Publication information

Title	Non-contact sensing system to measure specimen volume during shrinkage test
Author(s)	Jain, Sumit; Wang, Yu-Hsing; Fredlund, Delwyn G.
Source	Geotechnical Testing Journal , v. 38, (6), November 2015, p. 936-949
Version	Published version
DOI	https://doi.org/10.1520/GTJ20140274
Publisher	ASTM International

Copyright information

Copyright ASTM International. All rights reserved, 2015. Downloaded via HKUST Institutional Repository, pursuant to Author/Copyright Owner Agreement. No further reproduction authorized.

Notice

This version is available at HKUST Institutional Repository via

<http://hdl.handle.net/1783.1/73343>

If it is the author's pre-published version, changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published version.

Geotechnical Testing Journal

Sumit Jain,¹ Y. H. Wang,² and Delwyn G. Fredlund³

DOI: 10.1520/GTJ20140274

Non-Contact Sensing System to Measure Specimen Volume During Shrinkage Test

VOL. 38 / NO. 6 / NOVEMBER 2015

Sumit Jain,¹ Y. H. Wang,² and Delwyn G. Fredlund³

Non-Contact Sensing System to Measure Specimen Volume During Shrinkage Test

Reference

Jain, Sumit, Wang, Y. H., and Fredlund, Delwyn G., "Non-Contact Sensing System to Measure Specimen Volume During Shrinkage Test," *Geotechnical Testing Journal*, Vol. 38, No. 6, 2015, pp. 1-14, doi:10.1520/GTJ20140274. ISSN 0149-6115

ABSTRACT

The shrinkage curve provides information of value for the interpretation of soil-water characteristic curve data. However, there is need for an accurate and precise volume measurement technique during the shrinkage test. This paper presented an inexpensive automated digital image processing technique, which allowed accurate and precise measurements of the soil specimen volume. The volume was computed by accurately measuring the radius and height over the entire lateral surface of specimen. The proposed volume measurement technique involved projecting a structured light laser on the soil specimen in order to provide the reference points for measurements. A 360° view of the specimen was then captured using a camera. High resolution images were then processed using functions developed within MATLAB. The computations also allowed the reconstruction of a 3D mesh model of the specimen. A validation test on a dummy object showed that the error in radius and height measurements at more than 75 % measurement points was less than ± 0.05 and ± 0.07 mm, respectively. A 99 % accuracy was achieved in the volume measurement of the soil specimen.

Keywords

shrinkage test, kaolinite clay, volume measurement, image processing, 3D reconstruction

Introduction

Shrinking and swelling clay soils can undergo significant changes in volume as the water content of the soil changes. The relationship between a water content related variable versus a pore volume related variable, from an initially high water content to completely dry conditions, is usually

Manuscript received December 16, 2014; accepted for publication April 27, 2015; published online May 20, 2015.

¹ Research Student, Department of Civil and Environmental Engineering, The Hong Kong Univ. of Science and Technology, HKSAR, China, e-mail: sjainaa@ust.hk

² Associate Professor, Department of Civil and Environmental Engineering, The Hong Kong Univ. of Science and Technology, HKSAR, China (Corresponding author), e-mail: ceyhwang@ust.hk

³ Senior Geotechnical Engineering Specialist, Golder Associates Limited, Saskatoon, Saskatchewan, Canada, e-mail: delwyn_fredlund@golder.com

described by the soil shrinkage characteristic curve (SSCC) (Cornelis et al. 2006). The shrinkage curve plays an important role in the interpretation of the soil-water characteristic curve (SWCC) data (Fredlund et al. 2011a). Fredlund et al. (1964, 2011b) and Fredlund and Houston (2013) showed that shrinkage curve measurements should be used in combination with a typical measurement of the SWCC in order to properly interpret the unsaturated soil property functions of high volume change soils. The shrinkage curve, used in combination with the SWCC allows for the calculation of the void ratio versus soil suction relationship (Fredlund et al. 2002; Fredlund and Zhang 2013). Cornelis et al. (2006) also stated that the modelling of water transport in the unsaturated soil zone not only requires the SWCC and the saturated coefficient of permeability, but also another relationship; namely, the shrinkage curve. According to Braudeau et al. (1999) and Assi et al. (2014), the shrinkage curve analysis allows an accurate quantitative assessment of the hydro-structural properties to be made. The shrinkage curve also provides an accurate quantification of the limiting shrinkage of a soil. The current and past ASTM standards for the shrinkage limit have important limitations. ASTM D427-04 was withdrawn because of health safety concerns. Both ASTM D427-04 and the current standard, ASTM D4943-08 were shown to produce results that are operator dependent (Cerato and Lutenegeger 2006).

The determination of shrinkage curve requires the simultaneous measurement of total volume of a soil specimen and its water contents. While the measurement of water content is easy, the challenge is to measure the total volume with sufficient accuracy. Current measurement techniques usually involve a limited number of measurement points. The conventional instruments used in the laboratory to measure displacements are the digital micrometer, the linear variable differential transformer (LVDT), and the Hall Effect sensor (Clayton et al. 1989). These measurement systems do not enable the volume of a soil specimen to be measured with high accuracy because of irregularities in the specimen during drying (Ng et al. 2002). An alternative volume measurement method involves immersing the soil specimen into a fluid and measuring the displaced volume of fluid. The use of Kerdane oil (i.e., a hazardous compound) as the displaced fluid was found to give the best results (Peron et al. 2007). The use of Kerdane oil is a destructive technique; hence it is not appropriate for performing repeated measurements on a single soil specimen. 2D/3D laser scanners were successfully used to measure the volume of solids (Zhang et al. 2005) and to measure rock joint surface roughness (Hong et al. 2006). These scanners are easy to use and provide high accuracy and resolution; however, they are quite costly. A similar but less expensive approach involves the use of digital image processing. Digital image processing has been successfully used to measure deformations in geotechnical physical model tests (White et al. 2001a, 2001b, 2005) and volume changes of soil

specimens in conventional triaxial tests (Macari et al. 1997; Alshibli and Al-Hamdan 2001; Gachet et al. 2007). These image processing techniques have revealed a number of limitations in determining volume change in drying soils. The technique does not provide precise and accurate results when taking pictures from only one direction (Sanchez et al. 2013a, 2013b). The research literature reveals that there is still need for an accurate, non-destructive, and inexpensive measurement technique for the determination of the volume of a soil specimen subjected to the drying process.

This paper proposes a new, relatively inexpensive approach for the measurement of total volume of a soil specimen during the shrinkage test. The approach is based on image processing and uses a structured light laser module. The approach can accurately measure the radius (i.e., with respect to central axis of the soil specimen) and height values over the entire lateral surface of specimen and hence takes the irregularity of specimen into account. The paper explains the experimental details related to the main components of setup, the setup installation in the laboratory, the working principle, and the procedure to implement the proposed methodology. The image processing functions developed within MATLAB are then discussed⁴. The resolution and accuracy that can be achieved when using this technique are also presented. Shrinkage curve results are shown for tests performed on a kaolinite clay specimen.

Experimental Details

OVERVIEW

Figure 1(a) is a photograph of the experimental setup in the laboratory, while Fig. 1(b) and 1(c) show a schematic representation of the basic setup. The basic setup requires the following main components: (1) laser diode modules; (2) diffractive optical element (DOE) lens (embedded in the laser); (3) laser mount; (4) 360° turntable; (5) camera; (6) tripod; (7) intervalometer; (8) calibration plate; (9) solid cylindrical objects. Table 1 shows the price range of the main components and the total cost associated with the volume measurement system.

Two simple laser modules were used with each laser projecting a single red dot. The single laser dot can be readily converted into a variety of different light beam patterns, (i.e., rings, lines, dot lines, grids, etc.), with the help of the DOE lens. Two different DOEs were used to achieve two different patterns. The specifications for the DOEs were provided by the supplier and are shown in Fig. 2. The first pattern is a dot line pattern which projects 19 dots in a single line at an angular spacing of 0.77°. The second pattern projects a continuous single line. Laser mounts were used to securely fasten the lasers to a rigid surface.

⁴Available at <https://github.com/sumitjainaa/Image-Processing-Functions.git>

FIG. 1

(a) Photograph of the experimental setup, (b) schematic representation showing the front view (section A-A), and (c) the top view (section B-B) of the experimental setup with the laser positions and alignment.

The turntable is a heavy duty turntable that can be operated by an on/off switch. The turntable has a constant speed and direction of rotation, and takes 90 s to complete one rotation (i.e., it rotates at $4^\circ/\text{s}$). The selected speed was sufficiently slow to allow the turntable motion to be smooth, avoiding any soil specimen

vibrations. A Canon EOS 7D DSLR camera was used to capture the images. The camera was rigidly fixed with the help of a tripod. An intervalometer (model TC-80N3, Canon) is an external camera attachment that allows the camera to take images at set intervals. A calibration plate was used with the dots printed

TABLE 1 Price range of the main components and the total cost associated with the basic experimental setup.

Name of Equipment	Price Range (USD)	Brand Used in this Study
1st laser with DOE (dot-line pattern) and laser mount	\$500–1300	Osela Inc., Canada
2nd laser with DOE (continuous line) and laser mount	\$200–300	RS Components, United Kingdom
360° turntable	\$100–150	Available at turntable360.com
DSLR camera	\$1500–2000	Canon
Tripod	\$100–250	Manfrotto, Italy
Intervalometer	\$100–200	Canon
Total Cost =	\$2500–4200	

FIG. 2
Specifications of the DOEs integrated with the laser modules in this study.

on an A4 sheet and pasted on an acrylic plate. Three solid cylindrical objects of known dimensions within an accuracy of ± 0.01 mm were prepared for radius and height calibration. The dimensions of the cylindrical objects were ~ 50 by 30 mm (diameter by height), 47.5 by 27.5 mm, and 45 by 25 mm. The sizes were selected to emulate a shrinkage specimen that deforms from ~ 50 to 45 mm in diameter and from ~ 30 to 25 mm in height during shrinkage.

SETUP INSTALLATION

As shown in Fig. 1, the turntable is placed in front of lasers, and a calibration plate is placed behind to avoid interference with the laser pathways. The center of the turntable, the alignment of the two lasers, and the calibration plate are the three main aspects of this setup. The main requirement of this setup is that all three should be in a single plane. This is an ideal condition, however, this condition might be difficult to achieve. Fortunately, a small deviation from the ideal condition does not result in a significant error in the measurements. An error calibration procedure can be used to reduce the errors in the measurements, and is later described in the text. A reference line was drawn on the turntable as shown in Fig. 1(c) to assist in the error calibration. The camera was set essentially parallel to the laser alignment, and held level in terms of both side to side and front to back. The camera was able to capture the calibration plate and the object to be scanned. The camera was connected to the computer via a USB port to remotely adjust the exposure settings without touching the camera. An intervalometer was externally attached to the camera to automatically take images at set intervals. The laser modules, the calibration plate, the

turntable, and the camera remain fixed during the entire experiment.

WORKING PRINCIPLE

The working principle of the proposed volume measurement system is based on the principle of laser triangulation (Jalkio et al. 1985). The laser triangulation technique has been widely used in 2D/3D laser scanners. In our technique, the soil specimen is placed on a turntable and is subjected to lasers. At any moment during the rotation there are n laser dots projected on the specimen in a single line when only the dot-line laser is switched on (see Fig. 3(a)). Each image will have n dots on the specimen, and m images will be taken as the specimen is rotated through 360° . Stated another way, a total of $m \times n$ measurement points are made of the surface of specimen. Figure 1 shows that there are also some fixed reference points lying in the same plane as the laser alignment and the center of the turntable. One of the reference points can be selected as the origin as shown in Fig. 3. The real coordinates of the laser dots ($m \times n$ points) on the surface of specimen can then be determined using plane-based close-range photogrammetry (CRP) (White et al. 2003). Using the x coordinates, x_{ij} , of these $m \times n$ surface points, the distance s_{ij} (see Fig. 3(a) and 3(c)) from the center of the turntable to the surface point is calculated as:

(1)
$$s_{ij} = d - x_{ij}$$

where:
 $i = 1$ to m ,
 $j = 1$ to n , and

FIG. 3

Radius and height estimation: (a) real coordinates of laser dots projected on the specimen, (b) real coordinates of end points of the laser line projected to measure the height, (c) radii measured with respect to the center of the turntable, and (d) radii converted with respect to the specimen's central axis.

d = the horizontal distance from the origin to the center of the turntable (see Fig. 3(a)).

The variable i denotes the image number and j resembles the dot number in that image. The distance, d , is measured during the calibration process as explained later. The distances s_{ij} for all the n points in an image can be estimated (see Fig. 3(a)) and the average calculated distance, s_i , is taken as the representative distance measured from the image.

$$(2) \quad s_i = \frac{1}{n} \sum_{j=1}^n s_{ij}$$

where $i = 1$ to m and m is the total number of images. In total, there are m average distances which are measured at regular intervals from a fixed point inside the specimen to the surface of specimen (see Fig. 3(c)). A polygon is then constructed based on these m number of average distances. The center of mass of this polygon was determined and taken as the position of the central axis of the specimen. The distances s_i are now converted to the radius r_i with respect to the central axis of specimen, as shown in Fig. 3(d). In this experiment, images were taken every 4° angle, which gives us 90 images for a 360° view, with around 10 points in each image. This results in a total of more than 900 measurement points on a 50 by 30 mm specimen (i.e., 50 mm diameter and 30 mm high).

The height h is measured by projecting the line laser on the specimen (Fig. 3(b)) and taking images at the same interval of 4° . Each image will capture the laser line projected on the specimen at different segments. The y coordinate of the end points of laser line in each segment is used to estimate the height in that segment of the specimen:

$$(3) \quad h_i = b_{i1} - b_{i2}$$

where $i = 1$ to m . Based on the computed radii and heights at each 4° interval, the volume of a small segment as shown in Fig. 4 is computed. Subtending an angle of 4° allows the calculation of the segment volume, V_i , as follows:

$$(4) \quad V_i = \left(\frac{\theta}{360} \times \pi r_i^2 \right) \times h_i$$

where:

$$\theta = 4^\circ,$$

$$i = 1 \text{ to } m,$$

FIG. 4 Small segment of soil specimen subtending an angle of $\theta = 4^\circ$.

FIG. 5

Schematic representation showing the top view of (a) the cylindrical object placed on the turntable for calibrating the distance between the center of the turntable and the origin, (b) the orientation relative to the center of cylinder, center of the turntable, laser dot, and the origin along a line, and (c) 180° rotation from orientation in Fig. 5(b).

r_i = the radius, and

h_i = the height of the i th segment.

The total volume V is calculated as the summation of all these small volumes and is given by:

$$(5) \quad V = \sum_{i=1}^m V_i$$

A calibration procedure is required in order to calculate the distance d from the origin to the center of the turntable. A cylindrical object of known dimensions is placed on the turntable (Fig. 5(a)) such that the center of the turntable lies within the object. The center of the cylinder may not coincide with the center of the turntable. Thus, the cylinder is rotated about the center of the turntable. After a certain rotation of the cylinder, the center of cylinder, the center of the turntable, the laser dot, and the origin will lie along the same line (Fig. 5(b)). The same situation will arise following a rotation of 180° (Fig. 5(c)). However, there will be a shift in the center of the cylinder and the laser dot. The distance d can now be calculated using the following relationships:

$$(6) \quad p + b = q + a$$

$$(7) \quad a + b = \text{diameter of cylinder (known)}$$

$$(8) \quad d = p + b$$

where p and q are the distances from the origin to the laser dot. These distances are determined using photogrammetry.

A function developed within MATLAB was used to automatically identify these two positions and calculate the desired distance d .

CALIBRATION AND TESTING PROCEDURE

A proper format and procedure needed to be followed while capturing the images because the functions developed in MATLAB adhere to a prescribed algorithm. The image format selected for all the images was readable by the “imread” command into MATLAB. The image names were in a fixed format as “IMG_k”, where k is any number (e.g., “IMG_4444”). The number, k , increases by one with every new image taken (i.e., the next image should be IMG_4445). A preliminary camera calibration image was taken in which the dots on the calibration plate were clearly visible and easily distinguishable.

The distance and error calibration (used for radius measurement) can be performed using the three cylindrical objects shown in Fig. 6(a). The calibration is performed prior to scanning the soil specimen. The 50 by 30 mm cylindrical object is first placed on the turntable with its central axis approximately coinciding with the center of the turntable. Only the dot line laser is switched on at this time. The aperture, ISO, and the shutter speed were adjusted in the DSLR camera via the computer. The camera settings are such that only the laser dots projected onto the object are visible in the image against a black background. The software available for Canon DSLR (i.e., Canon EOS utility) was used to control the exposure parameters via the computer. The exposure parameters selected to capture

FIG. 6

Solid cylindrical objects of dimensions, from left to right, of 50 by 30 mm (diameter by height), 47.5 by 27.5 mm, 45 by 25 mm, and 42.5 by 22.5 mm used for (a) distance and error calibration and (b) accuracy evaluation.

the laser dots were aperture $f/20$, ISO 200 and shutter speed $1/1000$ s. The turntable was then switched on. As soon as the reference line marked on the turntable came into the plane of the laser alignment (see Fig. 1(c)), images at constant interval of 4° were taken throughout a rotation of 360° . Two other cylindrical objects were then placed onto the turntable one by one and the above steps were repeated. The purpose of scanning the objects from the same starting position on the turntable and along the same direction was to calibrate the error with the rotation.

The height calibration was performed by placing the 50 by 30 mm cylindrical object once again on the turntable. The dot-line laser was now switched off while the continuous line laser was projected onto the object. The exposure settings (i.e., aperture $f/20$, ISO 320, and shutter speed $1/20$ s) in the camera were selected to capture the projection of red laser line. The exposure settings were selected such that the line laser has the highest red color value in the image, and so can be easily extracted from the image. The images at constant intervals of 4 or 8° were taken until a rotation of 360° was completed.

After completing the two calibrations, the soil specimen was placed onto the turntable. The same steps were then taken to capture a 360° view of the soil specimen with both laser patterns (i.e., one after the other). All of the images could now be analyzed using the functions developed by the authors. The functions are available as free download software. Some open source functions, e.g., geoCENTROID8, and geoCALIBRATE8, were also used.

Image Processing

The following steps were performed to process the images, estimate the volume of the specimen, and reconstruct a 3D mesh model of the lateral (or vertical) surface:

STEP 1. SEPARATE THE IMAGES

The images were first separated into different folders, such that each folder contains the images captured during a single scan of each object or specimen. Four different objects (i.e., three cylinders and a soil specimen) were scanned for radii measurements, and two objects for the height measurements (i.e., one cylinder

and a specimen). Consequently, six different folders in one directory were needed to separate the images. The image taken for the camera calibration (White et al. 2003) was stored in the same directory with six folders.

STEP 2. SET UP LAUNCHER FILES

The functions developed in MATLAB runs with the help of a launcher file called *slaunch*. The launcher file tells the function which images to analyze and what analysis parameters to use. The image names are in a fixed format as “IMG_k,” and in each folder, k increases by one when going to the next image. The k corresponding to the first image in a folder is the first parameter for the launcher file of the folder. The second parameter assigned is the number of images taken for this object during a single rotation. The third parameter is used to extract the red color from the images and is denoted as the threshold value ε , which transforms the original image into a binary image. Let us assume that b_{ij} is the binary value of a pixel in the binary image. Then the transformation can be expressed as:

$$(9) \quad \begin{aligned} b_{ij} &= 0 \text{ (black) if } a_{ij} \leq \varepsilon \\ b_{ij} &= 1 \text{ (white) if } a_{ij} \geq \varepsilon \end{aligned}$$

where a_{ij} are the initial red color values in the image at the (i, j) pixel coordinates.

The number of times a single object is scanned is given using the fourth parameter, as multiple scanning can reduce the error. The fifth parameter decides the filename. If the filename is given as 32, a text file “PIV_32_32” will be created where all the pixel coordinates are stored for further analysis. The sixth, seventh, eighth, and ninth parameters are the pixel coordinates used to crop the images into a smaller rectangular search region outside which the functions should not detect any red dots in any of the images. The pixel coordinates (xb, yb) of the bottom right corner of this search region will be decided by the sixth and seventh parameter, respectively. Similarly, the pixel coordinates (xu, yu) of the top left corner of this search region will be decided by the eighth and ninth parameter, respectively. Here, the seventh parameter should be the y pixel coordinate of the bottom-most point of object. It is assumed that bottom y pixel value is the same everywhere for a flat bottom object and only the top point (detected by the function) shifts as the object

height varies. A sample launcher file for reference can also be downloaded from the website where all the functions developed by the authors are available. The launcher file should be setup for each object and saved in the same folder with the images of a particular object.

STEP 3. RUN THE FUNCTION TO DETECT THE PIXEL COORDINATES OF POINTS

The folder containing the images to be analyzed was opened within MATLAB. The function “sjdots()” can automatically read all the images and identify the pixel coordinates of the centroid of the laser dots shown in **Fig. 3(a)**. The function “sjendpoints()” can detect the pixel coordinates of the topmost point of the laser line shown in **Fig. 3(b)**. These two functions outputs the pixel coordinates in an ANSI text file created by the function in the same folder.

STEP 4. PERFORM CAMERA CALIBRATION

The text file created by the functions “sjdots” and “sjendpoints” is compatible with the camera calibration procedure given by [White et al. \(2003\)](#). The calibration procedure is based on the principles of close-range photogrammetry. The sources of image distortion are explicitly modelled as part of the calibration procedure, yielding a 14-parameter transformation method as proposed by [Heikkila and Silven \(1997\)](#). Two functions can be used to perform the calibration. The function geoCENTROID8 can be used for the reference point identification and geoCALIBRATE8 for the transformation optimization. The reference points were identified in the camera calibration image. The geoCALIBRATE8 function outputs the real coordinates into a variable assigned by the user in the workspace of MATLAB (suppose *xydata* was assigned).

STEP 5. DISTANCE CALIBRATION

After performing the above steps for the 50 by 30 mm cylindrical object, the function “sjdistcalib” was used to calibrate the distance from the origin to the center of the turntable (**Fig. 5(a)**). The function takes two variables as input, i.e., *xydata* calculated in fourth step and the actual radius *actrad* of the cylinder. The radius of cylinder was measured using a digital micrometer within an accuracy of ± 0.01 mm. The syntax of this function is as follows:

$$[cdist, incline] = sjdistcalib(xydata, actrad)$$

The function stores the calibrated distance *d* in the variable *cdist*. The calibration needs to be performed once for a non-interrupted setup and allows for the calculation of the radius of any other object in the next step.

STEP 6. RADIUS CALCULATION

Steps 2–4 were repeated on the images taken of any other object with the dot line laser. The function “sjradcalc” was

TABLE 2 Format of variable “errval” for storing error values (in mm). The error is measured at discrete angles for three cylindrical objects of radii $r = 25.02$, 23.79 , and 22.56 mm.

Number	Angle	25.02	23.79	22.56
1	0	0.117963	0.221927	0.367123
2	4	0.150027	0.306471	0.408023
3	8	0.205974	0.286858	0.40789
4	12	0.162822	0.287055	0.348875
5	16	0.118884	0.239424	0.319473
6	20	0.070913	0.162727	0.236723
7	24	0.033639	0.094607	0.234304
8	28	−0.06414	0.079803	0.235301
9	32	−0.05556	0.091888	0.228272
10	36	−0.04937	0.096473	0.241962
11	40	−0.06136	0.104497	0.233672
12	44	−0.05565	0.099909	0.230345
13	48	−0.06655	0.094264	0.204325
14	52	−0.08367	0.052316	0.186031
15	56	−0.05325	0.066462	0.196825
16	60	−0.11631	0.054248	0.149467
17	64	−0.12298	−0.02778	0.136768
18	68	−0.15472	−0.02983	0.149724
19	72	−0.16414	−0.01493	0.13588
20	76	−0.11208	0.003544	0.189001

then used to calculate its radius, while *xydata*, *cdist*, and *incline* were given as the inputs. The syntax of this function is as follows:

$$[r, allrad, ydist, remdistort] = sjradcalc(xydata, cdist, incline)$$

The function outputs the average radii at regular intervals (4°) in the variable *r* and the radius at each point in the variable *allrad*. The variables *ydist* and *remdistort* are later used to find the 3D coordinates of the surface points.

STEP 7. ERROR CALIBRATION

The radius calculated from step 6 still has some error (see **Table 2**) because of the deviation from the planned setup. The error can be calibrated as a function of the radius and the rotation angle from starting position since everything is fixed during the experiment.

Steps 2–4 and step 6 were performed on three cylindrical objects with known radii (i.e., $r = 25.02$, 23.79 , and 22.56 mm). The error at each point in the average radius stored in variable *r* during step 6 was evaluated for each object. A variable *errval* of size $(m + 1) \times 3$ was created in the workspace of MATLAB to store these error values. Here, *m* is the number of images for a particular object. The first row contains the actual radius of the object. The remaining *m* rows in the same column contain the error values for that object (see **Table 2**). The first two columns

FIG. 7 (a) Error versus angle from 0° to 360° corresponding to three different radii r , measured using three cylindrical objects of different dimensions and (b) circular view of error (radial coordinate) versus angle (angular coordinate).

are shown for reference, while only the last three columns are copied in the variable *errval*. The error is evaluated at 90 discrete angles, and **Table 2** only shows the first 20 values, while the remaining values are shown in **Fig. 7**. Each angle has three error values corresponding to three different radii r . It is therefore possible to establish a quadratic relationship between the error and the radius at discrete angles, as shown below:

$$(10) \quad \text{error } e_i = p_i \times r^2 + q_i \times r + c_i$$

where:

p_i , q_i , and c_i are the polynomial coefficients of the quadratic relationship, and

$$i = 1 \text{ to } m.$$

A function “*sjerrelim*” was developed to take this variable *errval* as input and automatically establish the relation shown in Eq 10.

STEP 8. RADIUS MEASUREMENT AND ERROR ELIMINATION ON SOIL SPECIMEN

Steps 2–4 and 6 were repeated on the images taken of the specimen with the dot line laser. The output after these steps is the radii having some error due to bias in the setup (mentioned in step 7). The function “*sjerrelim*” was used to eliminate the bias error.

$$[r, \text{allrad}] = \text{sjerrelim}(r, \text{errval}, \text{remdistort})$$

The final corrected radii will be stored in the variable r and is later used to calculate the volume of specimen.

STEP 9. HEIGHT CALIBRATION

Steps 2–4 were performed on the images taken of the 50 by 30 mm cylindrical object to determine the height calibration

factor *htfac*. The function “*sjheightfac*” takes the input as the actual height *actheight* of the object and calculates the *htfac*, as follows:

$$(11) \quad \text{htfac} = \frac{\text{Actual Height}}{\text{Estimated Height}}$$

where the actual height of cylinder was measured using a digital micrometer within an accuracy of ± 0.01 mm. The “estimated height” is the height measured from the image. The syntax of the function is as follows:

$$[h, \text{htfac}] = \text{sjheightfac}(\text{xydata}, \text{actheight})$$

STEP 10. HEIGHT MEASUREMENT

Steps 2–4 were performed on the images of specimen taken for height measurement. The function “*sjheightcalc*” was then used whose syntax is as follows:

$$[h] = \text{sjheightcalc}(\text{xydata}, \text{htfac})$$

The function outputs the calibrated height values of the specimen into the variable h .

STEP 11. VOLUME CALCULATION

The final radii r and heights h of the specimen evaluated in steps 8 and 10, respectively, were given as input to the function “*sjvolcalc*.” The function calculates the volume using the Eqs 4 and 5, and has the following syntax:

$$[\text{vol}] = \text{sjvolcalc}(r, h)$$

The calculated volume of the specimen is stored as the variable *vol*.

STEP 12. 3D COORDINATES EVALUATION

The function “sjcoord” was used to evaluate the 3D Cartesian coordinates of the specimen to reconstruct 3D mesh models at various stages. The function takes the input as *allrad* and *ydist* calculated in steps 8 and 6, respectively. The syntax is shown below:

$$[x, y, z] = \text{sjcoord}(\text{allrad}, \text{ydist})$$

This outputs the x , y , and z coordinates of all the $m \times n$ points detected on the specimen.

STEP 13. 3D RECONSTRUCTION

Reconstruction of the 3D model was performed using an open source function “surf2stl” (McDonald 2004), downloaded from MathWorks. The function writes a stereo lithography (.stl) file for a surface with the geometry defined by three matrix arguments, x , y , and z coordinates. The syntax of the function is as follows:

$$\text{surf2stl}('3\text{dsample.stl}', x, y, z, 'ascii')$$

Resolution and Accuracy

The resolution of the proposed technique is adjustable and depends on the test apparatus being used. The turntable used in this study completed one rotation in 90 s, and the images were taken every 1 s. So, the horizontal resolution h_{res} for a 50 by 30 mm cylindrical object can be given as:

$$(12) \quad h_{\text{res}} = \frac{\text{Perimeter}}{\text{No. of images}} = \pi * \frac{D}{m} = 3.14 \times \frac{50}{90} = 1.744 \text{ mm}$$

Taking the images at a faster rate or reducing the speed of the turntable, or both, can improve the horizontal resolution of the setup.

The vertical resolution v_{res} depends on the DOE lens being used with the laser. This is because the DOE lens decides the number of dots, n , projected on the object in a single line. The DOE lens used in this study can project 19 dots in a single line at a spacing of $\beta = 0.77^\circ$ between each dot as shown in Fig. 2. The spacing is proportional to the distance of the object from the laser. At a 100 mm distance, the vertical resolution is given by:

$$(13) \quad v_{\text{res}} = \tan(0.77^\circ) \times 100 \text{ mm} = 1.344 \text{ mm}$$

The vertical resolution can also be improved by using a better DOE or putting the laser closer to the object, or both.

The accuracy of the setup was checked by performing a trial test on a cylindrical object of known dimensions as shown in Fig. 6(b). The dimensions of the trial cylindrical object significantly differed from the one used for calibration. Radius

measurements at 889 points were successfully performed using this technique. More than 50 and 75 % of the measured points had an error of less than ± 0.03 and ± 0.05 mm, respectively. The maximum error observed was +0.13 mm, while the average error was -0.003 mm. Similarly, the height was also measured at 45 different points, out of which more than 75 % of the points had an error of less than ± 0.07 mm, while the average error was 0.013 mm.

The accuracy in measuring the volume was estimated by comparing the volume of soil specimen measured using the described technique and the volume measured by a high resolution (0.08 mm) 3D scanner (ATOS Core 200, GOM, Germany). The 3D scanner offers a point accuracy of 0.012 mm in all the directions. The comparison between our technique and the 3D scanner was made at the final stage of shrinkage test. The two measurements did not differ significantly and the difference was found to be 0.397 cm^3 (i.e., 1 % of total volume). The results show that the proposed technique provides 99 % accuracy in measuring the volume of a soil specimen.

Shrinkage Test on Saturated Kaolinite Clay

The proposed technique was applied to the measurement of shrinkage curves, in the range from an initially high water content to a completely dry condition. The shrinkage test was performed under controlled temperature and relative humidity conditions.

MATERIALS AND SPECIMEN PREPARATION

The soil used in this test was Speswhite Kaolin, composed of 38 % Al_2O_3 and 47 % SiO_2 . The particle sizes are mostly smaller than $2 \mu\text{m}$, and the pH value was about 5 ± 0.5 (provided by Imerys Minerals Ltd., UK). The specific gravity and surface area are 2.60 and $14 \text{ m}^2/\text{g}$, respectively (Dong and Wang 2008). The kaolin clay has a liquid limit of 57.9 % and plastic limit of 29.7 % (Wang and Siu 2006). A uniform and saturated soil specimen was prepared close to its liquid limit (Sanchez et al. 2013a, 2013b) by applying one-dimensional consolidation to the clay slurry, following the procedure described in Wang and Siu (2006). Entrapment of air bubbles was minimized during the specimen preparation. After consolidation was complete, the specimen was trimmed to the desired size using a cylindrical cutter with internal dimensions 50 by 30 mm. A thin layer of hydrophobic coating (NeverWet) was applied inside the cutter to minimize the effects of adhesion and to reduce side friction while removing the cutter.

TESTING ON SOIL SPECIMEN

The specimen with an initial size of approximately ~ 50 mm diameter and 30 mm height was placed on an acrylic plate (see Fig. 1(a)), which allowed movement of the specimen in different locations during drying. The setup for measuring the volume

TABLE 3 Measurements on the soil specimen during the shrinkage test. M_p = weight of acrylic plate = 54.08 g.

Total Weight M_T (g)	Specimen Weight $M_T - M_p$ (g)	Water Loss (g)	Specimen Bulk Volume) (mm^3)	Changes in Bulk Volume (mm^3)	Gravimetric Water Content (%)	Volumetric Water Content (%)	Void Ratio	Degree of Saturation (%)
141.94	87.86	–	55675	–	59.83	59.07	1.443	100
140.48	86.4	1.46	54394	1281	57.17	57.78	1.387	99.42
138.81	84.73	1.67	52878	1516	54.13	56.28	1.320	98.90
137.38	83.3	1.43	51600	1278	51.53	54.90	1.264	98.32
135.71	81.63	1.67	50017	1583	48.49	53.30	1.195	97.90
134.11	80.03	1.6	48439	1578	45.58	51.73	1.125	97.68
132.59	78.51	1.52	47042	1397	42.82	50.04	1.064	97.05
131.01	76.93	1.58	45747	1295	39.94	48.00	1.007	95.64
128.69	74.61	2.32	43551	2196	35.72	45.10	0.911	94.58
126.28	72.2	2.41	41160	2391	31.34	41.86	0.806	93.78
124.78	70.7	1.5	39583	1577	28.61	39.73	0.737	93.64
123.38	69.3	1.4	38559	1024	26.06	37.16	0.692	90.85
121.7	67.62	1.68	38612	–53	23.01	32.76	0.694	79.94
118.99	64.91	2.71	38703	–91	18.08	25.68	0.698	62.45
116.17	62.09	2.82	38709	–6	12.95	18.39	0.698	44.72
113.55	59.47	2.62	38570	139	8.18	11.67	0.692	28.50
110.12	56.04	3.43	38767	–197	1.94	2.76	0.701	6.70

FIG. 8

Shrinkage curves measured for Speswhite Kaolin clay from an initially high water content to almost dry conditions: (a) void ratio versus gravimetric water content and (b) void ratio versus volumetric water content.

FIG. 9 Plot between net changes in bulk volume versus net water loss during shrinkage.

was installed and the calibration images on the cylindrical objects were previously taken. A high-capacity precision weighing balance (GS3202, SHINKO DENSHI, Japan) with a resolution of 0.01 gs was used to measure the weight of the specimen during drying. The weight of the acrylic plate M_p , and the initial total weight M_T of the specimen with the acrylic plate were measured and recorded. Immediately after measuring M_T , the specimen was placed on the turntable and its 360° view was captured. The images were saved in a computer, and later processed by the functions in MATLAB to measure the bulk volume V by the methodology described in this paper. The specimen was then allowed to dry, and similarly at different water contents the bulk volume V and mass M_T was measured until the water content became almost zero. The final dry weight M_D was also measured and used to calculate the water content at every measurement stage.

Results and Discussion

The gravimetric water content and void ratio at each measurement stage were calculated and shown in **Table 3**. The shrinkage curves plotted using these data points is shown in **Fig. 8**. Initially, the shrinkage curve showed a linear drying portion between the void ratio and water content. Then there was a distinct break in curvature, after which there was no significant change in void ratio with decreasing water content. It can be observed from **Table 3** that the soil was initially near saturation and the decrease in water volume resulted in an almost equal

change in bulk soil volume. **Figure 9** shows that the slope of the fitted line between the net changes in bulk volume versus the water loss for this zone is equal to 0.933, with an R^2 value of 0.9996. This also demonstrates the accuracy of the measurement technique. Upon further drying, a point was reached where the soil dried without any significant change in overall volume. A horizontal line from this point to the saturation line is referred to as the “shrinkage limit” value of the clay. The shrinkage limit was estimated as 28.7 %, which is close to the plastic limit of 29.7 % for this clay. The shrinkage limit generally lies slightly below the plastic limit of the soil (Fredlund et al. 2011a). A 3D mesh model of the specimen at different volumetric strains was also constructed using the technique described in this paper and can be seen in **Fig. 10**. The 3D mesh model gives a better idea of the irregular shape of the soil specimen. The 3D mesh can be used to visualize the shrinkage process.

Summary and Conclusions

A methodology based on image processing and structured light laser modules was presented in this paper. The method can measure the volume of soil specimen and can construct a 3D mesh model during the shrinkage process. Laser modules were used instead of placing permanent reference markers on the specimen in order to provide reference points for the measurement of volume. A 360° view of the specimen was taken by a fixed camera and images were then analyzed by the functions developed within MATLAB to estimate the radii and heights over the entire specimen and thus calculate the volume. A procedure is also suggested to eliminate the error caused by the deviation in the laboratory setup from the planned layout. The accuracy at each radius and height measurement point was assessed by comparing the measurements using this technique with the actual surface profile of an object with known dimensions. The volume measurement on the soil specimen was validated using a high resolution 3D laser scanner. It is shown that a small volume change can also be measured accurately and precisely using this technique. The proposed procedure shows great promise for the accurate measurement of the volume of soil specimen during the shrinkage test. It is suggested that the same technique can be used to measure the volume of soil specimen during the other laboratory soil tests.

FIG. 10

3D mesh model of the lateral surface of specimen reconstructed using this technique at different volumetric strains ϵ_v , and (a) $\epsilon_v = 0\%$, (b) $\epsilon_v = 18\%$, and (c) $\epsilon_v = 30\%$.

ACKNOWLEDGMENTS

This research was supported by the Hong Kong Research Grants Council (HKUST9/CRF/09 and HKUST6/CRF/12R).

References

- Alshibli, K. A. and Al-Hamdan, M. Z., 2001, "Estimating Volume Change of Triaxial Soil Specimens From Planar Images," *Comput. Aided Civ. Infrastruct. Eng.*, Vol. 16, No. 6, pp. 415–421.
- Assi, A. T., Braudeau, E. F., Accola, J. J. O., Hovhannissian, G., and Mohtar, R., 2014, "Physics of the Soil Medium Organization Part 2: Pedostructure Characterization Through Measurement and Modeling of the Soil Moisture Characteristic Curves," *Soil Processes*, Vol. 2, No. 5.
- ASTM D427-04, 2004: Standard Test Method for Shrinkage Factors of Soils by the Mercury Method, ASTM International, West Conshohocken, PA, www.astm.org.
- ASTM D4943-08, 2008: Standard Test Method for Shrinkage Factors of Soils by the Wax Method, ASTM International, West Conshohocken, PA, www.astm.org.
- Braudeau, E., Costantini, J. M., Bellier, G., and Colleuille, H., 1999, "New Device and Method for Soil Shrinkage Curve Measurement and Characterization," *Soil Sci. Soc. Am. J.*, Vol. 63, No. 3, pp. 525–535.
- Cerato, A. B. and Lutenecker, A. J., 2006, "Shrinkage of Clays," *Proceedings of the 4th International Conference on Unsaturated Soils*, Carefree, AZ, April 2–6, ASCE, Reston, VA, pp. 1097–1108.
- Clayton, C. R., Khattrush, S. A., Bica, A. V. D., and Siddique, A., 1989, "The Use of Hall Effect Semiconductors in Geotechnical Instrumentation," *Geotech. Test. J.*, Vol. 12, No. 1, pp. 69–76.
- Cornelis, W. M., Corluy, J., Medina, H., Diaz, J., Hartmann, R., Van Meirvenne, M., and Ruiz, M. E., 2006, "Measuring and Modelling the Soil Shrinkage Characteristic Curve," *Geoderma*, Vol. 137, No. 1, pp. 179–191.
- Dong, X. and Wang, Y. H., 2008, "The Effects of the pH-Influenced Structure on the Dielectric Properties of Kaolinite–Water Mixtures," *Soil Sci. Soc. Am. J.*, Vol. 72, No. 6, pp. 1532–1541.
- Fredlund, D. G., 1964, "Comparison of Soil Suction and One Dimensional Consolidation Characteristics of a Highly Plastic Clay," *Technical Report No. 245*, National Research Council of Canada, Division of Building Research, Ottawa, Ontario, Canada.
- Fredlund, D. G. and Houston, S. L., 2013, "Interpretation of Soil–Water Characteristic Curves When Volume Change Occurs as Soil Suction is Changed," *Advances in Unsaturated Soils, Proceedings of the 1st Pan American Conference on Unsaturated Soils*, Cartagena de Indias, Colombia, Feb 20–23, CRC Press, Boca Raton, FL, pp. 15–31.
- Fredlund, D. G., Stone, J., Stianson, J., and Sedgwick, A., 2011a, "Determination of Water Storage and Permeability Functions for Oil Sands Tailings," *Proceedings of the International Conference on Tailings and Mine Waste*, Vancouver, BC, University of British Columbia, Vancouver, BC, p. 15.
- Fredlund, D. G., Stone, J., and Stianson, J., 2011b, "Obtaining Unsaturated Soil Properties for High Volume Change Oil Sands Materials," *AP-UNSAT 2011, Proceedings of the 5th Asia Pacific Conference on Unsaturated Soils*, Pattaya, Thailand, Nov 14–16, Kasetsart University, Bangkok, Thailand, pp. 415–420.
- Fredlund, D. G. and Zhang, F., 2013, "Combination of Shrinkage Curve and Soil–Water Characteristic Curves for Soils that Undergo Volume Change as Soil Suction is Increased," *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France, Sept 2–6, ISSMGE, London, pp. 1109–1112.
- Fredlund, M. D., Wilson, G. W., and Fredlund, D. G., 2002, "Representation and Estimation of the Shrinkage Curve," *UNSAT 2002, Proceedings of the Third International Conference on Unsaturated Soils*, Recife, Brazil, March 10–13, CRC Press, Boca Raton, FL, pp. 10–13.
- Gachet, P., Geiser, F. X., Laloui, L., and Vulliet, L., 2007, "Automated Digital Image Processing for Volume Change Measurement in Triaxial Cells," *Geotech. Test. J.*, Vol. 30, No. 2.
- Hong, E., Lee, I., and Lee, J., 2006, "Measurement of Rock Joint Roughness by 3D Scanner," *Geotech. Test. J.*, Vol. 29, No. 6, pp. 482–489.
- Heikkilä, J. and Silvén, O., 1997, "A Four-Step Camera Calibration Procedure With Implicit Image Correction," *1997 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, San Juan, Puerto Rico, June 17–19, IEEE, New York, pp. 1106–1112.
- Jalkio, J. A., Kim, R. C., and Case, S. K., 1985, "Three Dimensional Inspection Using Multistripe Structured Light," *Opt. Eng.*, Vol. 24, No. 6, pp. 966–974.
- Macari, E. J., Parken, J. K., and Costes, N. C., 1997, "Measurement of Volume Changes in Triaxial Tests Using Digital Imaging Techniques," *Geotech. Test. J.*, Vol. 20, No. 1, pp. 103–109.
- McDonald, B., 2004, "surf2stl, MATLAB Central File Exchange," <http://in.mathworks.com/matlabcentral/fileexchange/4512-surf2stl> (Last accessed 11 Sept 2014).
- Ng, C. W. W., Zhan, L. T., and Cui, Y. J., 2002, "A New Simple System for Measuring Volume Changes in Unsaturated Soils," *Can. Geotech. J.*, Vol. 39, No. 3, pp. 757–764.
- Péron, H., Hueckel, T., and Laloui, L., 2007, "An Improved Volume Measurement for Determining Soil Water Retention Curves," *Geotech. Test. J.*, Vol. 30, No. 1, pp. 1–8.
- Sanchez, M., Atique, A., Kim, S., Romero, E., and Zielinski, M., 2013a, "Exploring Desiccation Cracks in Soils Using a 2D Profile Laser Device," *Acta Geotech.*, Vol. 8, No. 6, pp. 583–596.
- Sanchez, M., Atique, A., Kim, S., Romero, E., and Zielinski, M., 2013b, "Study of Desiccation Cracks in Soils Using a 2D Laser Scanner," *Geo-Congress 2013: Stability and Performance of Slopes and Embankments III*, San Diego, CA, Mar 3–7, ASCE, Reston, VA, pp. 804–807.
- Wang, Y. H. and Siu, W. K., 2006, "Structure Characteristics and Mechanical Properties of Kaolinite Soils. I. Surface Charges and Structural Characterizations," *Can. Geotech. J.*, Vol. 43, No. 6, pp. 587–600.
- White, D. J., Take, W. A., Bolton, M. D., and Munachen, S. E., 2001a, "A Deformation Measurement System for Geotechnical Testing Based on Digital Imaging, Close-Range Photogrammetry, and PIV Image Analysis," *Proceedings of the 15th International Conference on Soil Mechanics and*

- Geotechnical Engineering*, Istanbul, Turkey, Aug 28–31, 2001, Vol. 1, pp. 539–542.
- White, D. J., Take, W. A., and Bolton, M. D., 2001b, “Measuring Soil Deformation in Geotechnical Models Using Digital Images and PIV Analysis,” *10th International Conference on Computer Methods and Advances in Geomechanics*, Tucson, AZ, Jan 7–12, CRC Press, Boca Raton, FL, pp. 997–1002.
- White, D. J., Take, W. A., and Bolton, M. D., 2003, “Soil Deformation Measurement Using Particle Image Velocimetry (PIV) and Photogrammetry,” *Geotechnique*, Vol. 53, No. 7, pp. 619–631.
- White, D., Randolph, M. F., and Thompson, B., 2005, “An Image-Based Deformation Measurement System for the Geotechnical Centrifuge,” *Int. J. Phys. Modell. Geotech.*, Vol. 5, No. 3, pp. 1–12.
- Zhang, X. and Morris, J., 2005, “Volume Measurement Using a Laser Scanner,” *Communication and Information Technology Research Report No. 170*, The University of Auckland, Auckland, New Zealand.