

A PHOTOGRAMMETRIC METHOD FOR VOLUME CORRECTION OF SOIL CORE

SAMPLES

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ABBREVIATIONS

IDW, Inverse Distance Weighted; SD, standard deviation; SfM, Structure-from-Motion

ABSTRACT

Soil volume is an important reference value that is often determined through standardized sampling cylinders. Methods exist for measuring missing soil volume, but they either modify the sample or are time-consuming. Our new method uses structure-from-motion photogrammetry to create a 2.5D model of the soil-filled sampling cylinders from which the missing volume can be determined. We quantified the influence of different lighting conditions, the number of pictures taken, the type of camera, and of soil texture. This method provided reproducible and robust results, making it an effective alternative to previous methods.

1 INTRODUCTION

The determination of bulk density and other volume-dependent soil properties requires accurate knowledge of the volume occupied by a soil sample. Undisturbed soil samples are therefore commonly collected using sampling cylinders of known dimensions and nominal volume. However, the actual soil volume may differ from the cylinder volume because of incomplete filling, material loss during sampling and handling, or shrinkage and swelling processes (Peng and Horn, 2005). Such deviations can introduce systematic errors whenever soil properties are expressed on a volumetric basis.

Several approaches have been proposed to quantify void space and correct sample volume. These include laser-based surface reconstruction techniques (Seyfarth et al., 2012) as well as the widely used Bulk-Sand method. However, existing methods are often labor-intensive, time-consuming, require specialized equipment, or may alter the sample during measurement. Consequently, a rapid, non-invasive, and inexpensive method for routine volume correction of soil-core samples is still needed.

We have developed a promising method by applying a photogrammetric approach called Structure-from-Motion (SfM; Westoby et al., 2012) to create a 2.5D digital model of soil core samples from multiple images. In contrast to methods that solely quantify void space, the SfM approach allows rapid determination of both the actual soil volume within a sampling cylinder and the corresponding missing volume. The method was tested for accuracy and reproducibility, compared with the traditional Bulk-Sand method, and evaluated for its limitations and applicability.

2 MATERIALS AND METHODS

Ten structured 200-cm³ soil cylinders (C1–C10) were used to evaluate the photogrammetric approach. Cylinders C1–C3 originated from a previous skid-trail study. Additional test and residual cylinders were included to extend the range of soil textures and degrees of underfilling. All samples were stored at 4 °C prior to analysis.

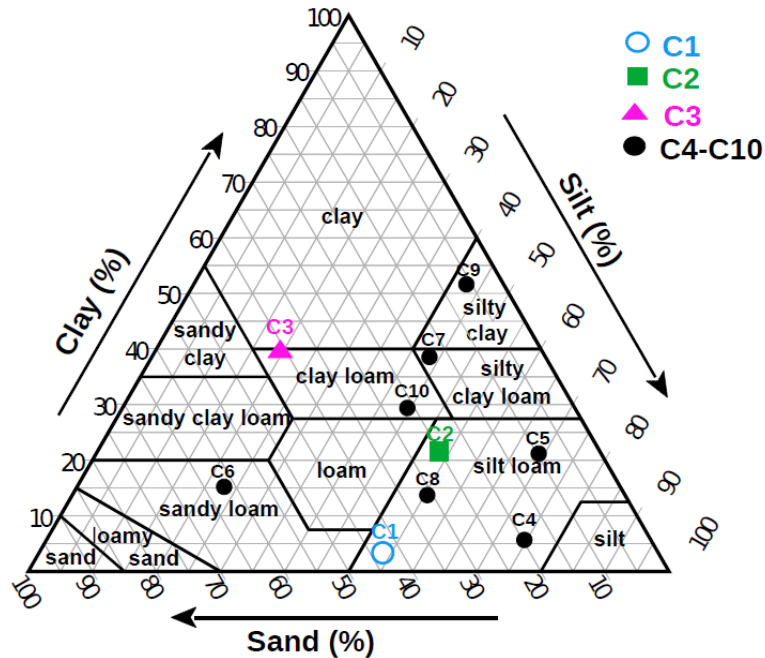


Figure 1. Soil texture classes of cylinders C1–C10 displayed in a USDA soil texture triangle based on the relative proportions of sand, silt, and clay. Cylinders C1–C3 are highlighted individually, whereas cylinders C4–C10 are represented by black circles.

First, the accuracy of the SfM method was evaluated using soil cores C1–C3. Before analysis, the soil cores were dried at 105 °C for at least 48 h. After attaching a recognition frame to the sampling cylinder, image sets consisting of 4, 8, 12, 16, or 24 photographs were acquired using a 1 Nikkor

AW lens (10 mm, f/2.8). In addition, the 4- and 24-image configurations were repeated using a Samsung smartphone camera (27 mm, f/2.2). Each image set was replicated ten times.

Void volume of the incomplete soil cores was quantified via SfM from images using the following steps: a) image conversion to TIF format, b) point cloud generation, c) distance interpolation, and d) boundary definition. Images were first converted to TIF format and subsequently processed in Agisoft Metashape Professional to generate point clouds with a maximum of 20 million points. By importing the reference values of the frame around the cylinder, each point cloud was calibrated and thus could be used as a vector data set. The point cloud was then interpolated to a raster surface in GRASS GIS (7.8.2) using Inverse Distance Weighted (IDW) interpolation. The resulting height-interpolated raster map was subsequently clipped to the circumference of the sampling cylinder, the height of the reconstructed surface was averaged, and multiplied by the surface area of the cylinder to derive void volume. This process was combined into a program chain and automated using Python (3.8.10) (see Supplement Material S1).

Accuracy and robustness of the SfM method were evaluated using R (2021.09.0) based on the repeated image sets. Additional validation procedures were conducted to identify potential systematic errors in the newly developed workflow. Variance analysis revealed significantly lower reconstruction variability when using 24 images compared to 4 images for all three cylinders (F-test, $p < 0.001$).

The SfM method was compared to the Bulk-Sand method using soil cores C4–C10 after drying for five days at 105 °C. Void volume was first quantified using the SfM approach with the Nikkor lens. For each cylinder, ten reconstructions based on 24 images were performed and averaged. Subsequently, void volume was quantified following the Bulk-Sand method described by

Grossman and Reinsch (2002): fill void spaces with fine sand until full, determine the change in mass, and convert mass to volume assuming a particle density of 2.65 g cm^{-3} .

3 RESULTS

The standard deviation within one image set ranged from 0.08 to 2.80 cm^3 (Table 1). Standard deviations decreased markedly with increasing image number (Figure 2). The strongest effect was observed for cylinder C3, where SD decreased from 2.80 cm^3 using four images to 0.12 cm^3 using 24 images. However, the reconstructed void space followed no such trend with increasing image count (Table 1). Differences between maximum and minimum reconstructed void space within one image set remained below 5 cm^3 .

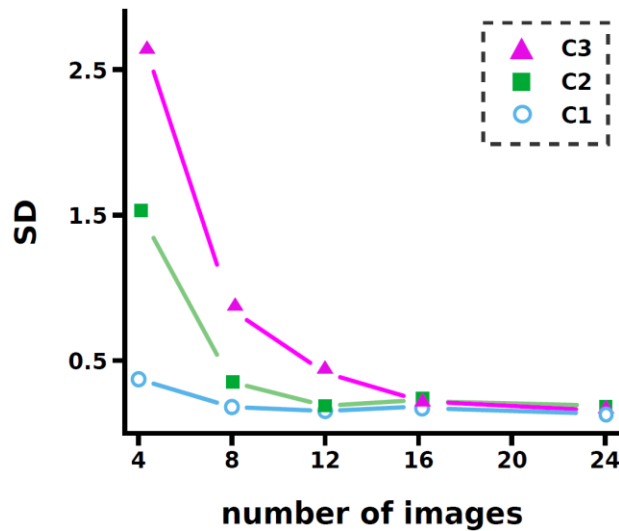


Figure 2. Decrease in reconstruction variability (SD) with increasing image number for cylinders C1, C2 and C3.

A comparison between camera and smartphone reconstructions using sets of 4 and 24 images, each repeated ten times, revealed no significant differences in reconstructed void space volume for any

cylinder (Welch's t-test: C1 $p = 0.237$, C2 $p = 0.170$, C3 $p = 0.804$). In several cases, smartphone-derived reconstructions showed standard deviations comparable to or lower than those obtained using the Nikon camera.

Table 1. Means and standard deviations (SD) of void space in C1-C3 for each image set and camera.

Camera	Number of Images	C1		C2		C3	
		Mean	SD	Mean	SD	Mean	SD
		cm ³	cm ³	cm ³	cm ³	cm ³	cm ³
Nikon	24	20.69	0.08	31.61	0.17	58.12	0.12
	16	21.25	0.18	30.28	0.23	53.30	0.23
	12	25.52	0.15	31.20	0.19	57.38	0.42
	8	25.07	0.18	30.14	0.35	56.14	0.85
	4	20.96	0.37	28.52	1.53	56.91	2.80
Samsung	24	20.79	0.24	31.52	0.10	58.10	0.22
	4	20.88	0.80	28.74	0.91	56.77	1.53

When applied to an empty 200 cm³ cylinder, repeated SfM reconstruction using 24 images yielded a reconstructed volume of 199.02 cm³. When applied to a matchbox with a known volume of 16.12 cm³, the SfM method estimated a volume of 17.45 cm³. The volume of stones was determined independently using water displacement in a water-filled 200 cm³ cylinder. The measured displacement volume was 12.21 cm³, whereas the SfM-based reconstruction estimated 12.46 cm³.

For soil cores C4–C8, the void space determined by the SfM method differed by less than 2.5 cm³ from that obtained using the Bulk Sand method (Table 2). Larger deviations were observed for C9 and C10 (Table 2).

Table 2. Comparison between the SfM method and the Bulk-Sand method for soil cores C4-C10.

SfM, structure-from-motion.

Parameter	C4	C5	C6	C7	C8	C9	C10
Soil Texture	Silt	Silt loam	Sandy loam	Clay loam	Loam	Silty clay	Clay loam
SfM [cm ³]	42.14	45.49	34.24	43.36	30.02	34.46	12.45
Bulk-Sand [cm ³]	40.57	45.23	34.01	42.36	32.44	48.63	20.74

4 DISCUSSION

The results demonstrate that the SfM approach can provide reliable and reproducible estimates of void volume under the conditions tested in this study. Standard deviation decreased markedly with increasing image number, whereas no significant differences were observed between reconstructions obtained with the Nikon camera and the Samsung smartphone. These findings suggest that image number is more important for reconstruction quality than camera type.

For most soil cores, the void volumes determined using the SfM and Bulk-Sand methods were comparable. Larger deviations were only observed for cylinders C9 and C10, which contained the highest clay fractions and showed visible structural changes after oven drying.

The strong influence of image number on reconstruction variability can be explained by differences in surface coverage during the SfM reconstruction process. Reconstructions based on low image numbers frequently failed to capture recessed soil structures and peripheral regions of the sample surface, resulting in incomplete point-cloud coverage and local gaps in the reconstructed surface (Figure 3, 4-image set). As image number increased, these uncovered regions progressively decreased, leading to lower reconstruction variability and more consistent void-volume estimates (Figure 3, 24-image set).



Figure 3. Reconstruction of cylinder C2 based on image sets containing 4, 8, 12, 16, and 24 images.

Missing surface areas directly affect void-volume estimation because recessed structures that are not reconstructed cannot be represented in the interpolated surface model. Similar limitations of image-based surface reconstruction and coverage dependency were also discussed by Haas et al. (2016). In some cases, comparable void-volume estimates were obtained despite incomplete coverage, suggesting that missing regions may occasionally compensate statistically across the reconstructed surface. Nevertheless, increasing image number reduced reconstruction artefacts and variability.

The larger deviations observed for C9 and C10 can be explained by the same fundamental limitation of optical surface reconstruction, but in a more pronounced form. Clay-rich soils are

prone to shrinkage during drying, which can create gaps between the soil core and the cylinder wall (Dane and Topp, 2002; Peng and Horn, 2005). Deeper parts of these shrinkage-induced gaps may remain partially hidden because of shadowing and restricted viewing angles. As a result, reconstruction uncertainty increases with depth and may lead to an underestimation of void volume in strongly shrunken samples. The dashed line in Figure 4 should therefore be interpreted as a conceptual visualization of the visible reconstruction limit, consistent with observations by Mohren et al. (2020).

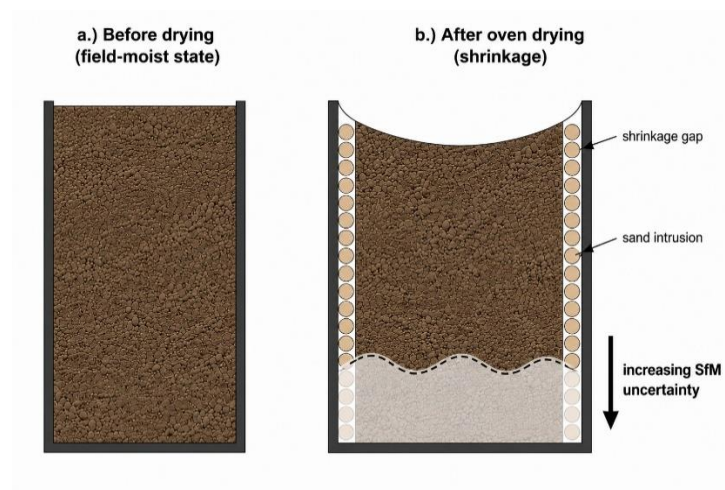


Figure 4. Conceptual illustration of shrinkage-induced gap formation between the soil core and cylinder wall after oven drying. While the Bulk-Sand method mechanically fills these gaps, deeper sections may remain partly inaccessible to SfM reconstruction because of shadowing and restricted viewing angles.

The results indicate that sufficient surface coverage is more important for reliable SfM reconstruction than the specific camera system used for image acquisition. More than 16 images and multiple viewing angles are recommended to improve reconstruction completeness and reduce reconstruction artefacts. In this study, low, medium, and steep viewing angles (e.g. 15°, 40°, and 80°) were combined to improve coverage of peripheral and recessed soil structures. Image

acquisition should ideally be performed before substantial shrinkage alters the original soil structure.

The SfM approach shows considerable potential as a rapid, low-cost, and non-destructive method for quantifying void volume and characterizing soil surface structure under both laboratory and field conditions. For most soil cores, SfM-derived void volumes were comparable to those obtained with the Bulk-Sand method while preserving the original sample structure. Beyond void-volume estimation, repeated SfM measurements before and after drying may provide a useful means of quantifying shrinkage-related volumetric changes in soils.

SUPPLEMENTAL MATERIAL

Supplemental Material S1 contains the workflow used for automated processing of SfM-derived point clouds and void-volume calculations. Supplemental Material S2 contains the experimental data and statistical analyses used in this study.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.