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Evaluating Soil Shrinkage Behavior using Digital Image Analysis Process

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Abstract. In this paper, the shrinkage behavior of silty clay soil widely found in Warangal is characterized under free evaporation condition over a wide range of suction. As a part of the research evaluation, a comprehensive laboratory test program was framed and conducted on the samples collected from Warangal. Slurries of soil samples were subjected to desaturation by evaporation and the change in the sample dimension was captured with camera still images and Vernier caliper. The captured images were processed and used for quantifying the overall volume change. The shrinkage behavior was represented as soil shrinkage curve (SSC) and the curve exhibited three zones. The proportional or normal shrinkage was dominant with volume of water lost from the pores equaling the volume change in the sample. The structural and residual shrinkage phase indicated the loss of water from both inter and intra aggregate pore space with gradual increase in time. The study showed the existence of bimodal porosity in low plasticity soil and also discusses the reliable efficiency of the proposed experimental procedure to study the shrinkage behavior of soils with low plasticity.

Keywords: Low Plasticity Soil, Shrinkage Curve, Suction, Volume Change, Digital Image Analysis.

1 Introduction

The behavior of soil related to water volume variation can be characterized as swelling or shrinkage. The volume change mechanism associated with the water volume variation has to be understood for determining the hydro-mechanical behavior of soil. The increase in water content of the compacted soil used in various geotechnical or geo-environmental field application has always been considered as the critical condition for analysis. The response of soil along the drying phase from the extreme saturated state possess an equal importance to be understood such that the wet-dry moisture variation effect can be explicitly characterized. The reduction in water content and the associated void volume change is generally represented as soil shrinkage curve (SSC) or shrinkage curve (SC). The SSC can be combined with the soil water characteristic curve (SWCC) or soil water retention curve (SWRC) and this will aid in understanding the effect of suction potential on the volume change of soil along varying moisture content [1–4]. The characterization of shrinkage curve generally involves four regime: i) structural phase, ii) proportional or normal phase, iii) residual phase and iv) zero or no shrinkage phase [2,3,5–8]

The contractive volume change is prominently induced by the internal forces such as suction stress existing at or near the particle contact surface [9–12]. The influence of suction stress and the microstructural change relative to the soil moisture movement evidently reveals the mechanism of shrinkage [13,14]. The contractive volume change characterization necessitates the measurement of water content change and the induced volume change at the same time throughout the drying phase. The moisture content decrease from the initial condition can be measured easily by determining the weight change of soil at regular time period. The accurate determination of volume change to represent the void ratio variation governs the exactitude of shrinkage characterization and the mechanism [8,15,16].

This paper aims at characterizing the shrinkage behavior of silty clay soil in Warangal, India with the use of digital image analysis technique and discusses in detail about the experimental set-up framed for the entire process and the reliability of prediction models is also highlighted. The changes observed in the dimension of the drying soil sample from slurry state to complete dryness are captured and studied to frame the shrinkage behavior as SSC. The cracking of soil during continued drying is eliminated by using a small sample size such that only subsidence is considered in the study. The 3D volume change study is more sophisticated and requires adequate knowledge whereas the use of micrometer or Vernier caliper for dimension measurement during the entire process of drying results in loss of sample due to handling errors. The vertical subsidence or the thickness can be determined easily with the use of thickness gauge whereas the horizontal shrinkage needs careful analysis such that volume computation will be reliable. There are notable research works that have used the 2D image analysis process to compute the volume change of samples and they have been recommended to be efficient in capturing the shrinkage of soil samples[8,17–21]. In this study, digital imaging was utilized for capturing the radial shrinkage and the image analysis was carried out using the open source 'ImageJ' version 1.52a software developed at the University of Wisconsin.

2 Materials and Methods

2.1 Soil

The soil obtained from NIT Warangal campus was used in this study. The collected soil samples were air-dried for a week and then oven dried. The over dry samples were sieved through 2.36mm IS sieve and stored in air-tight containers for laboratory study. The liquid limit and plasticity index of the soil was 42% and 11% respectively. The specific gravity was 2.61 and the soil was classified as silty clay exhibiting low to medium plasticity. The standard proctor compaction test was conducted and the maximum dry density was 17.12 kN/m^3 at an optimum moisture content of 15.5%.

2.2 Test procedures

The sample used for suction measurement was statically compacted to optimum moisture content and allowed for air-induced drying. The suction value was determined at predefined moisture content values. The total suction was measured using the chilled mirror hygrometer technique and the measured suction values were fitted using the Fredlund and Xing (FX) model as in equation (1) [22] and Van Genuchten (VG) model as represented in equation (2) [23]

$$w(\psi) = w_s \left[1 - \frac{ln\left(1 + \frac{\psi}{h_r}\right)}{ln\left(1 + \frac{10^6}{h_r}\right)}\right] \langle \left\{ ln\left[exp(1) + \left(\frac{\psi}{a_f}\right)^{n_f}\right]\right\}^{m_f} \rangle^{-1} \quad (1)$$

Where w_s is the saturated water content; ψ is the suction in kPa; a_f, n_f and m_f are fitting parameters and h_r is the residual suction.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha\psi|^n)^m} \quad (2)$$

$$m = 1 - \frac{1}{n} \quad (3)$$

θ_r and θ_s denotes the residual and saturated volumetric water content; α and n are independent fitting parameters.

The sample used for shrinkage measurement was prepared at an initial moisture content greater than that of the liquid limit. The sample was allowed to mellow for 24 hour sealed in a plastic press bag for moisture equilibrium. The sample was then transferred to an aluminum circular mold of size 42mm diameter and 12mm height. The sample container was coated with silicone gel to allow free shrinkage. The sample was placed over a weighing balance and set to allow for air-drying. The detailed experimental set-up is as shown in Fig.1. The measured void ratio and water content was fitted with the parameter fitting model proposed by [7]. Equation (4) was used to fit the experimental data and the fitting parameters were determined using the solver tool in Microsoft excel. The captured images were processed and analyzed to compute the radial shrinkage for every 2 hours from the starting of the test. The experimental set-up utilized a 12MP (Megapixel) hand camera held at a fixed distance to capture the surface area of the sample placed over a weighing balance during the entire process.

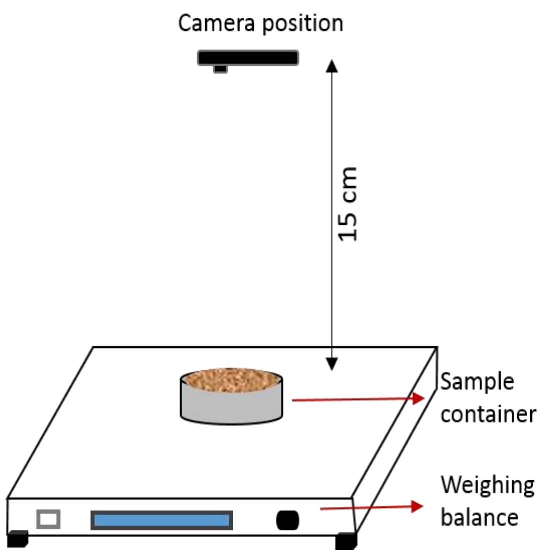

Fig. 1. Experimental set-up for radial shrinkage measurement

$$e(w) = e_r + \frac{e_s - e_r}{\left[1 + \left(\alpha(w)\right)^{-p}\right]^q} \quad (4)$$

e_s and e_r are the void ratio corresponding to saturated and residual water content; α, p and q are the fitting parameters to be determined using the measured experimental data. The temperature variation during the drying period is shown in Fig. 2 and when the weight change was negligible, the sample was placed in the oven maintained at 60 °C for 24 hours. The final weight measurement and dimensional change was recorded after oven drying the sample.

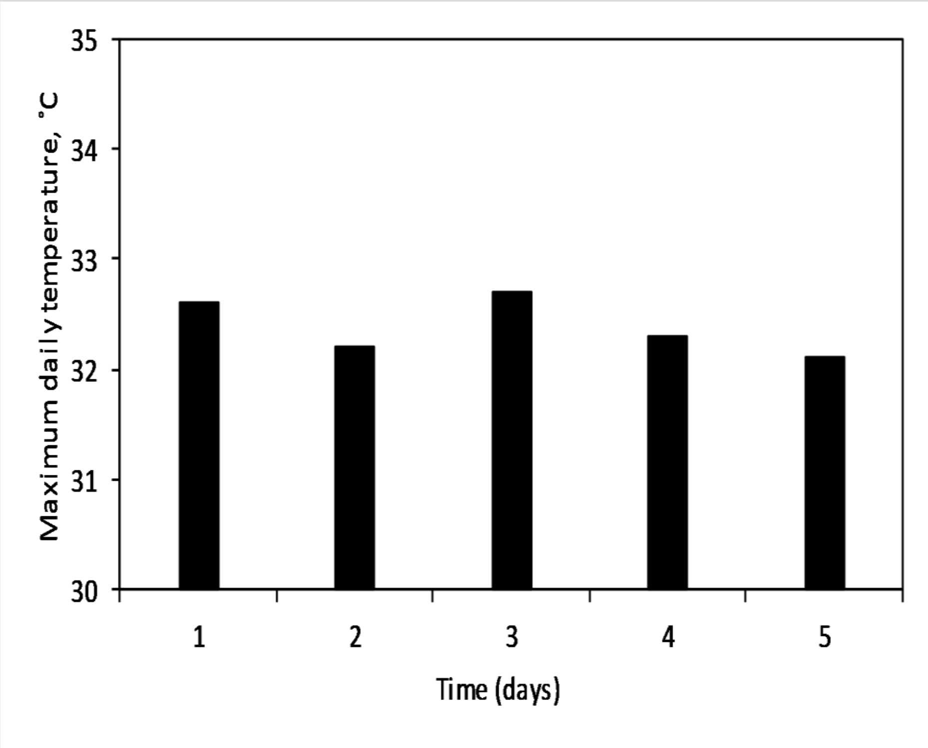

Fig. 2. Maximum daily variation of temperature

3 Results and Discussions

3.1 Soil water characteristic curve

The soil water retention behavior of the statically compacted soil specimen along the drying phase was fitted using the Van Genuchten model [23] to predict the suction potential up to 1000 MPa (Mega Pascal). The fitting parameters were determined using the SWRCfit software developed by [24] and the unimodal soil water retention behavior was compared with Fredlund and Xing (FX) model [22]. There was negligible difference in the prediction capability of both the models and based on the prediction model adopted for shrinkage characterization, Van Genuchten (VG) model was chosen as the appropriate prediction model for the experimental result (Fig. 3)

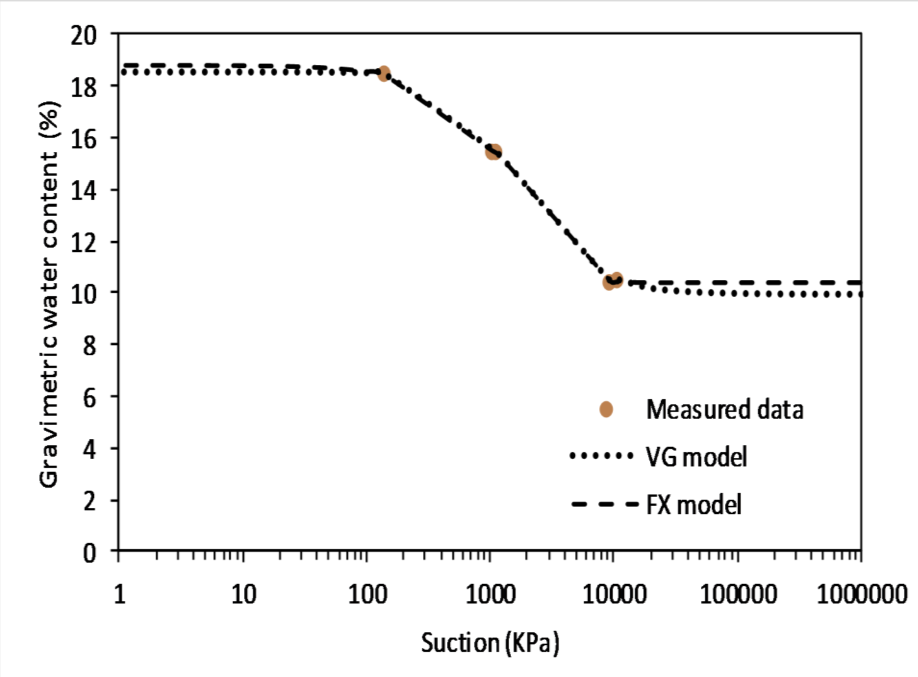

Fig. 3. Comparison of soil water retention behavior of silty clay during drying

3.2 Soil shrinkage curve

The shrinkage curve was plotted for the soil prepared at an initial moisture content of 1.5 times the liquid limit. The volume change of sample subjected to air-drying was determined by measuring the dimensions at regular intervals of time until there was negligible change in the weight and the dimension. The weight change was used for the computation of moisture content and the dimensional change was determined by two approaches. The change in height of sample in saturated state was computed using small pointed pins (Fig.4) and with further drying, the sample height and diameter was measured using thickness gauge and Vernier caliper respectively. The sample height was averaged for computing the volume change during the entire process of desaturation. There was a simultaneous capture of digital still images of samples and the diametrical change was computed using the image analysis with a simple and user –friendly open source 'ImageJ' software.

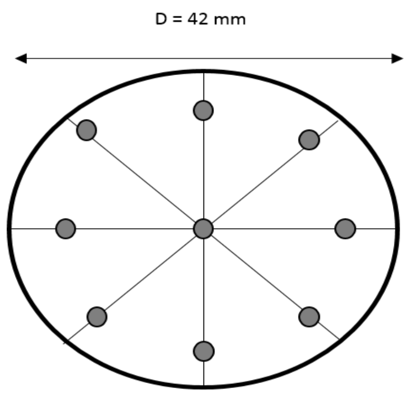

Fig. 4. Points for thickness measurement in saturated sample

The image processing of the sample was carried out in four steps as shown in Fig. 5

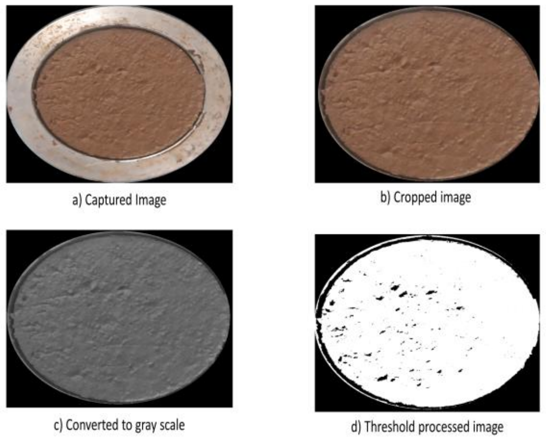

Fig. 5. Process of image analysis for volume measurement

The image captured was converted into an *8-bit gray scale* image and then the *set scale* option was provided with the original dimension of the sample container. This value is the initial size of the sample[19,21]. The image was further cropped and analyzed to *threshold* the gray scale image. This threshold value will help in demarcating the difference between sample and its background. The threshold process will convert the 8-bit image into a binary image such that the black background and white foreground is visualized. The binary image is then measured using the *measure* option in *analyze tool* to determine its area at various fixed points and this value is used for volume computation. The volume measured with this image processing is compared with the manual measurement value and the results show a variation of about 3%. This variation seems to be very less and this is mainly due to the small size of the sample and the extreme care followed to avoid loss of sample. The testing of large sized samples will result in high variation due to the chances of occurrence of cracks accompanied with subsidence. The results are obvious that the proposed 2D image processing technique is reliable and provides more accurate result determination compared to the direct measurement practice, especially when the soil is tested in a completely saturated or slurry state. The radial deformation measured with Vernier caliper was higher than that measured from image analysis and this expected to be the result of loss in sample when handling it for measuring manually. Fig. 6 shows the shrinkage curve of the silty clay indicating the presence of structural, proportional and residual shrinkage zone

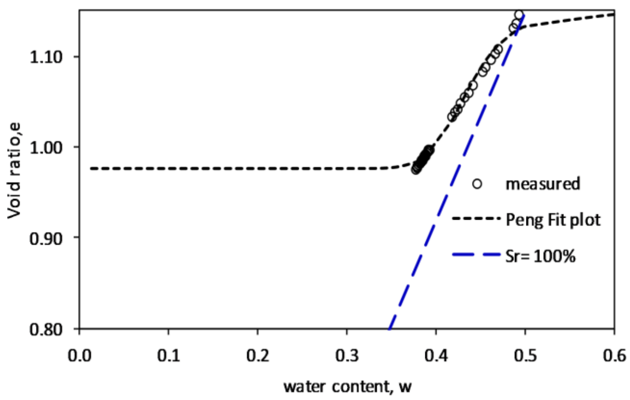

Fig. 6. Soil shrinkage curve for fully saturated silty clay soil

The shrinkage curve model proposed by [7] fits the experimental data well and the entire curve seems to be an inverse of the soil water characteristic curve. The desaturation of water from the intra aggregate pores is quantified from the structural shrinkage phase, proportional shrinkage is dominant and followed by the evaporation of water from the inter aggregate pores and this represents the entry of air into the soil pore system [25]. The shrinkage in each zone is quantified to be 19.4%, 72.9% and 7.7% respectively using the relationship proposed by [7]. Fig .7 shows the comparison of measured and the predicted void ratio obtained from image analysis results. The line of equity for data points are in high correlation.

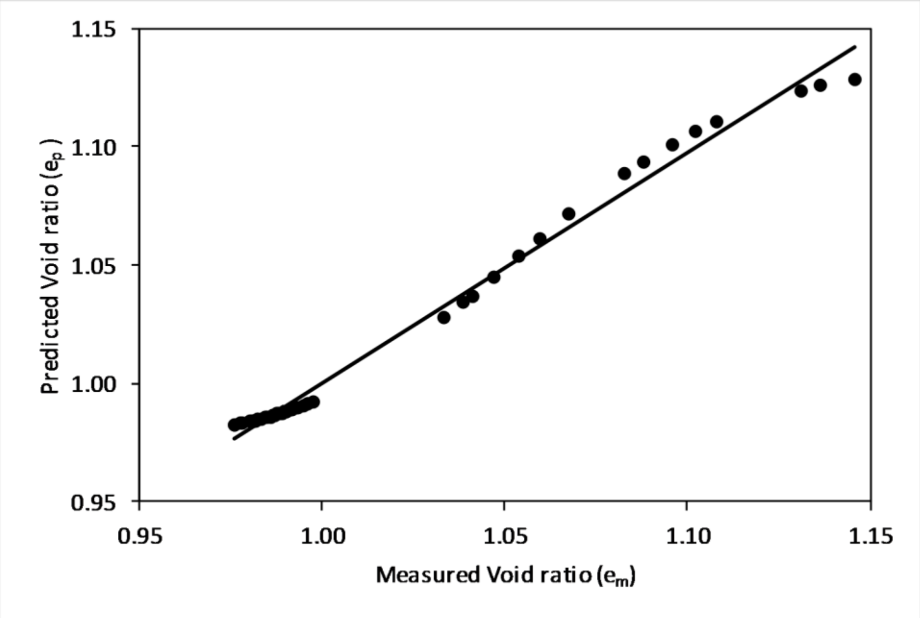

Fig. 7. Comparison of measured and predicted void ratio

4 Conclusions

This paper proposes an efficient, inexpensive non-contact image analysis procedure for quantifying soil shrinkage. This procedure can be used to characterize the shrinkage behavior of plastic soils subjected to moisture flux by evaporative dehydration. The simple comparative results show that the image analysis process to compute the dimensional change during shrinkage is advantageous over the conventional practice which usually results in loss of sample crumbs due to manual handling. The single mathematical model proposed by [7] proves to fit the data computed by image analysis with a high goodness-of-fit depicting the water loss from both intra and inter aggregate pores of the soil. The characteristic of shrinkage exists in three zones such as structural, proportional and residual. The dominant shrinkage exists for about 79% in the proportional zone indicating that the volume of water lost is equal to the volume of voids. The independent measurement of horizontal and vertical shrinkage is useful in quantifying the anisotropy of contraction due to desiccation. This proposed method can be used for laboratory determination of shrinkage behavior of wide variety of soils which may or may not exhibit the four phases of shrinkage. The shrinkage characterization and the mechanism will help in explicit understanding of hydro-mechanical behavior of low plasticity soils.

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