling and resist shrinkage when organic matter creates macropores (Peng & Horn, 2007).

This complexity has led to an emphasis on empirical characterizations of the shrink-swell behavior of natural soils, primarily through the soil shrinkage curve (SSC). The SSC quantifies the relationship between soil moisture ratios and volume ratios throughout the phases of soil shrinkage (e.g., Sposito, 1973; McGarry & Malafant, 1987; Braudeau et al., 2004; Peng & Horn, 2013). However, in addition to moisture content, expansion and contraction also depend on temperature (Kittrick, 1969) and overburden pressure (Talsma, 1977; Bronswijk, 1990), and are hysteretic (Groenevelt & Bolt, 1972; Tambach et al., 2006; Peng & Horn, 2007). Therefore, detailed interpretation of physical processes from SSCs is not always possible, and simplified model forms for SSCs have been developed for practical use (e.g., Stewart et al., 2016a).

Various methods of measuring soil shrinkage and SSCs have been developed, based on samples that are ground then repacked (Boivin et al., 2004) or made into a paste (Schafer & Singer, 1976b ; Simon et al., 1987; Chertkov, 2003), core samples (Yule & Ritchie, 1980; Grossman & Reinsch, 2002), or intact clods (Brasher, 1966; Tariq & Durnford, 1993). Of these, ground and core samples are the easiest to manipulate and measure, whereas intact clods maintain the most native properties of soils that SSCs seek to capture. Methods to control soil moisture and measure dimensions and water contents of clods have varied widely, each with their own advantages and disadvantages.

Typically, SSCs are constructed by repeatedly measuring volume as soil clods dry. Measuring volume using fluid displacement is a common approach of doing this, but preventing that fluid from altering soil moisture is difficult. Brasher (1966) inhibited infiltration during volume measurement by coating samples in resin, and Tariq and Durnford (1993) encased samples in balloons and applied a vacuum to force balloons to conform to samples. These techniques both have drawbacks, including imperfect prevention of infiltration, imperfect adhesion of coatings to clod exterior, and interference with the shrink-swell properties the tests are intended to measure (Schafer & Singer, 1976; Sander & Gerke, 2007). More recently, sample volumes have been measured using multiple-perspective photography (Stewart et al., 2012a) and 3D scanning (Rossi et al, 2008; Sander & Gerke, 2007; Wong, 2019). These techniques are generally more precise than volume displacement but require more complex equipment and analyses. At the same time, nearly all published techniques to measure shrink-swell properties rely on relatively few samples. Thus, many SSCs carry little information about the variability of the soils they seek to characterize.

In this paper, we present a method of measuring soil shrinkage that circumvents many typical measurement problems and facilitates construction of SSCs from large numbers of undisturbed samples, with the goal of producing a SSC that is representative of natural, undisturbed soils. In short, we measured volume and moisture content of a large number of samples, each only once, and used this data to construct a SSC. We compare the resulting SSC to existing SSCs obtained using other techniques and quantify the statistical stability of the obtained SSC for smaller subsets of data.

2. METHODS

2.1 Sample collection

Soil samples were collected from the floodplain of the Mississippi River (30.282° N, 91.089° W) in Iberville Parish, Louisiana. The soil is mapped by USDA-NRCS as Sharkey clay, a very-fine, smectitic, thermic Chromic Epiaquert, which, together with its hyperthermic version Schriever clay, extends over more than 16,700 km^2 of the alluvial valley of the Mississippi River. The soil is well structured, composed of weak, medium (<30 mm) peds that were subangular and blocky or wedge-shaped with slickenside boundaries typical of Vertisols. The collection site was forested, with tree species dominated by sugarberry (*Celtis laevigata*), green ash (*Fraxinus pennsylvanica*), and American elm (*Ulmus americana*).

The basic units of measurement for this study were 200 naturally formed peds extracted with minimal deformation in the laboratory from two neighboring, 19 L, intact, cylindrical soil monoliths. The soil monoliths were obtained in the field from 15 to 60 cm in depth (omitting the organic-rich surface layer). This was done by removing the soil surrounding the samples to the desired depth, then gently picking away at the edges of the monolith until a 19 L (5-gallon) bucket could slide over it. With the bucket over the monolith, a shovel was used to pry the sample from the ground, then the monolith was immediately covered with plastic wrap to reduce evaporation. Organic matter was 1-3%, estimated by loss on ignition at 550°C; texture was 2% sand, 60% silt, and 38% clay (≤ 2.00 μm), estimated by laser diffraction, though the silt was very fine and the clay fraction was ~53% when corrected for bias compared to the sieve-pipette method (Morales et al., 2021).

2.2 Sample analysis

Individual peds, averaging 17.6 cm^3 and ranging from 6.47 to 30.7 cm^3, were removed from the large monoliths for analysis by picking with a knife, which caused the soil peds to naturally break away. Fifteen to twenty sample peds were extracted every 3-5 days for almost two months, and were analyzed for volume, mass, and gravimetric moisture content. Each ped was individually placed into a 250 mL overflow beaker for 2 minutes and the mass of water displaced by the ped out of the overflow beaker was recorded. The contents of the beaker (water, ped, and any slaked soil) were then poured through a coffee filter that had previously been weighed. The filters and soil samples were then dried at 105°C for 48 hr and the oven-dry mass of each sample was obtained.

The soil monoliths were nearly at field capacity when they were collected and left loosely covered with plastic wrap between sample ped extractions to allow the soil to slowly dry and shrink. We wanted to characterize the SSC for the typical range of soil moisture for these lowland sites, which experience frequent rainfall and are often connected to shallow groundwater, so we omitted the dry end of the SSC.

The moisture ratio, ϑ (volume of water / volume of solids) of each ped, was obtained as

$$\vartheta = \frac{(W_f - W_o)/\sigma_w}{W_o/\sigma_c}, \quad (1)$$

where W_f and W_o are mass of fresh and oven-dry peds, respectively, and σ_w and σ_c are density of water and clay, respectively. The void ratio, e (volume of voids / volume of solids), was obtained as

$$e = \frac{V - W_o/\sigma_c}{W_o/\sigma_c}, \quad (2)$$

where V is total volume of the ped. We assumed densities of σ_w = 1.00 g·cm^{-3} and σ_c = 2.75 g·cm^{-3} (Flint & Flint, 2002).

2.3 Volume measurement calibration

Measuring volume using an overflow beaker requires a correction factor because overflow continues for tens of seconds as the final drips overcome surface tension, generating error (Hughes, 2005). To reduce this error, we performed an experiment in which we added known volumes of water to the overflow beaker and measured the mass of the outflow every 10 s for 2 min. We used the results to standardize time in the overflow beaker and to obtain a correction factor to estimate volumes. Based on results, we standardized submersion time for each ped at 2 min and added 6.6% to the estimated volume of each ped.

2.4 Modeling and statistical analysis

Given that an important motivation of this work is to fit practically applicable SSCs created from soils that were collected under field conditions instead of theoretically detailed SSCs generated by imposed lab conditions, we fit the simple model form derived by Stewart et al. (2016a) to our data, as

$$\phi_{ped}(U) = (\phi_{max} - \phi_{min})\left(\frac{\varepsilon+1}{\varepsilon+U^{-q}}\right) + \phi_{min}\ , \quad (3)$$

where $\phi_{ped} = e/(1+e)$ is porosity of the ped at normalized moisture ratio $U = \vartheta/\vartheta_{max}$ and ε and q are fitting parameters related to structural and residual shrinkage, respectively. The bounds ϕ_{max}, ϕ_{min}, and ϑ_{max}, are practical limits under the assumption that soils are within the range of typical field moisture and relatively non-hysteretic equilibrium in the field following repeated shrink-swell cycles (as described by Tripathy et al. 2002). We chose values of $\phi_{min} = 0.35$ ($e_{min} = 0.53$) from a separate test of the bulk density of oven-dried soil, $\phi_{max} = 0.73$ ($e_{max} = 2.70$) empirically from our data, and assumed $\vartheta_{max} = e_{max}$ (complete occupation of voids by water; Peng & Horn, 2005; Stewart et al., 2016a). We fitted ε and q numerically, using a Gauss-Newton numerical iteration in SAS 9.4 (SAS Institute; Cary NC, USA) to minimize sum squared error for the model fit to data.

To examine the sensitivity of ε and q to sample sizes smaller than the full 200 peds, we also fitted ε and q for 30 subsamples each of sizes n = 10, 20, …, all peds, with each subset consisting of n observations chosen randomly, without respect for sample moisture, and without replacement from the full dataset.

3. RESULTS

The combination of the choice to use a large number of peds, combined with the rapid water displacement method to estimate ped volume and moisture, resulted in some outliers (Figure 1). We excluded thirteen nonphysical datapoints (i.e., with measured $\vartheta > e$) but retained all others. Filtering data to further exclude more outliers resulted in small changes to parameter estimates for the SSC. In short, the method proved robust to outliers.

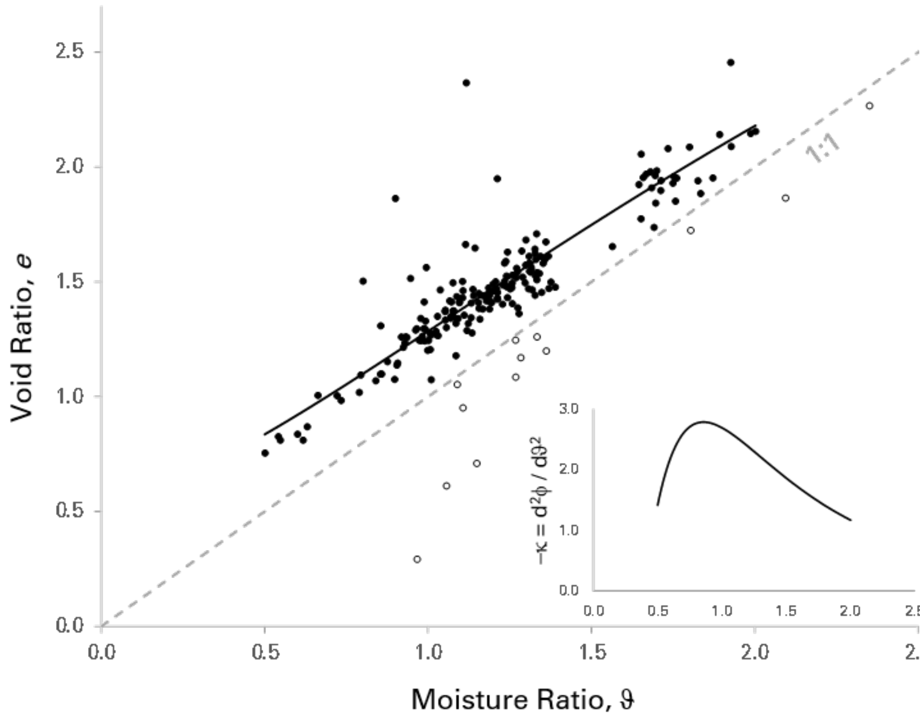

Figure 1. Soil shrinkage curve of Stewart et al. (2016) fitted to observations of individual ped moisture ratios and void ratios. Open circles indicate nonphysical results that were removed before curve fitting. Inset is κ, the second derivative of the soil shrinkage curve, plotted as –κ following Groenevelt and Grant (2001).

The best-fit SSC we obtained ($\varepsilon = 3.2$, $q = 1.5$) was dominated by peds with ϑ between 0.9 and 1.4. Several weeks of slow drying in the laboratory produced no samples where $\vartheta < 0.5$. In the range we measured, the soil was undergoing proportional shrinkage, where ϑ and e were nearly linearly related with slope near 1. Behavior of the wettest samples suggests the possibility of structural shrinkage (slope < 1). However, there was no inflection in the second derivative of the SSC (κ) that has been used to identify the transition point between proportional and structural shrinkage (Figure 1 inset), possibly because data were too sparse in this region for robust interpretation. The fitted curve indicated a transition between proportional and residual shrinkage by an inflection point in κ near $\vartheta = 0.5$, but lacking any data for drier samples, this inflection point is only conjectural.

The SSCs generated using randomly selected subsamples of peds resulted in similar curve shapes as the full dataset of 200 peds (Figure 2). However, using fewer peds resulted in greater variability and some aberrational curve fits (e.g., curves generated using 20 peds; Figure 2a). The least variation in the fitted curves across the subset fits was near $\vartheta = 1.0$ where the data were densest. The best-fit SSC model parameter sets were influenced by aberrational fits for smaller sample sizes (Figure 3). Increasing the number of sampled peds n = 70 for q and n = 110 for ε was required for ± one standard deviation limits to become <10% of the parameter values.

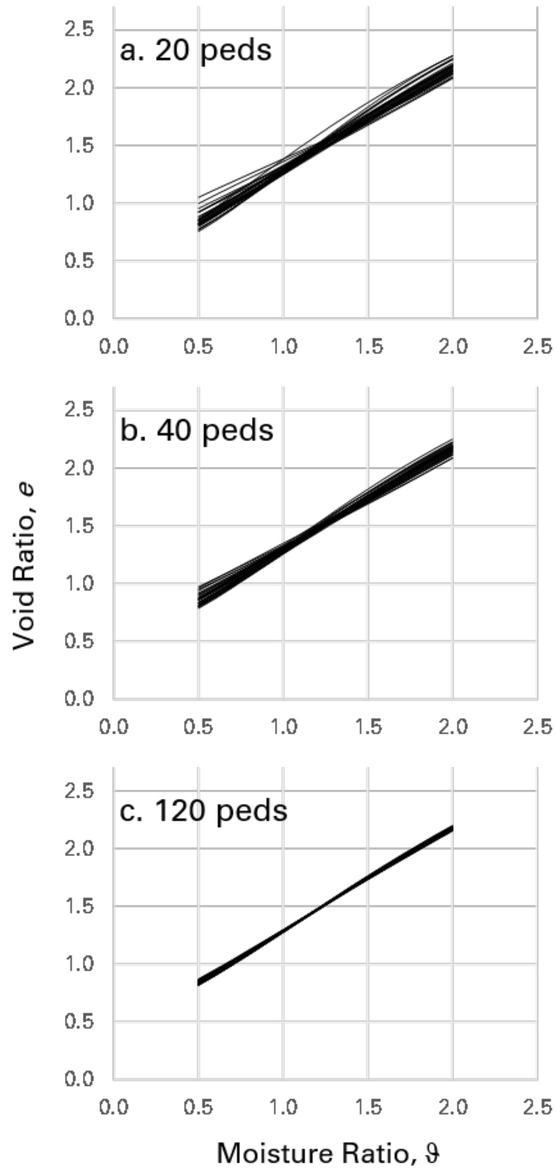

Figure 2. Realizations of fitted soil shrinkage curves from 30 subsets of (a) 20, (b) 40, and (c) 120 peds per subset; each subset consisted of peds selected randomly without replacement. Each panel contains 30 lines.

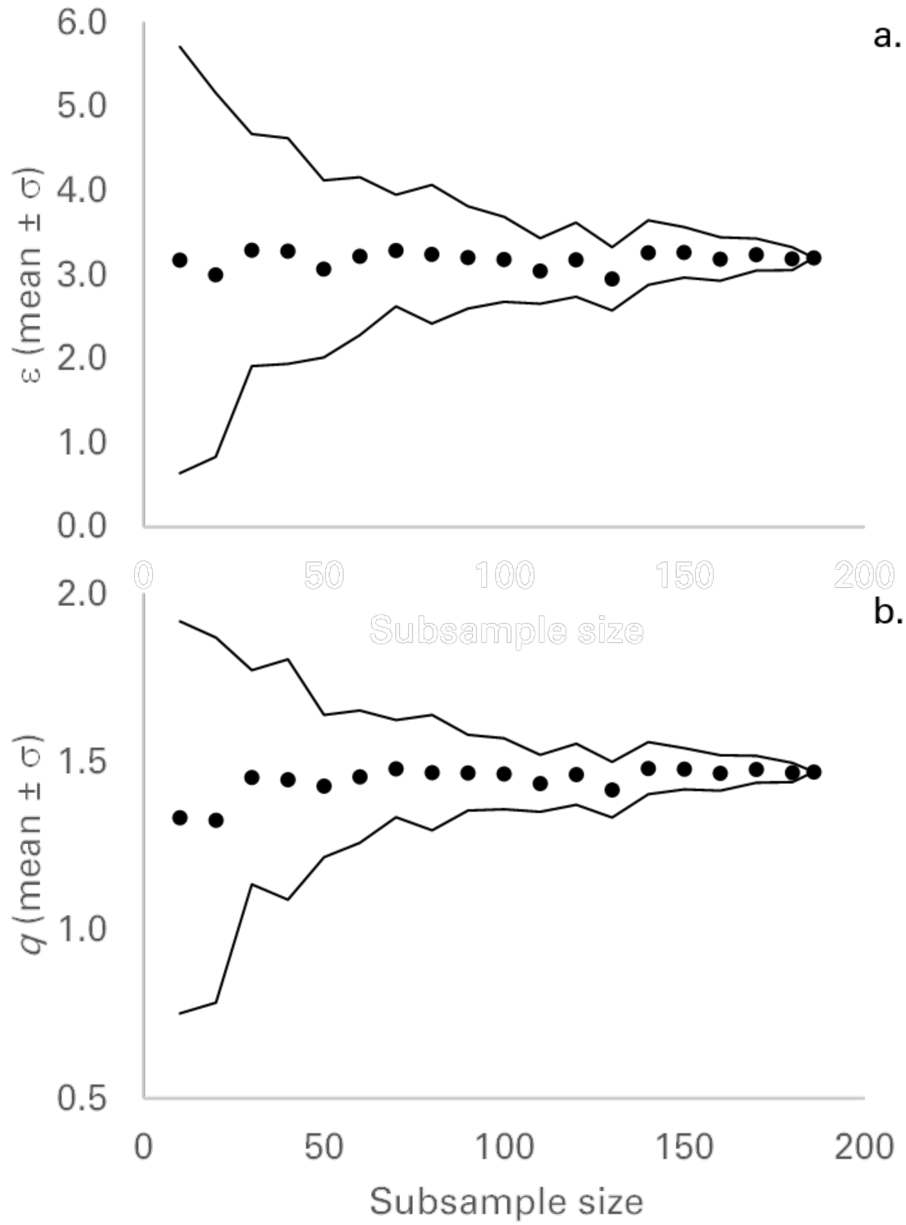

Figure 3. Effect of sample size on parameter estimates of (a) ε and (b) q, obtained from 30 subsets of peds of varying sizes selected randomly without replacement. Circles indicate mean and solid lines indicate ± one standard deviation of estimates obtained in each 30-subset population.

4. DISCUSSION

Our method of creating SSC by collecting rapid, one-off measurements of volume and moisture content for each of 200 undisturbed peds produced results comparable to previous studies (Tariq & Durnford, 1993; Sanders & Gerke, 2007; Stewart et al., 2016a). However, because our method is based on multiple peds, it may produce different results compared to traditional measurements, which typically use a single ped to generate SSCs or to calculate simplified shrinkage indices such as the coefficient of linear extensibility (COLE). As an example of the latter, the $e_{\max}$ and $e_{\min}$ values used while fitting our SSC curve (Figure 1) resulted in a relatively large estimate for COLE: 0.30 for our samples, compared to 0.14-0.18 for whole-soil COLE measured by the National Cooperative Soil Survey (NCSS) in a nearby soil pit (Pedon ID: 88LA047002). This discrepancy can likely be attributed to uncertainty in our constrained $e_{\max}$ and $e_{\min}$ values. For one, using multiple samples increased the likelihood of outlier values, either by bad measurements or inherent soil variability. Estimating $e_{\max}$ and $e_{\min}$ from clusters of data at the upper and lower extrema of the SSC, rather than the individual extreme values, yields a COLE ≈ 0.19, which is much closer to the NCSS-measured values. For another, our method does not allow for control of the water potential of the samples, making it impossible to determine the exact sample volume (and void ratio) associated with 1/3 bar potential, which is used in traditional COLE measurements (Soil Survey Laboratory Methods Manual, 1996). Finally, the peds used in this study were nearly six times smaller than the saran-coated clods analyzed by the NCSS (i.e., ~100 cm^3). Oven-dry bulk densities are often over-estimated when using relatively small soil samples, as these sample exclude crack space that forms within and between larger clods (Tisdale, 1951). Future users should keep these differences in mind when reporting COLE values using this method. At the same time, additional studies should investigate relationships between ped-based estimates of the SSC versus those fitted using other methods.

Natural variability in the studied field soil plays an important role in the estimated SSC using this multiple-ped technique. The resulting characteristics of the SSC can be considered assets or liabilities depending on eventual use of the SSC. For instance, if using the SSC as the basis for field water flux modeling (e.g., Stewart et al., 2016b), parameter estimates based on multiple samples at different ϑ would be desirable. Our subsampling provided mostly consistent SSC curves and parameters with as few as 20 peds and no constraints on ped moisture content; designing the data collection to ensure a wide range of water contents could further reduce methodological uncertainty. On the other hand, the SSC we obtained is more statistical than physical because each ped was measured only once. Therefore, the data may be less useful for robust parameter estimates for curves with multiple inflection points that allow extraction of physically meaningful parameters. Heterogeneities in, for example, organic matter, could smooth out inflection points and make them difficult to identify.

The SSC we obtained is not fully representative of shrink-swell behavior in the field at macro scale because all data we obtained was for the unloaded state, and because we used natural aggregates (peds) as samples rather than a full solum or natural clod that includes cracks. For this reason, *in situ* methods that characterize crack dimensions and connectivity may be necessary for robust hydrological modeling in expansive clay soils (e.g., Favre et al., 1997; Stewart et al., 2012b; Stewart et al., 2013; Ackerson et al., 2017). Nonetheless, the proposed method is low cost and easy-to-use, and therefore can be widely used by those interested in characterizing the shrinkage behaviors of natural soils.

CONFLICTS OF INTREST: The authors declare no conflict of interest.

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