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An Image-Based Method for Determining Bulk Density and the Soil Shrinkage Curve

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Abstract

Current laboratory methods for determining volume and bulk density of soil clods include dipping saran-coated clods in water (a destructive process due to the permanent coating), performing physical measurements on samples with well-defined geometries, or using expensive equipment and proprietary software (such as laser scanners). We propose an alternative method for determining the volume and bulk density of a soil clod, which is non-destructive, low-cost and utilizes free and open-source software. This method (the *clodometer* method) uses a standard digital camera to image a rotating clod, which allows for reconstruction of its three-dimensional surface and subsequent calculation of its volume. We validated the method through comparison to the standard displacement method, and then used the method to create a soil shrinkage curve for the Waldo silty clay loam soil. The method had acceptable precision (relative standard errors of the mean between 0.4 – 1.6%), which may be further improved through future software development.

Abbreviations: coefficient of linear extensibility (COLE); soil shrinkage curve (SSC)

Introduction

Expansive clay soils are characterized by hysteretic shrinking/swelling dynamics that continuously alter the pore structure and cause quantifiable changes in bulk density. These soils have been observed to seasonally affect and be affected by the hydrology of entire basins (Harvey, 1971; Lindenmaier *et al*., 2005), and are known to strongly influence transport of water (e.g. Messing and Jarvis, 1990; Greve *et al*., 2010) and solutes (e.g. Harris *et al*., 1994; Bronswijk *et al.*, 1995; Weaver *et al.*, 2005). The most common methods to describe the shrinkage behavior of such soils are based on laboratory analysis of individual soil clods or cores. In general, the shrinkage behavior of these soil samples are described using either (1) the soil shrinkage curve (SSC), where the gravimetric water content of a sample is related to its specific volume or void ratio; or (2) the coefficient of linear extensibility (COLE), where a sample's volume is compared at a matric potential of -30 kPa and after oven drying (e.g. Gray and Allbrook, 2002). For the SSC, a number of analytical models have been proposed to relate water content to specific volume (e.g. Giraldez *et al*., 1983; McGarry and Malafant, 1987; Tariq and Durnford, 1993a; Braudeau *et al*., 1999; Braudeau *et al.*, 2004; Boivin *et al*., 2006; Sander and Gerke, 2007), which typically account for distinct shrinkage phases. On the other hand, the COLE index is typically used as a single, lumped value per soil type (Gray and Allbrook, 2002) and cannot distinguish the different phases of shrinkage.

Both SSC and COLE require an accurate determination of the sample's volume at different moisture contents. Volume is most commonly determined by placing a resin- or paraffin-coated clod into water or kerosene and measuring the fluid displacement, utilizing Archimedes' principle (Brasher *et al*., 1966; Bronswijk *et al*., 1997). However, coating the clod has a number of significant drawbacks. For paraffin-coated samples, the SSC is found by analyzing the specific volume of distinct samples prepared at different matric potentials (Cornelis *et al.*, 2006), rather than on a single specimen. For resin-coated samples, it has been observed that the coating can inhibit swelling of the sample (Tunny, 1970), particularly as the sample nears saturation (Schafer and Singer, 1976), or can pull away during shrinkage (Tunny, 1970). Furthermore, the resin loses mass during oven drying (Bronswijk *et al.*, 1997; Sander and Gerke, 2007) and thus without proper correction can cause over-prediction of water content. In addition, coating the samples is effectively a destructive process, as they can no longer be used for other physical or hydrological testing (Sander and Gerke, 2007).

Schafer and Singer (1976) coated clods at oven-dry, air-dry, 1/3 bar (33 kPa) matric potential, and saturated conditions, and found that the clods coated at saturation became compacted (mostly due to handling) and subsequently had lower measured volumes. Therefore, because the standard method for calculating soil shrinkage curves (Bronswijk *et al.*, 1997, modified from Brasher *et al.*, 1966) specifies that the clods should be saturated at the time of coating, it is likely that the coated clod will have higher bulk density and lower volume than a similar non-coated specimen.

It has been observed that the resin can penetrate into the pores, which causes the clod to retain less water in subsequent water content measurements, particularly for small clods (Schafer and Singer, 1976). On the other hand, it has also been observed that the resin may not adequately coat deep pores, which can allow water to penetrate into the clod during submersion (Sander and Gerke, 2007) and cause underestimation of clod volume; this is particularly of concern for oven-dried specimens (Bronswijk *et al.*, 1997). During displacement measurements, Sander and Gerke (2007) observed air bubbles within the saran coating, macropores which may have been incompletely sealed, and a color change in the clods indicative of water penetrating the coating, all of which led to erratic or artificially low volume measurements. In summary, the evidence shows that the saran coating impacts soil shrinkage measurements, and the displacement method generally under-predicts the volume of soil clods.

Another displacement method for determining soil volume is the rubber balloon method of Tariq and Durnford (1993b), where a soil is packed into a rubber balloon which is suspended in water; volume changes are measured using Archimedes' principle. This method generally requires the clod to be disturbed, either through smoothing down of edges (Tariq and Durnford, 1993a) or else through sieving (Cornelis *et al.*, 2006).

Other common methods utilize direct physical measurement of the specimen dimensions. Typically, this is done using calipers, rulers, or strain gauges on a core with a well-known geometry (e.g. Berndt and Coughlan, 1972; Toker *et al.*, 2004; Cornelis *et al.*, 2006; Perón *et al.*, 2007). Axisymmetric shrinkage is typically assumed. Due to the irregular geometries of soil clods, direct physical measurements have not often been used to measure shrinkage for undisturbed soil clods.

More recent methods to quantify soil clod volume and shrinkage behavior include lasers (Rossi *et al*., 2008) and 3D optical scanning (Sander and Gerke, 2007) which scan the surface of the clod and compute its volume. While initial results with these methods are promising, the equipment needed is relatively expensive and utilizes proprietary software for analysis, with little control over the process. Thus, we see the need for a low-cost alternative which makes use of freely available software. In this paper, we present an alternative, non-destructive, low-cost method for determining the volume of a soil clod. The method utilizes completely free and open-source software. Compared to the traditional saran-coated clod displacement technique, this method does not use harsh chemicals.

Materials and Methods

Volume Analysis Method (The Clodometer)

To determine clod volumes, the samples were placed on a rotating imaging stand (Figure 1), which includes a calibration object with known volume. The calibration object used for this test was a standard golf ball, painted in a multi-colored, random pattern (to maximize surface features). Its actual volume ($V_{calibration,\ actual}$ = 40.4 cm^3) was determined by measuring its displacement when suspended in water. The clod and calibration sphere were then photographed using a 6-megapixel PENTAX® K100d dSLR camera with a 35mm f/2.8 lens. The clod and calibration sphere were positioned 0.38 meters from the camera focal plane. Images were taken at approximately every 4° of the stand's rotation (this value represents a combination of efficiency and adequate coverage, but can be adjusted as needed). In this manner, the clod and calibration volume were imaged from all 360°, using a total of approximately 90 images. With the tested setup, we could collect an image approximately every 2-4 seconds, which meant the collection process required around 3-5 minutes per sample.

The photos were joined together using Microsoft®'s free web-based program, *Photosynth*®. *Photosynth*® uses common points between photos to create three-dimensional point clouds of x,y,z- and r,g,b-referenced vertices. Next, the freeware program *SynthExport*© was used to convert the *Photosynth*® files into .ply (polygon) format, which were then manipulated using the freeware program *Meshlab*©. Within *Meshlab*©, color selection filters and manual removal of extraneous vertices were used to isolate the point clouds which correspond to the clod and the calibration object. Poisson surface meshes were then applied to both the clod and the calibration object point clouds. Finally, a script (based on Getreue, 2004, Giaccari, 2008a, and Giaccari, 2008b) was used in *Octave*© to calculate the relative volumes of the point clouds for the calibration object ($V_{calibration,\ relative}$) and clod ($V_{clod,\ relative}$). This was performed by summing the tetrahedra formed by the surface mesh (as referenced to a common datum). For each image set, individual calculations were performed to find the relative volume of the clod and the calibration volume. The actual clod volume (V_i) was then determined by Equation 1:

$$V_i = V_{clod,relative} * (V_{calibration,actual} / V_{calibration,relative}) \quad (1)$$

where V_i has the same units as the calibration object ($V_{calibration,actual}$).

Method Validation

The validation of the method was divided into two phases. First, the volumes of six saran-coated clods measured using the proposed imaging analysis method were compared to the volumes obtained using the standard displacement method (Bronswijk *et al.*, 1997). These clods came from two silty clay loam series [Waldo (18-55% clay) and Witham (27-60% clay)] and ranged in volume from 15 cm^3 to 40 cm^3. Percent difference between the two methods was calculated by dividing the volume difference of both methods by the displacement-measured volume.

Before imaging, each soil clod was double-coated in a 1:4 Dow® Saran Resin F-310/MEK (Methyl Ethyl Ketone) solution. After the coating dried, the clod was imaged using the *clodometer* method. After completion of the imaging procedure, the clod was weighed and its volume was determined through a water displacement test. Due to concerns about water filling pores and/or penetrating the coating, the displacement method was repeated on the clods until the measured volume was unchanged between successive tests. The clod was reweighed after each displacement test.

Second, the precision of the method was tested by calculating the volume of a clod using three independent sets of images. This was done for five different clods (tests) where results were summarized with the mean volume, as calculated from the three independent measurements, and the standard error of the mean for those three measurements.

Soil Shrinkage Curve

After validation, the *clodometer* method was used to obtain a soil shrinkage curve for the Waldo silty clay loam soil. Four uncoated clods (volume at field capacity ranging from 25 to 53 cm^3) were allowed to air dry from field capacity water content at room temperature with limited temperature and humidity fluctuations. The clods were weighed and imaged at ten intermediate water contents, before being oven-dried at 105°C and then weighed and imaged again. The image sets were analyzed to determine clod volumes, using the methodology described above.

To convert the data into a full SSC, we chose to employ the four-phase SSC model of Tariq and Durnford (1993a). Thus, the measured volumes were converted to void ratios (e) using Equation 2:

$$e = \frac{V_i - V_s}{V_s} = \frac{V_i - (m_{oven\ dry}/\rho_s)}{m_{oven\ dry}/\rho_s} \qquad (2)$$

where V_i is the clod volume, V_s is the volume of the solid particles, $m_{oven\ dry}$ is the weight of the oven dry sample, and ρ_s is the density of the solid particles. Moreover, the corresponding water contents were converted into volumetric moisture ratios (ϑ) using Equation 3:

$$\vartheta = \frac{m_w / \rho_w}{m_s / \rho_s} = \frac{(m_i - m_{oven\ dry}) / \rho_w}{m_{oven\ dry} / \rho_s} \tag{3}$$

where m_i is the weight of the sample at each intermediate water content, $m_{oven\ dry}$ is the weight of the oven dry sample, and ρ_w is the density of water. For the purpose of this analysis, ρ_s was assumed to equal 2.67 g/cm^3.

Results and Discussion

During displacement measurements, air bubbles emerged from several clods, indicating large air-filled voids hidden within the clod and/or incomplete coatings. This in turn led to an initial underestimation of displacement volume. This was also detected by variation in weight of coated clods before and after dipping. Therefore, we decided to repeat the displacement measurements until the measured weight of displacement was unchanged between measurements. This required between 3 and 7 measurements for each clod (Table 1).

Similarly, Sander and Gerke (2007) observed larger volumes from their 3D imaging method as compared to the displacement method. They attributed those differences to saran coating imperfections and to general limitations with the displacement method. By assuming a greater loss of coating mass during drying and that 0.3 to 0.8 g of water penetrated into the clods during submersion, Sander and Gerke (2007) were able to achieve a high level of agreement between the displacement method and their 3D scanning method.

While the initial displacement measurements with saran-coated clods were 3-17% smaller than the imaging-measured volumes, the second displacement measurements were within 5% of the imaging method (Table 1). The final displacement measurements (taken when the displacement did not change between subsequent tests) were generally larger than the imaging-measured volumes (3 – 10% larger, with the exception of sample 6, which was still 5% smaller). We conclude that the second measurement is likely to be the most accurate estimation of actual clod volume, as during this measurement any voids in the clod were water-filled and thus did not cause an underestimation of sample volume, while at the same time the clods did not yet have time to swell due to any water penetration. Assuming that the second test is the most accurate estimate of actual clod volume, our imaging results show good consistency with the traditional method of volume determination.

Results based on triplicate independent volume measurements of five different clods (using the imaging method) are shown in Table 2. The standard errors of the mean were between 0.4 and 1.6% of the mean volumes, which shows the method to have sufficient precision to measure individual clod volumes and determine soil shrinkage curves.

Soil Shrinkage Curve

The *clodometer* was used to monitor the shrinkage behavior of four Waldo silty clay loam clods (Figure 2). Results of these tests were combined to construct a characteristic Soil Shrinkage Curve, using the four-phase model of Tariq and Durnford (1993a). The Tariq and Durnford model assumes that soil shrinkage has four distinct phases: 1) structural shrinkage, where water is lost only from macropores and other large discontinuities, without greatly altering the soil bulk volume; 2) normal shrinkage, where water is lost from the soil pores without being replaced by air (it is often assumed that there is a 1:1 relationship between the volume of water lost and the decrease in soil bulk volume; Braudeau *et al.*, 1999); 3) residual shrinkage, where air enters the pores and the volume of water lost is greater than the decrease in bulk soil volume; and 4) zero shrinkage, where the soil has reached its minimum bulk volume and any additional water loss has no effect on the bulk volume.

The Waldo silty clay loam clods did not exhibit structural shrinkage, likely because the analysis began with the samples at field capacity water content, rather than being fully-saturated. Most of the data points occurred in the normal shrinkage phase, and closely followed the theoretical 1:1 line between decrease in water and soil bulk volume. At the dry end of the spectrum, the observed soil shrinkage curve began to level off, indicative of the residual and zero shrinkage regions. It should be noted that the transition between residual and zero shrinkage occurred while the clods were in the oven, so no data was collected at that point. Finally, though there was an observed offset in the void-moisture ratio values of the different clods, all samples demonstrated similar relative change in volume and moisture content.

Utility of Method

Our prototype implementation of the *clodometer* was relatively time- and labor-intensive; though collecting the photographs took only a few minutes, the generation of a single volume required anywhere from 15 to 60 minutes of imaging and processing time. This contrasts with the traditional displacement method, where each measurement can be performed in less than 5 minutes (though initial preparation and coating of the clod may take 24 hours or more). Furthermore, when measuring the bulk density of a soil clod (where typically only a single measurement is made per sample), the time difference between methods will be minimal, and the *clodometer* method has the additional advantage of leaving the clod undisturbed for use in further analyses. Therefore, even with this current level of required effort, the *clodometer* method is of great potential value to researchers due to its low-cost, accuracy, and preservation of the samples. At the same time, we envision future implementations that will automate much of the imaging and analysis processes, thus increasing the utility of the *clodometer* method and widening its function to include application in areas like soil anisotropy detection and strain calculation.

Conclusions

We combined a standard digital camera with freely available software to provide a low-cost and accurate way to measure bulk density of soil clods. Performing this analysis on soil clods at multiple water contents was then used to characterize their shrinking and swelling behavior. The system (which we call the *clodometer*) gave results that were consistent with the traditional water-displacement method, after considering causes of error in the displacement method. Moreover, measurements of clod volumes done in triplicate showed that the method had acceptable precision, as relative standard errors of the mean were between 0.4 – 1.6%.

While currently more time-intensive than other volume determination methods, the *clodometer* method offers several advantages compared to other approaches. It does not require expensive, specialized equipment or hazardous chemicals (such as methyl ethyl ketone). Samples are not destroyed or modified during testing, and expansive soil clods can shrink and swell without impediment. Finally, future software modifications and improvements will likely increase accuracy and decrease processing time for the *clodometer* method, which will only its overall utility.

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Table 1: Imaging Method Validation, comparing displacement-measured to imaging-measured volumes. The Initial Displacement Measurements were always smaller than the imaging- measured volumes, whereas the Final Displacement Measurements (when successive displacement measurements were unchanged) had better agreement with the results of the Imaging Method. Percent difference indicates the difference in volume between the Imaging and the Displacement Methods, divided by the volume from the Displacement Method.

Sample	Soil Type	Displacement Measurement[1]	Volume[‡] – Displacement Method (cm^3)	Volume – Imaging Method (cm^3)	% Difference – Imaging v. Displacement	Clod Weight (g)
1	Waldo	1	16.4	19.2	17%	31.81
		2	19.5		-2%	34.92
		6	20.9		-8%	36.86
2	Waldo	1	36.1	39.5	9%	70.99
		2	40.1		-2%	74.75
		7§	44.0		-10%	79.1
3	Waldo	1	26.9	27.8	3%	50.8
		2	28.9		-4%	53.17
		5	29.6		-6%	54.34
4	Witham	1	16.5	17.5	6%	26.56
		2	17.1		2%	28.16
		5	17.7		-1%	29.38
5	Waldo	1	29.0	30.1	4%	45.98
		2	30.1		0%	48.21

		6	30.9		-3%	50.49
6	Witham	1	15.0	16.3	8%	23.38
		2	15.5		5%	24.24
		3	15.5		5%	24.43

† Iteration number for the displacement method: first, second, and last iteration.

‡ Volume corresponding to the iteration number obtained by the displacement method.

§ The sample did not have successive identical displacement methods due to coating imperfections. Swelling was visually evident after the seventh measurement, so the test was discontinued.

Table 2: Imaging Method Precision. Triplicate independent measurements were performed on five different clods. Mean volumes and standard errors of the mean are shown for each test.

Test	Mean Volume (cm^3)	Standard Error of the Mean
1	42.8	0.18
2	37.2	0.32
3	28.7	0.46
4	95.5	0.92
5	41.0	0.63
Mean		0.50

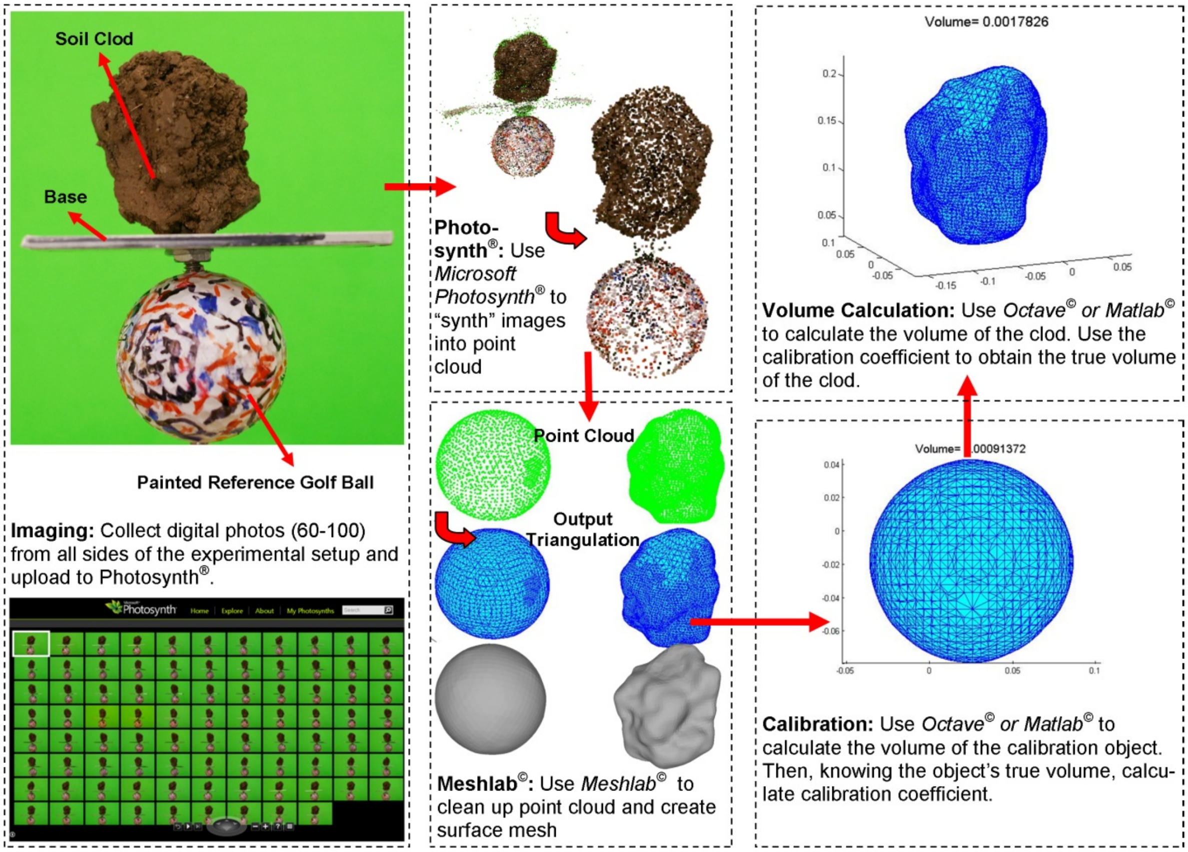

Figure 1: Steps to calculate clod volume using the *clodometer* method.

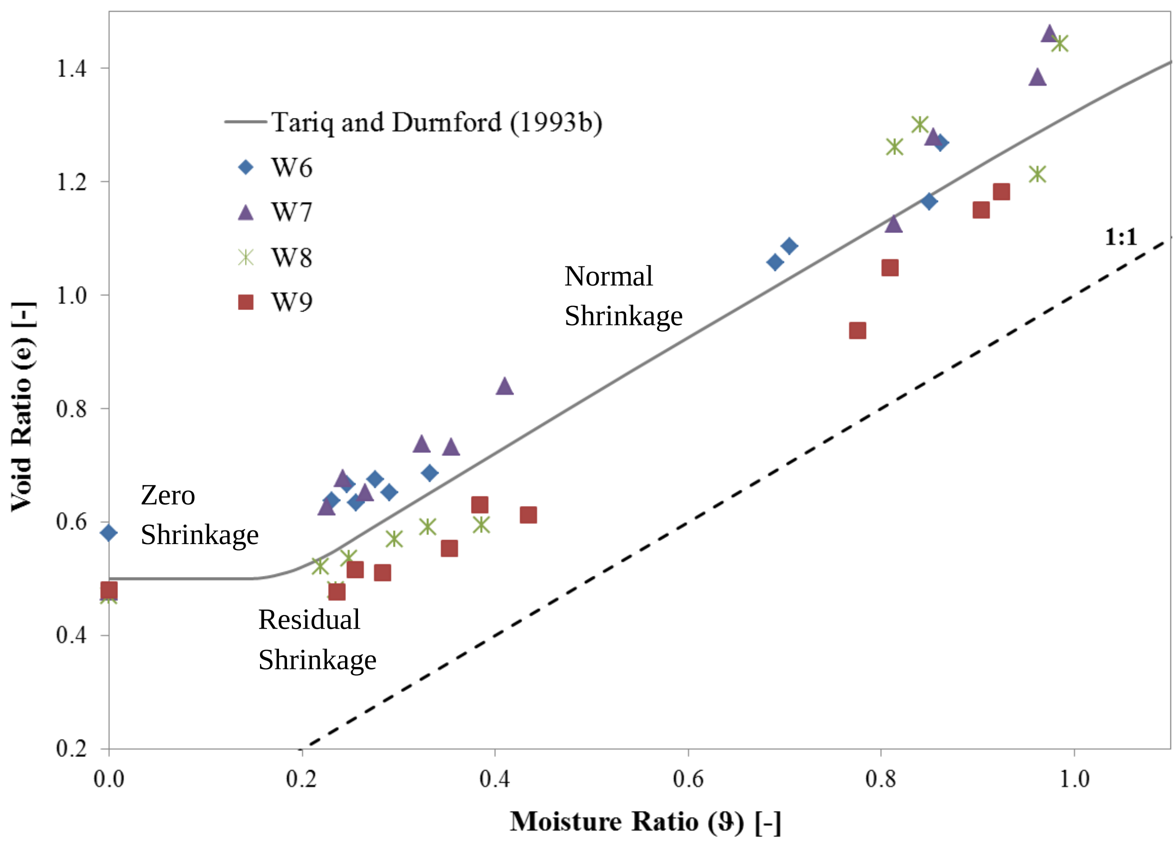

Figure 2: Soil shrinkage curve for Waldo Silty Clay Loam clods. The four phase analytical model (Tariq and Durnford, 1993b) was fit to the data to show the zero, residual and normal shrinkage zones for the soil (structural shrinkage was not observed).