Three-dimensional scanning for measurement of bulk density in gravelly soils

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Abstract

The measurement of bulk density in gravelly soils (>15% soil particles >2 mm) is more time-consuming than for other soils. The excavation method, usually employed for measurement of bulk density in gravelly soils, includes excavating a void and calculating volume of the void from the weight and density of the material (e.g. sand and plaster cast) used to fill the void. A 3-dimensional (3D) scanning system was developed to measure the volume of the void created when using the excavation method. The 3D scanning system combined a time-of-flight camera (Kinect™), the KinectFusion algorithm, MeshLab and a portable computer to produce a 3D model of the void or plaster cast. Experiments were completed at three field sites where soil gravel (>2 mm) content ranged from 35 to 71% to assess the performance of the system. The void volume measured using the 3D scanning system was highly correlated with measurements using the plaster cast method ($r = 0.99$). The cumulative time taken to measure soil bulk density using 3D scanning was significantly ($P < 0.001$) less than for the sand replacement at 0–10, 10–20, 20–30 and 30–40 cm depth. The faster measurement of subsurface bulk density is a significant advantage of the 3D scanning system; the time taken to measure bulk density to 40 cm in 10 cm increments using the 3D scanning system was about one-third of the sand method.

Keywords: Soil bulk density, gravel, 3-D scanning, time-of-flight, excavation method, in situ

Introduction

Soil bulk density is the ratio of soil dry mass to bulk volume and is an important component of soil fertility for crop production. It is an important factor for crop growth because of its effect on soil strength; soil strength increases as bulk density and soil matric potential increase, leading to a reduction in root elongation rate (Unger & Kaspar, 1994; Kirby & Bengough, 2002) and access to soil water and nutrients (Shierlaw & Alston, 1984; Lipiec & Stpniewski, 1995) by the crop. Compaction of surface and subsurface soil by heavy machinery leads to an increase in soil bulk density (Voorhees et al., 1986). Knowledge of bulk density can guide decisions about treating subsoil compaction (Spoor et al., 2003) and provide accurate accounting of soil carbon stocks (e.g. Holmes et al., 2012); however, it is measured less frequently than other soil properties (e.g. nutrients and carbon) because it is labour intensive and time-consuming, particularly for gravelly soils.

The measurement of bulk density in gravelly soils (>15% soil particles >2 mm) (e.g. plinthic horizon, IUSS Working Group WRB, 2015) is more difficult than for soils without gravel. For soils with no or low soil gravel content, the core method (Blake & Hartge, 1986) is used most frequently (Hao et al., 2007; Throop et al., 2012). The core method involves inserting a metal cylinder into soil, extracting the intact core and measuring sample volume and dry mass. In gravelly soils, it is difficult to obtain an accurate measurement of bulk density because the gravel particles can prevent the core from being inserted or may be pushed into or away from the core by the cutting edge as it is being inserted, leading to erroneous measurements of soil dry weight.

In gravelly soils, the excavation method (Blake & Hartge, 1986) is often used to measure soil bulk density because it can accommodate the irregularly shaped void that is created when excavating a sample from gravelly soils. The volume of the irregularly shaped void has been measured by filling it with sand, expanding foam, water, beads or a plaster cast (Flint & Childs, 1984; Grossman & Reinsch, 2002; DeLong et al., 2012; Frisbie et al., 2014). When a plaster cast is used, void volume is measured by water displacement. For the other methods (sand,
foam, beads or water), void volume is calculated from the mass and density of the material used to fill the void.

The time taken for a single measurement of soil bulk density using the excavation method is significant, ranging from 10 to 30 min Holmes et al. (2012) found that the excavation method took more time than other methods: the time taken using the nuclear density meter (NDM), core, clod and excavation methods was 4, 20, 20 and 30 min, respectively. In a study on stony soils, the excavation method was also more time-consuming than NDM, although the material used to measure void volume was an important factor. The time taken per sample using NDM was 6 min and was 10, 14 and 27 min using foam, sand cone and a frame with the excavation method (DeLong et al., 2012). These time values are for the in-field component of the measurement only, that is, the time taken for work required after the in-field component has been completed were not included.

Three-dimensional (3D) scanning may offer an increase in speed for measurement of soil bulk density, particularly for gravelly or stony soils where the shape of the void is irregular (Hirmas et al., 2016). 3D scanning has successfully been used to measure the bulk density of soil clods (Rossi et al., 2008) in the laboratory. Here, we investigate the use of 3D scanning to measure void volume for the excavation method under field conditions. The 3D scanning approach uses a depth-detection camera and interpretative software to construct a 3D model of the void and calculate its volume. This method was tested in gravelly soils in field conditions for the measurement of soil bulk density in the surface (0–10 cm) and subsurface (10–20, 20–30, 30–40 cm) soil layers. Two experiments were completed to assess the performance of the 3D scanning system. In Experiment 1, the volume measured by 3D scanning of a soil void was compared to volume measured using the plaster cast method. In Experiment 2, the time taken to measure soil bulk density with the excavation method using 3D scanning was compared to the sand replacement method.

### Method

**3D scanning system and augered void volume determination**

Image data were acquired using a Microsoft Kinect™ for Windows version 2 (Microsoft Corporation, Washington, USA). The Kinect camera simultaneously captures a depth image using a time-of-flight sensor and an image from the visible spectrum using a RGB camera (Zhang, 2012). This camera streams video data at high resolution (1920 × 1080 pixels) and speed (2 GB of data per second), allowing 3D models of objects to be reconstructed in real time by moving the camera around the object. The depth range for this camera is specified by the manufacturer as 80–400 cm; however, data were successfully captured from a depth of approximately 50 cm from the soil surface in our experiments.

The KinectFusion algorithm (Newcombe et al., 2011) was used to construct a 3D model from data from the Kinect camera using the freely available 3D Scan (Microsoft Corporation, Washington, USA) software. While the quality of depth images captured by a Kinect camera is remarkable given its low cost (from approximately $150 AUD), a number of issues remain challenging. In particular, the depth images contain holes and depth outliers generated by materials or scene structures which do not reflect infrared light, very thin and complex structures or surfaces at glancing incidence angles.

The KinectFusion algorithm (Newcombe et al., 2011) constructs a 3D model from images captured by the Kinect camera from multiple viewpoints in three stages. In the first stage, a bilateral filter (Tomasi & Manduchi, 1998) is applied to a raw depth image, captured to obtain a discontinuity-preserved depth image with reduced noise. Then, the resultant depth image is converted to an oriented 3D point cloud.

In the second stage, to calculate the global camera pose and track this pose as the Kinect camera moves in each frame, an iterative alignment algorithm is utilized to obtain the correspondence between two consecutive frames. Thus, the system always knows the current camera pose relative to the initial starting frame. More precisely, the algorithm aligns 3D point clouds calculated from the reconstruction with new incoming 3D point clouds from the Kinect camera.

The third stage is the fusion of the depth images from the known camera position into a single volumetric representation of the space around the camera. This integration of the depth images is performed per-frame. As a moving camera captures a surface from slightly different viewpoints, any gaps or holes where the depth data are not present in the original depth image can also be filled in (e.g. moving the camera around the void to fill in the bottom of the void) and surfaces are continuously refined with newer high-resolution data as the camera approaches the surface more closely (e.g. moving the camera towards the bottom of the void).

**3D void model refinement and volume calculation**

The 3D model constructed by the KinectFusion algorithm was cleaned using MeshLab (Cignoni et al., 2008). In some cases, the 3D model created by KinectFusion was noisy and contained unrelated points and some holes. MeshLab was used to remove the unrelated points, which belong to the ground surface around the void, by fitting a surface to these points. To fill the holes of the 3D void model, a hole filling algorithm (Liepa, 2003), which consists of four main steps; boundary identification, hole triangulation, refinement and fairing, was applied on the 3D void model. As shown in Figure 1, this process results in a closed manifold mesh that can be used for volume estimation.
The volume of the 3D models was calculated using the triangulated mesh of the surface of the void created by the 3D scanning and cleaning. For each triangle on the surface of the mesh, the origin of the 3D model was used to create a tetrahedron and calculate its volume. The volume of the void was calculated as the sum of all the tetrahedrons.

Site descriptions

The sites were located in south-west of Western Australia (SWWA) at Badgingarra (30°20′25.76″S, 115°32′17.16″E), Darkan (33°29′46.17″S, 116°42′15.15″E) and Pingelly (32°27′41.36″S, 117°0′21.61″E). The soil classifications were Ferric-petroferric Tenosol at Badgingarra and Ferric Kandosol at Darkan and Pingelly in the Australian Soil Classification (Isbell, 2002), which correspond to Plinthic Arenosol and Orthoplinthic Ferrasol, respectively in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Soil gravel (>2 mm) content ranged from 35 to 71% at these sites. The physical properties of the soil at each site are shown in Table 1.

Experiment 1

Void volume was measured at the field sites using the 3D scanning system and the plaster cast method (Frisbie et al., 2014). At each site, voids were augered for the depth treatments 10, 20, 30 and 40 cm depth and were arranged in a randomized complete block design with three replicates, on a 1 × 1 m grid. The voids were augered using a 15 cm inner diameter posthole auger (Cyclone®, Victoria, Australia) after preliminary testing showed it performed better than other soil sampling augers at extracting a soil sample at these sites. The augered holes were scanned using the 3D scanning system described above.

The same scanning procedure was used for each void. The scanning system allowed the user to view the 3D model on the laptop being constructed in real time as the field of view of the camera was moved by hand to capture all of the surfaces of the void. To begin the scan, the Kinect camera was held about 50 cm above the centre of the void, data recording was started, and the camera was slowly raised to about 100 cm over a period of 5–10 s. The camera was lowered back to its starting position at about the same speed, tilted slightly, then rotated to capture the 3D surface of the wall of the void. Sections of the 3D model that were not resolved by the KinectFusion algorithm in the first pass appeared blank in the 3D Scan software and were resolved by moving the camera to different positions to gain a better view of these sections. Data recording was stopped when the 3D model was complete, and the scanning data were captured in a single data file. A hand-held sunshade was used to prevent reflection of direct sunlight by the void walls.
because the Kinect camera was unable to obtain a depth image from areas of the void where there were reflections.

Following scanning, a 1:1 mixture of casting plaster (CSR, New South Wales, Australia) and water was poured into the void, levelled at the soil surface and allowed to cure for 72 h. The plaster casts were extracted from the soil by carefully removing soil from around the cast to avoid damaging the edge of the cast, until it could be easily lifted from the soil. The casts were then dried in a forced-draught oven at 45 °C for 3 days and were then cleaned using a light brush to remove loosely adhered soil and gravel particles.

The plaster cast method was used to measure the shape and volume of the void because preliminary work showed it conformed to the shape of the void better than expanding foam. Previous work suggests that this method is well suited to gravelly soils (Frisbie et al., 2014).

Two additional measurements were completed in a laboratory. The plaster casts were scanned indoors using the 3D scanning system to allow a comparison of the 3D model of the void obtained from overhead in the field, that is, a restricted view, to the 3D model obtained from an unrestricted view around the plaster cast in the laboratory. The actual volume of the plaster casts was measured by water displacement. To assess the accuracy of the 3D models obtained from overhead scanning of voids in the field, we compared them to 3D models obtained from scanning the plaster casts in the laboratory. The Iterative Closest Point (ICP) algorithm (Besl & McKay, 1992) was used to quantify the morphological similarity of the 3D models obtained from scanning the void and the plaster cast. In the ICP algorithm, the void model (point cloud) is kept fixed, while the cast model (point cloud) is transformed to best match the void model. The algorithm iteratively revises the combination of translation and rotation needed to minimize an error metric, which is the average distance from the cast to the void point cloud.

A subsample of the soil extracted from each depth treatment was dried at 105 °C for 48 h, and the dry mass of the whole sample was calculated. Bulk density was calculated by dividing the dry mass of soil extracted from each void by its volume measured by water displacement of the plaster cast.

Experiment 2

A comparison of the time taken to measure soil bulk density using the excavation method with 3D scanning or sand replacement to measure void volume was completed at the Pingelly site. This experiment was arranged as a split-plot design on a 1 × 1 m grid, where the main treatments were method for measuring void volume (3D scanning and sand replacement), and the subtreatments were depth of measurement (0–10, 10–20, 20–30 and 30–40 cm). There were four replicates. For the 3D scanning method, one hole was augered at the centre of each main plot (1 × 1 m) and the

| Location     | Soil depth (cm) | Clay (−<0.1 mm) | Silt (0.1–2 mm) | Sand (2–2000 mm) | Fine gravel (19–45 mm) | Medium gravel (4–19 mm) | Course gravel (>5 mm) | Munsell colour | Whole soil bulk density (g/cm³) | Matrix texture | Gravel          |
|--------------|----------------|-----------------|-----------------|------------------|-----------------------|------------------------|-----------------------|---------------|-------------------------------|----------------|----------------|
| Badgingarra  | 0–10           | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 10–20          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 20–30          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 30–40          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
| Darkan       | 0–10           | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 10–20          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 20–30          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 30–40          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
| Pingelly     | 0–10           | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 10–20          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 20–30          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
|              | 30–40          | 0               | 0               | 0                | 0                     | 0                      | 0                     | 0             | 2.1                           | 10YR 4/3       | 10YR 6/3       |
total time for each depth increment was recorded to: auger the hole for the depth increment, bag and label the soil sample, weigh the soil sample, scan the hole, save the scan and process the data to calculate the volume. For the sand method, a hole was augered to the lower level for each depth treatment within each main plot (i.e. four separate voids were augered within each main plot for the sand replacement treatment). For each depth treatment and replicate, the total time was recorded to: auger the hole, bag and label the soil sample, weigh the soil sample, fill the void with preweighed bags of sieved (<1 mm) sand, weigh the sand remaining in the bag to determine the weight added to the void and the time taken to bag and weigh the sand prior to the field work. For the sand replacement method, the diameter of the holes created by the auger used was too large to use the sand cone apparatus efficiently; therefore, the sand was poured directly into the void from the bag, until it was level with the soil surface. A separate void was augered for each depth treatment in the sand replacement method because it takes less time to auger four separate voids and calculate bulk density than it does to measure soil bulk density using the sand replacement method, remove the sand, then repeat the process for each depth increment. The dry mass of the soil samples removed for the 3D scanning and sand replacement methods was calculated after measuring gravimetric water content (Cresswell & Hamilton, 2002) of a 1 kg subsample.

Statistical analysis

For Experiment 1, the accuracy of the 3D scanning system for measuring void volume was assessed with mean error, relative root-mean-square error (RRMSE) and Pearson’s correlation coefficient (r) (e.g. Wallach, 2006). Results from Experiment 2 were analysed using analysis of variance in Genstat version 16 (VSN International, 2013) taking into account the split-plot design with replicate and method within replicate as blocking terms.

Results

Void volume measured by 3D scanning

The void volume measured by 3D scanning showed a high correlation (r = 0.99) with the volume measured using water displacement of a plaster cast (Figure 2). The 3D scanning system produced the most accurate estimates of void volume at 0–10 and 0–20 cm; the RRMSE at these depths was 2.9 and 2.4%, respectively. The accuracy of the void volume measured by 3D scanning decreased as the depth of the void increased; RRMSE was 4.3 and 6.0% for 0–30 and 0–40 cm, respectively. The mean error for the void volume was positive for 0–10 and 0–20 cm and negative for the other depths (Table 2).

Morphological accuracy of 3D scanning in the field

The distance between corresponding points for the 3D models obtained from scanning overhead in the field with a restricted view and scanning of the plaster cast in the laboratory with an unrestricted view was small relative to the dimensions of the hole. The mean distance between corresponding points for the two models was 3.3 mm, whereas the diameter of the void ranged from approximately 15–20 cm and void depth was 10–40 cm. The distance between corresponding points for the two models increased as depth increased; it was 2.5, 3.5, 3.3 and 4.0 mm for 0–10, 0–20, 0–30 and 0–40 cm, respectively. Figure 3 shows examples of this; the absolute distance between the 3D models of the cast and void is greatest at the bottom and the top of the void.

| Soil depth (cm) | Plaster cast mean volume (cm³) | 3D scanning mean volume (cm³) | Mean error (cm³) | RRMSE (%) |
|----------------|-------------------------------|-----------------------------|-----------------|----------|
| 0–10           | 4119                          | 4132                        | 12              | 2.9      |
| 0–20           | 7749                          | 7848                        | 99              | 2.4      |
| 0–30           | 12 035                        | 11 943                      | –91             | 4.3      |
| 0–40           | 16 370                        | 16 147                      | –222            | 6.0      |
Comparison of 3D scanning with the sand method

The time taken to measure soil bulk density using 3D scanning was less than the sand replacement method; the method × depth interaction was significant ($P < 0.001$) (Table 3). The time taken to measure bulk density was significantly different for the two methods for each depth interval (l.s.d. (5%) = 1.56) and the difference in time between methods increased as the depth of measurement increased. For 0–10 cm, the mean time for 3D scanning was 54% of the sand replacement method, 5.0 and 9.3 min, respectively, and to measure bulk density to 40 cm with 3D scanning required 32% of the time taken using the sand replacement method (Table 4).

The bulk density measured by 3D scanning and the sand method did not differ at any depth (Table 4); the depth × method interaction was not statistically significant ($P > 0.1$). The main effect of depth was significant; bulk density at 0–10 cm was significantly lower ($P < 0.001$) than at the other depth intervals (l.s.d. (5%) = 0.17). The bulk density measured in Experiment 2 was slightly greater than that measured in Experiment 1 at Pingelly. The locations for experiments 1 and 2 were about 10 m apart.

Discussion

The 3D scanning system described here can increase the speed of soil bulk density measurements using the excavation method. The time taken to make a measurement of soil bulk density in the surface layer using the 3D scanning system was about half the time taken using the sand replacement method and about one-third of the time when measuring soil bulk density to 40 cm in 10 cm increments. Importantly, there was no indication of a loss of measurement precision. Analysis of Experiment 2 showed that bulk density measured with the 3D scanning method was not different to the sand replacement method. The RRMSE in void volume we observed would lead to a 3–6% error in soil bulk density, which is less than the error observed when bulk density measured using an hydraulic-push corer, a rotary corer and hammer corer were compared to bulk density measurements from a pit face (mean error = 8.5%) (Beem-Miller et al., 2016).

The increase in speed of measurement of subsurface soil bulk density is a significant advantage of the 3D scanning system. Typically, measurement of bulk density becomes increasing difficult and time-consuming as the depth being measured increases (Holmes et al., 2012). For example, to measure bulk density in the subsoil using the core method, a pit needs to be excavated to provide access to the subsoil and to extract the core. The time taken to obtain a bulk density measurement for each depth increment in the subsurface layers (10–20, 20–30 and 30–40 cm) was about 5 min, which is equivalent to the time taken using the fastest method to date; NDM (4 min) (Holmes et al., 2012). However, the time taken to measure soil bulk density in our
study included subsampling and measuring soil dry mass, which was not reported in the studies cited here using NDM. The 3D scanning method has advantages over NDM in that is a direct measurement, eliminating the need for a calibration for gravelly soils (Holmes et al., 2012), no special licenses are required to operate it and there are no restrictions on its transport.

There are additional advantages to the 3D scanning system. The 3D scanning system has the advantage of flexibility in the scale of measurement. The depth of the void can be varied according to the experimental design, such as regular depth intervals or by horizon. The width of the void can be varied to meet theoretical requirements, such as representative elementary volume, which is particularly important for gravelly soils, when the sample weight should be at least 100 times the weight of the largest particle (Buchter et al., 1994). The 3D scanning method may also have a time advantage in gravel-free soils. A single measurement with the core method can take 20 min (Holmes et al., 2012), which is about four times the time taken with the 3D scanning in Experiment 2.

There are also some limitations to the use of the 3D scanning system. The need to have a computer in the field limits the weather conditions (rain and dust-free) that are suitable for obtaining measurements. However, it is worth noting that the ideal weather conditions are the same for all field methods for measuring soil bulk density. Direct sunlight can interfere with

Table 3 Comparison of the cumulative time (minutes) taken for soil bulk density measurements to various depths using the 3D scanning and sand replacement methods. Data shown are mean of 4 replicates ± standard error. All values are rounded to two significant figures.

| Depth (cm) | 3D scanning | Sand   |
|-----------|-------------|--------|
| 0–10      | 5.0 ± 0.03  | 9.3 ± 0.25 |
| 10–20     | 9.7 ± 0.12  | 21.0 ± 0.40 |
| 20–30     | 15.0 ± 0.36 | 41.0 ± 0.46 |
| 30–40     | 20.0 ± 0.52 | 63.0 ± 1.10 |

Table 4 Comparison of soil bulk density (g/cm³) measured at each depth using the 3D scanning and sand replacement methods. Data shown are mean of 4 replicates ± standard error. All values are rounded to two significant figures.

| Depth (cm) | 3D scanning | Sand   |
|-----------|-------------|--------|
| 0–10      | 1.5 ± 0.06  | 1.4 ± 0.06 | 1.5 ± 0.06 |
| 10–20     | 1.7 ± 0.03  | 1.8 ± 0.10 | 1.8 ± 0.07 |
| 20–30     | 1.8 ± 0.05  | 1.8 ± 0.11 | 1.8 ± 0.08 |
| 30–40     | 1.8 ± 0.07  | 1.8 ± 0.09 | 1.8 ± 0.08 |

Conclusion

The 3D scanning system was faster than using sand replacement for measuring soil bulk density with the excavation method. The time taken for a measurement at 0–10 cm using 3D scanning (5 min) is similar to other studies that have included NDM (reported as 4–6 min, although the times required to determine the dry mass of soil and obtain a value of bulk density adjusted for soil moisture were included in those studies). The gain in speed for measuring subsurface bulk density is an advantage of the 3D scanning system: the time taken for measurements to 40 cm with 3D scanning was about one-third of the sand replacement method. The 3D scanning system is also relatively accurate; the RRMSE for volume was less than has been reported for other studies that have evaluated the accuracy of current methods for measuring soil bulk density.

The 3D scanning system provides a rapid and cost-effective method for measuring bulk density in gravelly soils, addressing the major barrier, time, to obtaining this measurement in these soils. Cost-effective measurement of bulk density will contribute to better agronomic management and carbon accounting for gravelly soils.

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