

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**DETERMINATION OF VOLUMETRIC
PROPERTIES OF COMPACTED SOIL
SPECIMENS USING IMAGE BASED 3D
RECONSTRUCTION TECHNIQUE**

by

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August, 2019

İZMİR

DETERMINATION OF VOLUMETRIC PROPERTIES OF COMPACTED SOIL SPECIMENS USING IMAGE BASED 3D RECONSTRUCTION TECHNIQUE

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**by
Araz GHAREHAGHAJLOU**

August, 2019

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**DETERMINATION OF VOLUMETRIC PROPERTIES OF COMPACTED SOIL SPECIMENS USING IMAGE BASED 3D RECONSTRUCTION**” completed by **ARAZ GHAREHAGHAJLOU** under supervision of **ASSOC. PROF. DR. OKAN ÖNAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.



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Araz GHAREHAGHAJLOU

DETERMINATION OF VOLUMETRIC PROPERTIES OF COMPACTED SOIL SPECIMENS USING IMAGE BASED 3D RECONSTRUCTION TECHNIQUE

ABSTRACT

The main purpose of this study is to introduce a noncontact and nondestructive methodology to determine the volumetric properties of soil specimens using multi-image 3D reconstruction technique. The 3D solid model of compacted soil specimens was generated with captured 2D images taken from different perspectives using a computational technique called Structure from Motion (SfM). This technique uses multiple overlapping photos of the same object from different perspectives to generate 3D reconstruction. A cylindrical shaped calibration object was produced by a high precision mechanical lathe tool for the validation of the proposed technique. The SfM method and the Archimedes test setup were verified for regular shaped solid calibration object by obtaining 0.02% and -0.047% relative errors in volume with respect to production dimensions. After validating the digital nondestructive methodology, the shrinkage behavior of four types of soil, having low to high expansive characteristics were investigated by both 3D reconstruction technique and conventional Vernier caliper measurement method.

Moreover, the proposed technique has been adopted to determine the volume and the bulk density of irregular shaped bulk soil specimens. Irregular shaped soil specimens were obtained by crushing the compacted soil specimens, which compaction energy and molding water content arranged as to have various matrix suction values. The results are compared with wax coating method and verified by Archimedes principle. Considering time consumed in conventional wax coating method and inherent health risks, the implemented method in this study offered a nondestructive way to obtain accurate volumetric properties for irregular shaped soil specimens.

Keywords: Bulk density, compacted soil, shrinkage, close-range photography

SIKIŞTIRILMIŞ ZEMİN ÖRNEKLERİNİN HACİMSEL ÖZELLİKLERİNİN GÖRÜNTÜ TEMELLİ ÜÇ BOYUTLU YENİDEN YAPILANDIRMA TEKNİĞİ İLE BELİRLENMESİ

ÖZ

Gerçekleştirilen tez çalışması, zemin örneklerinin hacimsel özelliklerinin belirlenmesinde çoklu resim üç boyutlu yeniden yapılandırma tekniği kullanarak temassız ve tahribatsız bir yöntem geliştirmeyi amaçlamaktadır. Sıkıştırılmış zemin örneklerinin üç boyutlu modelleri, Hareket Tabanlı Yapısal Algılama yöntemi kullanılarak farklı açılardan alınan 2 boyutlu görüntülerle oluşturulmuştur. Bu teknik aynı nesnenin farklı perspektiflerden alınan görüntülerini üst üste bindirerek nesnenin üç boyutlu modelinin oluşturulmasını sağlayan sayısal bir yöntemdir. Önerilen tekniği doğrulamak amacıyla, yüksek hassasiyetli torna tezgâhı ile silindirik bir kalibrasyon nesnesi üretilmiştir. SfM yöntemi ve Arşimet test düzeneği, üretilen kalibrasyon nesnesi için, üretim boyutlarına kıyasla hacimce %0,02 ve %-0,047 nispi hatalar elde edilerek doğrulanmıştır. Sayısal yöntemin doğrulanmasından sonra yüksek ve düşük şişme potansiyelin sahip dört farklı zeminin büzülme davranışı geleneksel Vernier kaliper ile ölçme ve üç boyutlu yeniden yapılandırma yöntemi ile incelenmiştir.

Bunun yanı sıra düzensiz şekilli zemin örneklerinin hacmini ve doğal birim hacim ağırlığını belirlemek için de SfM tekniği uygulanmıştır. Sonuçlar parafin metoduyla kıyaslanmış ve Arşimet prensibi kullanılarak doğrulanmıştır. Doğal birim hacim ağırlığı tayini yapılan zemin örnekleri, sıkıştırılmış numunelerinin kırılması suretiyle elde edilmiştir. Örneklerin sıkıştırma enerjileri ve su içerikleri yüksek emme potansiyele sahip olacak şekilde düzenlenmiştir. Geleneksel yönteme kıyasla tez çalışmasında kullanılan yöntemin laboratuvar örneklerin hacimsel özelliklerinin yüksek doğrulukla belirlenmesinde tahribatsız ve insan sağlığına zararlı olmayan bir yöntem olarak kullanılabileceğini ortaya koyulmuştur.

Anahtar Kelimeler: Birim hacim ağırlık, sıkıştırılmış zemin örnekleri, büzülme, yakın mesafe fotogrametrisi

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CHAPTER ONE

INTRODUCTION

The quantification of volumetric properties of laboratory specimens is a demanding process which usually relies on indirect and destructive techniques. For the soil mechanics laboratories, it is essential to quantify the volume of a soil sample for the determination of the bulk density, void ratio, porosity, degree of saturation and shrinkage limit. The quantification of the volume of a soil specimen is crucial since the weight-related parameters such as dry, bulk and saturated densities are determined by considering the total volume of a soil sample. On the other hand, the determination of the shrinkage limit of a soil is only possible by measuring the volume of a molded dry soil specimen.

The conventional methodology to determine the volume of a bulk soil specimen is to use the Archimedes principle. To use this method, the specimen is coated with wax in order to isolate the inter-granular voids and weighed in the water. The function of wax is to prevent the water to penetrate into the soil. In this way, the soil structure is preserved. However, this method is destructive since the wax coated specimens cannot be used for further undisturbed laboratory tests. On the other hand, previous studies showed that the coated specimens may include gaps in the coat layer, which resulted in swelling due to an increase in the water content (Stewart et al., 2012).

For the determination of the shrinkage limit of soil, the volume of a molded and dried soil specimen has to be determined. This test method uses mercury as a displacement liquid, and mercury is a hazardous substance in use and disposal. In this manner, a nondestructive and accurate methodology to determine the volume of a soil specimen is needed.

Determination of soil shrinkage behavior is essential to predict the hydraulic properties in expansive soils during wetting-drying cycles (Tang et al., 2011). Expansive soils have potential for significant volume change. Expansive soils tend to heave during hydration and shrink during dehydration in result of change in water

contents. These movements cause structural damages especially to low-story buildings, which usually don't have enough contact pressure to overcome the swell pressure. Annually damage cost, originated from shrink and swell behavior, range from \$10 to more than \$13 billion in United States. Whenever water is lost through desiccation, shrinkage cracks appear where the capillarity pressure surpass the tensile strength of the soil. For the evaluation of the expansive characteristics of the soil, the volume change of the soil specimens during drying has to be determined. For that purpose, Vernier caliper measurements are used to calculate the volumes of regular shaped laboratory soil samples. However, development of cracks leads to a complicated and irregular geometrical shape. The deformed shape makes the caliper readings unpractical and erroneous. Therefore, a better methodology for determining the volume change of compacted soil specimens should be adopted for the quantification of the volumetric properties.

Soil shrinkage mechanism may be divided in three stages. In the first shrinkage stage, which is called the initial stage, reducing in water content cause slight volume changes and specimen loses surface water. As the second shrinkage stage, the volume reduces rapidly during water loss and this stage is named as primary stage. In the residual and final stage, small volume changes occur as the water content decrease. In the literature, this shrinkage stages were presented by the researchers as a diagram by plotting void ratio versus water content (Yong & Warkentin, 1975). This curve is known as soil shrinkage characteristic curves (SSCC) and the plotting of this diagram requires sequence volume determination of compacted soil specimens during shrinkage. To evaluate soil specimen volume, two conventional methods may be used. These methods are mercury and wax methods and are based on the replacement of the liquid in which the soil is submerged. These techniques are labor-intensive, and wax method involves health risk. Displacement methods are widely used to obtain shrinkage limit and shrinkage ratio of the soil. However, these approaches are indirect methods and may include errors due to the techniques used.

On the other hand, computer vision algorithms emerge in a wide variety of applications in recent decades (Gonzalez & Woods, 2002). Several technical

programming languages provided image processing toolbox libraries for researchers and commercial grade software developers. However, one of the early attempts for the utilization of the image processing techniques on laboratory soil specimens for volumetric calculations has been adopted by Puppala et al. (2004). This study showed that image processing methods could determine the volumetric shrinkage strain values of expansive soils. The comparison between volumetric shrinkage strain values obtained by Vernier caliper measurements and image-based calculations happened to be in the range of 0.3% to 4.5%. Three years later, Ören et al. in 2007 proved that the volumetric shrinkage strains of compacted bentonite and sand mixtures might be determined even at minimal strain levels (i.e. <5%) using digital image processing techniques. This study had to be adopted a rather complicated calculation methodology, in order to prove the success of the image processing techniques on the quantification of the volumetric shrinkage of the compacted soils even in the small strain levels. The average error between manual and digital measurements for 16 specimens have been found as 0.27%. However, both studies were dealing with laboratory compacted soil specimens, having a rather regular cylindrical shape. Therefore, their methodologies are using geometric volume calculation formulae, which are totally incapable of highly irregular shaped soil specimens. On the other hand, the calculated volumetric strains have been compared with the manual measurements, performed by Vernier caliper, which are mostly operator dependent and yields erroneous volumetric results with increased irregularity of the laboratory specimen. In this respect, Gapak et al. (2017) have made a critical appraisal about the laboratory determination of the volumetric shrinkage. They compared four conventional technique for the volumetric shrinkage of montmorillonite-rich clays and concluded that the results are containing notable errors due to the measurement techniques.

Apart from the mentioned studies, recent developments in the image matching algorithms have made it possible to three dimensionally model a soil specimen using two dimensional images with a technique called as Structure from Motion (SfM). SfM is a technique, which uses images from multiple viewpoints of an object in order to constitute the three-dimensional geometry. This photogrammetric technique can use

close-range or aerial images taken from non-metric low-cost cameras. In this respect, first attempt for the determination of the bulk density and soil shrinkage curve with SfM technique was made by Steward et al. in 2012. In this study, a standard off the shelf camera and non-commercial software are used to measure the bulk density and soil shrinkage curve of the soil clods and founded that the method has acceptable precision. A similar study was performed by Moret-Fernández et al. in 2016. The SfM technique has been adopted to determine the volume and the bulk density of small soil aggregates. However, both studies are using a rotating imaging stand, and the soil specimens were fixed on to this surface by some adhesives. Therefore, although the methods used for the volume calculations are comprehensive, the contact surface of the soil specimen cannot be considered into account and assumed as flat. This yields erroneous results depending on the area of the contact surface and the size and shape of the soil clod. Such a problem was the main concern of the 3D models created by the SfM technique because the object needs to be statically laying on a plane during the photo acquisition period. One solution for this was the creation of two separate 3D models of the same object by replacing the object at the latter model and then merging them together. This technique allows all the points to be modelled for a particular object. Nowadays, the state of the art SfM software allows complicated point to point comparison and registration algorithms for merging cloud points. This method was found to be used in the literature by a researcher from a rather different discipline. Porter et al., (2016) have created 3D models of lithic examples from the early upper Paleolithic sequence. Since two separate models have been completed the whole object, successful digital recreation of artifacts, using all possible perspectives, could be obtained. However, the main concern in this study was the visual quality of the digital creation and the accuracy was out of the scope of this work.

A comprehensive approach was also made by Li and Zhang in 2019. Researchers used close-range photogrammetry technique to obtain soil shrinkage curve by monitoring volumetric strains of drying soils. Soil specimens were prepared in oedometer test cells, thus perfectly shaped cylindrical soil specimens were the subject of this study. To this end, the bottom surfaces of the specimens were assumed as flat and non-uniform shrinkage of this surface was neglected in this study. Specimens were

put on a turntable and overlapping images were captured. Although employing the same technique used in Steward et al. and Moret-Fernandez et al., they adopted six solid calibration cylinders into their study to evaluate the accuracy of the shrinkage monitoring setup. They also located turntable and specimens on an electrical balance in order to simultaneously monitor the water content of the specimens. However, proposed methodology in current form is not able to measure the volume of an irregular soil specimen.

In this respect, volumetric quantification of highly irregular laboratory soil samples and compacted soil specimens were performed using SfM technique by focusing to maintain highest possible accuracy. For this purpose, a precise cylindrical calibration object was manufactured on mechanical lathe tool. The performance of the methodology was verified by comparing the volumes of the calibration object by measurements with Vernier caliper and Archimedes principle. For the imaging, a rotating base stand was used, in order to take the photos of the soil specimens from varying perspectives. To avoid uncertainty and probable errors in 3D modeling processes, the rotating base was positioned into a photo tent, which provided a black background for the images and diffused the emitting light from the light sources. The proposed reconstruction technique is applied for bulk density determination of bulk soil specimens and shrinkage monitoring of compacted regular shaped soil specimens. For bulk soil specimens, two different oriented cloud points of the same sample have been created and merged using on-specimen markers to constitute the whole bulk soil specimen. After the creation of the detailed sample, the calibration has been performed based on the scaled base stamp, located under the bulk soil specimen. Bulk densities of six irregular shaped soil samples from three soil classes were determined by using Archimedes and SfM methods in order to compare and verify the proposed technique.

As the second implementation attempt of the proposed image processing technique, the shrinkages of the compacted laboratory soil specimens were monitored. For that purpose, three natural soils and one artificially mixed soil (bentonite and sand) were studied. The soils were so selected as to observe low to high expansive characteristic. Compaction tests in Standard Proctor (SP) energy level was conducted to determine

the compaction characteristics of the soil classes. According to these tests, maximum dry density and optimum water content values are determined for each soil class. Soils are compacted at the water content, which is 10% higher than optimum water content and allowed to dry until no volume change was observed. For each volumetric modeling stage, 54 images were captured, and images were imported in Agisoft Metashape software. For the shrinkage monitoring, the proposed image processing procedure was applied to compacted soil specimen images; however, only one point cloud is constructed and the volume quantification was performed by this reconstruction. In this manner, the bottom surfaces of the compacted specimens are assumed as flat.

Simultaneously, the volumes of the compacted specimens were determined directly by Vernier caliper. The water contents of the specimens were also monitored by digital balance during drying. Soil shrinkage characteristic curves were plotted for volumes by using the data acquired by caliper readings and SfM method. Obtained results for both methods were compared with each other.

In chapter two, a brief introduction about photogrammetry has been explained. In this chapter, the workflow of the structure from motion photogrammetry technique has been introduced. In the third chapter, the camera setup, the process of the photogrammetry modeling of the soil samples and the index properties of soils used in this study were presented. The fourth chapter is about obtained results and their discussion. Fifth and the final chapter is the conclusion chapter.

1.1 The Objective of this Thesis

The SfM technique makes it possible to construct a 3D visual model by capturing a sequence of multi-view images from an object. This technique implements a non-contacted measurement to evaluate the geometric characters of an object. In this digital 3D modeling technique, object surface is generated with full features and therefore all surficial details can be accounted for the volumetric quantification of the object, being imaged.

In soil mechanics science, there are several manual methods to measure the volume of the soil specimens, but the applicability of these methods is difficult and, in most cases, conditional results are possible. The accuracy of the evaluation of each method depends on the type of materials that have been used and also the proficiency of the operator.

Under desiccation, compacted soil loses volume by the reduction of water from the soil pores. The common method to determine the volume decrease during drying is using Vernier Caliper. During shrinkage, soil specimens may subject to non-homogenous deformations and cracks may appear on the structure. Therefore, calculating the soil specimen volume with manual measurement techniques usually end up with erroneous results.

On the other hand, the bulk density determination for laboratory soil specimens requires reliable determination of the volume of the specimens. Paraffin coating method is used for this purpose in geotechnical laboratories. However, this method has also several drawbacks and a new nondestructive methodology is needed for this test.

To accomplish these demands, a 3D volumetric quantification methodology for the laboratory soil specimens based on the principles of the SfM method have been proposed for the determination of volumetric properties of compacted soil specimens.

CHAPTER TWO

PHOTOGRAMMETRY

2.1 Structure from Motion

Photogrammetry is the art and science of obtaining precise mathematical measurements and three-dimensional data from two or more photographs (Matthews, 2008). Traditionally, photogrammetry is assumed in the context of aerial photography. However, these techniques can be applied to virtually any source of imagery. Structure from motion technique is a digital-based photogrammetry technique. The main architecture of the SfM is developed according to photogrammetry principles. SfM works by taking multiple photos of the same object from different angles and having the algorithms to detect overlapping patterns and build up a 3D reconstruction of that which has been photographed. In this technique, a 3D structure can be resolved from a series of overlapping images where an iterative procedure solves the geometry of the scene, camera positions and orientation without the need to specify a known network of target coordinates (Westoby et al., 2012). SfM technique requires to extract similar features in the overlapping images. As long as images are captured with stereoscopic overlap, the performance of the SfM technique will dramatically increase. To derive accurate 3D data at a specific range of scale, an object recognition algorithm called Scale Invariant Feature Transform (SIFT) was developed and implemented by Lowe in 1999 in SFMToolkit3. SIFT algorithm recognizes features in each image that is invariant to the image scaling and rotation and partially invariant to changes in illumination condition and 3D camera viewpoint (Lowe, 2004). Unlike the traditional photogrammetry technique, the exact coordinates of the camera locations are not needed in SfM, since the matching features in each image i.e. tie points are used to solve the geometry of the scene, camera location, and orientation simultaneously by an iterative procedure. So, the constructed structural points of any object in the scene will not reflect the real scale and coordinates unless calibration is made by using known coordinates of at least three points in the model or by using an object of known dimensions in the composition. After the calibration, this technique will allow you the ability to take an accurate measurement of the object which has been imaged.

On the other hand, the technique is not effective at reconstructing smooth, shiny perfect featureless surfaces that have little to no details. However, the compacted soil specimens generally have good natural visual patterns, and bulk specimens usually have rough surfaces with lots of indents and outdents, which make them a perfect candidate for SfM technique.

2.2 Acquisition of Digital Images

Converting an image to pixels is named as digitizing. There are numerous ways to digitize pictures. Digital cameras are a direct way to record images. By using a sensor, it is possible to convert the light to an electrical signal. Light beams radiate on the object from the light source. The reflected light rays, which inherit electromagnetic spectrum energy, pass through the camera lens and hit the imaging sensor. The sensor is sensitive for ray energy and digitizes the beam by changing the wave into digital quantity. The reflected light onto image plane represented by two-dimensional functions. Images are expressed by a scalar quantity function in the form of $f(x, y)$. This function is an equivalent value which implicates the source of the picture. By these continuously imaging workflows, radiated lights from the object are converted into a digital image. The digital image represented as a matrix and each element of this matrix called pixel. Pixel contains the light intensity value known as pixel intensity. The color pixel represented intensity value range is between 0-256. An image is compound with three primary colors, red and blue and green (referred as RGB). Each primary color consists of 256 level, in this manner, each black and white image uses three times less memory than a color version (Note, 2014).

2.3 Digital Cameras

Digital cameras have several features such as resolution, focal length, aperture, shuttle speed and ISO setting. In the following paragraphs brief introduction will be made for this features.

In photography camera resolution is explained by pixels. The resolution of a camera is related to how many pixels can be captured by the camera. High resolution images which contain more pixel includes more detail compare to low resolution versions.

Focal length range is the general description of a photographic lens and commonly described in millimeters (mm). It is the measurement of the distance between the point of the light ray reflected from object or scene and digital sensor or 35mm film at the focal plane in the camera. The focal length shows the magnifications and how large a picture can be captured, also it speaks for the angle of perspective giving information about how much of the scene can be captured. For the longer focal length, the angle of view will become narrower resulting a higher magnification level. In the shorter focal lengths, the magnification level reduces, and the angle of view will become wider.

The camera aperture allows the light pass to through the sensor. Aperture is measured by the f/stop scale. The number expresses how wider the aperture is. The diameter of the aperture affects the exposure and depth of field. In this scale the lower the number, the wider the aperture. The f/stop scale is as includes: f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22. In f/stop scale, the aperture decreases to half its size by changing each number to the next, thus allowing 50% less light through the lens in each one f/stop.

Shutter lets the sensor be exposed by the light at the time of camera firing. After collecting light and data, it closes immediately. The time between opening and closing the shutter for exposing light onto the sensor is called shutter speed. It has different effects on the images. The images are taken by fast speed be freeze, and there is not any motion effect, but in a slow shutter, moving objects indicate a sense of motions. Shutter speed represent by a fraction of seconds.

ISO setting describes how a sensor become sensitive for converging light ray. By rising ISO setting up the sensitivity of the sensor increases for light absorbing.

2.4 Photogrammetry History

Photogrammetry is the science of obtaining three dimensional points and producing maps. Without any physical contact, it can be possible to accomplish certain properties of the surfaces and objects in a non-contact sense. The photogrammetry name originated from the Greek word “photo” meaning light, and “gramma” meaning measure. In this technique, surfaces are identified by capturing images through absorbed electromagnetic radiant energy. In photogrammetry, by overlapping the acquired images, it could be possible to obtain surface points coordinate to generate maps for different applications. One of the current utilities of the photogrammetry is aerial triangulation. In this approach, 3D coordinate points are defined by processing overlapped photographs.

Photogrammetry stemmed from the invention of photography and the development of technology. Thanks to the invention of airplanes, the principle of photogrammetry has been employed to create large maps using aerial images. With the introduction of the computers, batch numerical calculations have been possible. After that achievement, photogrammetry technique developed in a level that generation of surface models have become possible through computer algorithms. In this manner, photogrammetry process was digitized by establishing algorithms that help to create massive maps for large projects. Development of photogrammetry was divided into four phases. With the development of stereophotogrammetry by Pulfrich in 1901 and stereoplotter by Orel 1909, practical steps were taken in the development of photogrammetry. Stereoplotter had made it possible to plot contours and features by overlapping at least two photographs. This performance had been used during World War II. These achievements still create the foundation of photogrammetry. The evolution of computers had a revolutionary effect on the advancement of the photogrammetry technique. Schmid was one of the pioneer photogrammetrists who created analytical photogrammetry by using matrix algebra, and that was the first attempt to digitize the photogrammetry process. Eventually, as the third phase, wide spreading electronic technologies and easy access to electronic devices made it possible for photogrammetry instruments to be accessible. Also, the advances in

storage device technology has made it possible to accelerate access to digital images in the last few years.

In photogrammetry method, the purpose of the technique is to obtain three-dimensional coordinates of an object. For an object which has two or more images captured from different perspectives, 3D coordinates of any point on it can be calculated. This photogrammetric 3D reconstruction technique contains sequential workflow process, which will be briefly mentioned in the following paragraphs.

2.4.1 Feature Extraction

Features can be described in three types; low level features, mid-level features, and high-level features (Förstner, 1993). Low-level features can be described as pixel arrays in the images. Mid-level features are introduced as surface geometry like points, edge, regions, and corners. High-level features are explained as complex structures. The fundamental goal of the feature extraction is searching for the same object points in two captured images to correlate the relationship between these features. In the feature extraction, interest points are extracted from images which are taken from different perspectives of a same object. Based on these points, the correspondences between two images are defined to use for 3D reconstruction. It is important that to find the distinct points which can be precisely localized. The more accurately those locations be known, the better the 3D reconstruction will be generated. Developed feature extraction algorithms are usually interested to detect mid-level features like point edge, regions or corners. The SIFT algorithm that proposed by Lowe et al. (2004) surveys single highly distinctive feature that has highly correct match possibility. High probability matching is accomplished by filtering the images by using differences of Gaussians functions to identify distinct feature locations.

2.4.2 Image Matching

Image matching is function of comparing features of the two or more images. In this approach, every image pair are overlapped to search and find the most similar

features. To recognize the same feature in an object, features extracted with SIFT stored as a database. Each database of the new image compared with the previous image database. Matching features contribute to creating a fundamental matrix. The fundamental matrix is crucial for 3D reconstruction algorithms conception. Any incorrect match which called outliers creates an unreliable estimation of the fundamental matrix. Fischler and Bolles in 1981 proposed Random Sampling Consensus (RANSAC) algorithm to estimate the exact matches.

2.4.3 Camera Calibration

During 3D surface reconstruction intrinsic and extrinsic parameters of the camera are essential to reconstruct the object points. The evaluation process to calculate the intrinsic and extrinsic parameters are called as camera calibration. These parameters are objective to resolve the relationship between image coordinates and world coordinates (Yi et al., 2014). Intrinsic parameters include the focal length and camera internal calibration. Extrinsic parameters are described as the location and orientation of the camera with respect to the real coordinates. Camera calibration is determining the relationship between image and world coordinates, according to the 2D matching feature (Yi et al., 2014). During the matching feature in corresponded images, simultaneously camera parameters can be predicted. It is known as self-calibration, but to accurate evaluation, an alternative procedure would be conducted.

Calibration procedure contains extraction of parameters from obtaining 3D corresponding coordinates and 2D corresponding coordinates. Usually, in calibration processes, a general procedure is to use a spatial calibration pattern. This pattern also known as a checkerboard includes a chessboard-like visual design and parallel lines filled with black and white squares. In calibration, images of a calibration pattern taken from several perspectives are used. The images of the calibration pattern should be taken from multiple sides with different distance and angles. After measuring the 3D positions of the markers on purpose, markers are extracted and identified in the image. By founding 3D-2D correspondences, a linearized calibration model is generated. It can use a non-linear optimization to improve the camera calibration.

2.4.4 Triangulation

Triangulation is a process in photogrammetry which establishes geometrical relationships between corresponded images to obtain supplemental 3D coordinates by using obtained relative position and orientation parameters. Image coordinate of an object point that appears in 2 or more images called as a tie point. The three-dimensional coordinates (X , Y , Z) of tie points in paired images are unidentified. During triangulation procedure, a sequence of mathematical relationships on camera parameters and photograph coordinates are performed to determine 3D position of a tie point. A tie point with 2D coordinates was represented in two images (p) in Figure 2.1. From two image frame, parallel line with a known distance of camera constant (c) is considered. Optical axes intersect the 3D tie point position from two 2D tie points that are representing the actual point in the images. The coordinates of the tie point $P(X, Y, Z)$ are calculated by the triangulation procedure based on the geometry process.

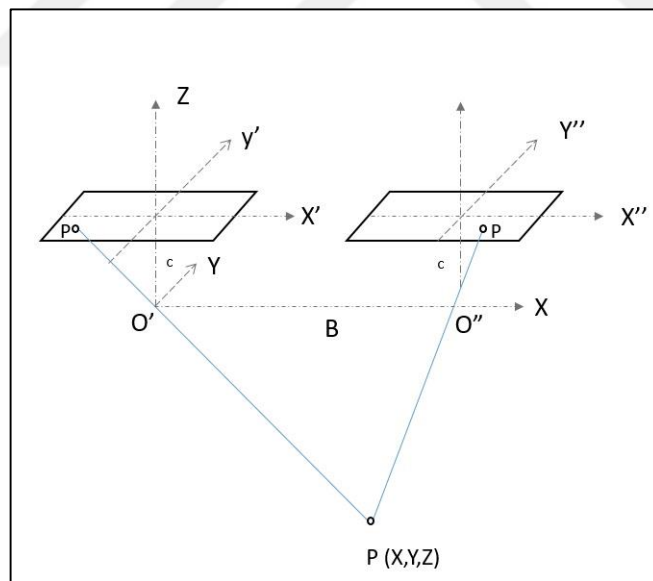


Figure 2.1 Presentation of geometrical scheme of triangulation process

The tie point coordinate can be determined by using a matrix form that was generated from the intersection of two optical axes. This can be written as:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} -\frac{B}{\rho_x} & 0 & 0 \\ 0 & -\frac{B}{\rho_x} & 0 \\ 0 & 0 & -\frac{B}{\rho_x} \end{bmatrix} \begin{bmatrix} x' \\ y' \\ c \end{bmatrix} \quad (2.1)$$

The corresponding point in the both cameras (p) are offset in the same X direction. These points have the same Y coordinates. The camera constant (c) also is same for both corresponding points. According to the matrix 2.1, it is possible to calculate the real-world coordinates by the cameras given right orientations. In matrix equation ρ_x is described as the parallax of X coordinates.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Materials

3.1.1 Camera

Since the SfM technique do not require sophisticated metric camera systems, a standard low-cost point and shoot style off the shelf camera was used for the image acquisition steps of this study. Images were taken with Canon PowerShot S100 digital camera, having a 7.44x5.58 mm CMOS sensor and 4000x3000 pixel resolution. The shutter speed and aperture combination were arranged manually as 1/10 and f8, respectively, in order to widen the depth of field area. Since the objects in the depth of field area are in acceptable focus, this combination maintained a sharp image for the region of specimen and calibration basement.

On the other hand, the best possible combination required a relatively long shutter time, which expose the image sensitive to camera vibrations. Therefore, it was mandatory to use a tripod to acquire non-blur, sharp images. A magnification corresponding to 50mm was used to gain a proper distance from the specimen being imaged. Also, ISO speed was selected as lowest value as possible (i.e. 100) to prevent grainy noise in the images. Although a rigid tripod was employed for imaging, optical image stabilization and two seconds shutter delay was used to eliminate the vibrations caused by operator hand.

3.1.2 Image Acquisition Setup

The soil specimens were imaged on a turntable in order to catch different perspectives of the specimens easily by rotating the table. The rotation of the table and adjustment of the height of the camera tripod enabled all possible camera positions for a specimen. The image acquisition was performed in a white colored textile photo tent

in order to diffuse the light to get uniform illumination. Black colored textile was used in the tent for the background. Black background ensured homogeneous hollow space for the 3D models. For the setup, a special two strip LED rig was manufactured, where each strip has 750 LEDs in 5 rows. The rig was stationed around the tent in vertical axis, so a diffuse lighting was maintained which bring out the details of the specimen to be imaged.

A scaled basement was located in the center of the turntable, on which the specimens will be placed. The scale contains signs to define rotation degrees and four reference points in defined distance. This scale was formerly prepared by Porter et al. (2016), to model archeological artifacts. The imaging setup and an actual footage taken from this setup have been shown in Figure 3.1

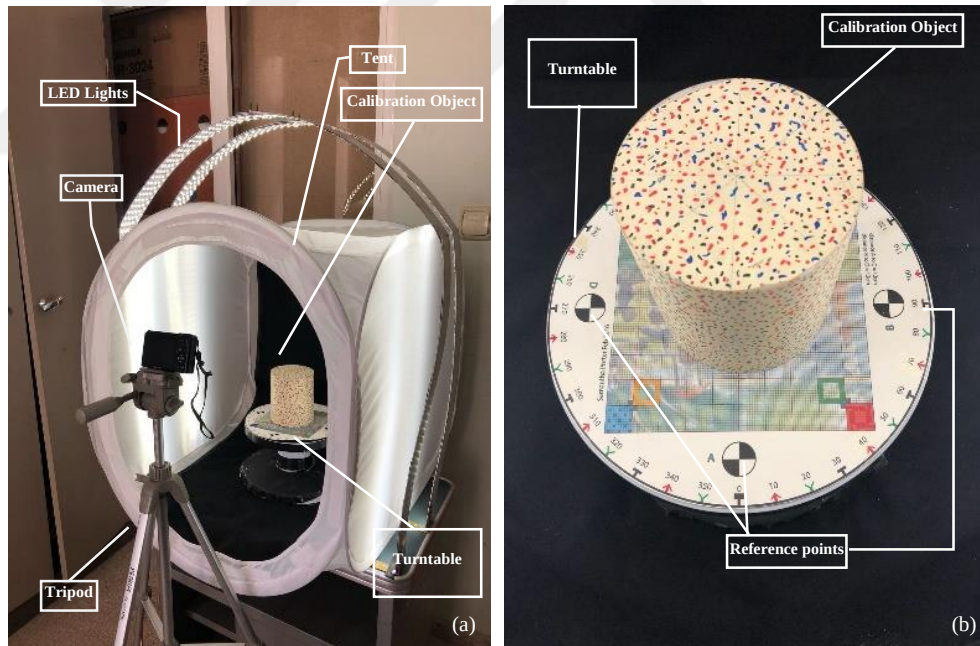


Figure 3.1 Image acquisition setup (a) and calibration object (b). (Personal archive, 2019)

3.1.3 Calibration object

A cylindrical calibration object was produced by a high precision mechanical lathe tool in order to calibrate and validate the procedures in this study. Calibration object

was made from plastic material and it was shaped in compaction mold dimensions of standard Proctor test mold size (ASTM D 698) by turning process with a precision of 1/10mm. The object covered with matte beige color to hide the reflective raw material. In next step, the object was painted in colored dot pattern to maximize the visual features to be detected by the image processing steps (Figure 3.1b).

3.1.4 Photogrammetric Software and Hardware

Since the popularity of the SfM technique emerged in recent years, several technical programming language libraries have provided tools for 3D model generation from 2D view images. OpenCV and MATLAB, image processing toolbox, has available SfM algorithms for 3D modeling which of both may be used for conducting research or commercial grade software development. On the other hand, web-based Photosynth software by Microsoft Live Labs was the pioneer standalone step to 3D model generation from 2d images. Another software solutions such as 123D Catch, Visual SfM, and Pix4D should also be mentioned for introducing the available SfM software. In this study, a commercial software called Metashape by Agisoft Company was used for the 3D construction of soil specimens to measure the volumetric quantities of the soil specimens. Aerial mapping, archaeology, forensic engineering and film industry are the other disciplines where Metashape software is mostly employed.

Since SfM algorithms have to process large number of high-resolution images with iterative procedures, the hardware requirements for this process is rather high by considering the computational time for modeling. Therefore, a computer having a 5 Ghz CPU with 64GB of ram cooperating with two high-end GPUs are used in order to shorten the computational process. It has been observed that the number of GPUs used for the process has a significant effect on the computation time.

3.1.5 Soil

3.1.5.1 Bulk Specimens

Six irregular shaped bulk specimens from three different soil classes have been used for this study. The soil classes have been selected as to have different visual appearances such as color and texture in order to verify the proposed methodology. Although the Soil 2 and Soil 3 have the same Unified Soil Classification System (USCS) group symbol as SC (i.e. clayey sand), Soil 2 have gravel fraction, which resulted in more rough surfaces than the Soil 2 in the bulk specimens. Each soil was compacted with standard and modified Proctor energies according to ASTM D-698 and ASTM D-1557, respectively, in order to verify the proposed technique for two different densities for each soil class. However, the modified Proctor specimens were compacted at the wet of optimum water contents, resulting in higher air-entry suction for these specimens (Tinjum et al. 1997). By this means, higher suction values were maintained for the modified Proctor specimens, in order to observe more distinctively the possible penetration of the paraffin and water in to the soil pores in the Archimedes method.

The bulk specimens have been obtained by crushing the compacted soils immediately after compaction. The sizes of the specimens were selected as to vary approximately between 50 to 150 cm³. Thus, two specimens, having standard and modified Proctor densities were obtained for each soil class. The samples were weighed and then photographed using the image acquisition procedure. Subsequently, specimens were covered with wax for Archimedes replacement method. The index properties and classifications of the soils based on USCS can be seen from Table 3.1.

Table 3.1 Properties of the soils

Soil #	Soil Name	+No.4 (%)	-No.200 (%)	Liquid Limit (%)	Plastic Limit (%)	USCS
1	CH-1	0.17	89.6	59	25	CH
2	SC-1	27.96	29.06	37	33	SC
3	SC-2	0	25.7	82	34	SC

3.1.5.2 Compacted Specimens

In this study four different soil samples were used to obtain the compacted soil specimens. In order to classify these soil samples, numerous laboratory tests were applied according to the Unified Soil Classification System (USCS). The sieve analysis, consistency limits and specific gravity tests were carried out. The geotechnical properties of the used samples were given in Table 3.2. Please note that the SC-1, CH-1 and CH-2 soils are the same soil used for bulk specimen study. In addition to that, an artificially prepared soil (SC-2) was prepared by mixing 30% bentonite clay with 70% sand by weight. Please note that the liquid limit of the SC-2 soil was determined by Casagrande method in order to reflect the behavior more realistically. For the other soil classes, fall cone method was applied.

Table 3.2 Geotechnical properties of the used samples

Soil	Specific weight (G_s)	Consistence Limits			Gradation (%)			Swell index	USCS
		LL	PL	PI	Sand	Gravel	Clay		
SC-1	2.61	37	16	21	43	28	29	1	SC
CH-1	2.80	59	25	34	10	1	89	4	CH
CH-2	2.72	93	33	60	13	4	83	6	CH
SC-2	2.73	82	34	48	68	0	32	13	SC

Compaction tests were performed in standard Proctor energy level to determine the soil specimen compaction characteristics. The operation was carried out in a mold which has a height of 11.68 cm, a diameter of 10.1 cm with 944 cm² volume, and a three-layer clay compacted in 593.7 kJ / m³ compaction energy produced by falling the 2.5 kg metal hammer from a height of 30.5 cm to each layer of clay sample. Hydraulic jack was used to remove the compacted sample from the mold. As a result

of these experiments, the dry unit weight and optimum water content of each clay sample were obtained. Table 3.3 shows the dry unit weight and optimum water content for different soil samples. Samples were compacted with water content of 10% more than optimum water contents and volumetric shrinkage was monitored.

Table 3.3 Compaction characteristics of soils

Soil	Dry Unit Weight (KN/m ³)	Optimum Water Contents (%)
SC-1	19.4	15
CH-1	15.1	22
CH-1	18.3	26
SC-1	15.7	20

3.1.6 Type II DI Water

Type II DI water was provided from the Environmental Engineering Laboratory of Dokuz Eylül University (Figure 3.2). This water was used in the determination of the bulk volume of the specimen using Archimedes principle. The density of the DI water was measured by hydrometer and determined practically as unity at room temperature.



Figure 3.2 Type II DI water supply (Sariavci, 2019)

3.1.7 Paraffin Pot and Wax

Solid paraffin wax was used to coat the specimen for eliminating the chance of water penetration into the voids of the specimen. The white color wax melts between 50-57 degree Celsius and the purity grade is 99% according to the producer company instructions. An electric powered metal pot device was used for melting the solid paraffin.

3.2 Methods

3.2.1 Soil Index Properties Tests

There are two prevalent classification systems, American Association of State Highway and Transportation (AASHTO) and Unified Soil Classification System (USCS). USCS system is a modified method based on Casagrande proposed system. This system modified by U.S. Bureau of Reclamation and Army Corps of Engineers in associate with Dr. A. Casagrande in 1952. American Society for Testing and Materials (ASTM) published technical standards for soil materials based on USCS classification system. Classification of soil is based on particular size characteristics and Atterberg limits.

Soils are characterized into groups and subgroups to predict their behavior. This classification requires to identify their specifications and describes their probable behavior. Classification solely based on the grain size of soil is not adequate for fine grained soils. These soils are affected by water content, so it is essential to conduct liquid and plastic limit tests for soils that contains fine grain. Soil index properties are described by grain size distribution analyses (i.e. sieve analysis and hydrometer test) and consistency limits.

3.2.2 Grain Size Distribution

Soil graded according to particle size fractions. Soil particle sizes are determined by sieve analysis (See Appendix _ A). In this procedure soil passes from different size sieves. These sieves are progressively set from large to small size. Soil masses, remaining in different size sieves are weighed by an electronic or mechanical balance. Soil fractions are separated as coarse (gravel and sand) and fine (silt and clay) according to mass remain in different specific sieve size ranges. If retained mass percentage is more than 50 percent on sieve No. 200 so the soil is defined as coarse grained soil. Soil is graded into gravel or sand by sieve No. 4. while retained coarse fraction greater than 50 percent and soil is defined as gravel. Contrary if 50 percent coarse soil is passed from No. 4, the soil is defined as sand. The grain-size curve is plotted by percent passing versus particle size values. This curve shows the distribution of soil particles due to grain-size. In USCS, coarse-grained soils are subgrouping by uniformity coefficient (C_u) and coefficient of curvature (C_c). These parameters can be used to describe some of the characteristics of soil to define if the soil is well-graded or poor-graded. These parameters are computed by calculating the ratio of passing fractions from particle diameter according to cumulative particle-size distribution curve. D_{10} , D_{30} , and D_{60} are the diameter of sieves which 10%, 30% and 60% of the soil sample would pass through, respectively. Uniformity coefficient is described by the ratio of fraction diameter size D_{60} to D_{10} . Coefficient of curvature is calculated by the ratio of square D_{30} to multiple of D_{60} and D_{10} . To classify the soil as well graded C_u and C_c should satisfy specific ranges. Between 1 and 3 is considered well graded for the coefficient of curvature, whereas C_u for gravels should be greater than 4 and 6 for sands.

Soil containing considerable fine fraction are graded by hydrometer analysis. This method is performed when gradation of coarse-grained soil is not satisfied or there is not coarse fraction at all in the soil. The hydrometer is used to classify the soil that is finer than No. 200 (75- μ m) sieve according to the ASTM D7928 standard. Essential apparatus in this test is a hydrometer, at least two glass cylindered with capacity of 1000 mL, and clock or stopwatch to measure the time. A mixer is being used to provide

suspension. Sedimentation (hydrometer) test results can be combined with sieve analysis results. The sample is prepared by passing dry soil from sieve No.40 (425- μm). Sodium Hex-metaphosphate (NaPO_3) is used for preventing soil suspension from coalescing to discriminate particles slurry mixing. Also distilled water is used for making slurry, the suspension is transferred into the 1000 ml cylinder and filled to 1000 ml with distilled water. With a hydrometer, readings are taken during specific times. It shall be taken approximately at 1, 2, 4, 15, 30, 60, 240, 1440 minutes. It is required that the hydrometer should be stand stable after placing into the sedimentation cylinder.

3.2.3 Consistency Limits

Consistency limits are one of the most prominent parameters that should be determined in geotechnical investigations. Water affects engineering behavior of fine-grained soil. Soil strength directly changes by water content variations. In a fine-grained suspension by decreasing moist gradually from soil pores, four states of the soil can exist, which are liquid, plastic, semi-solid, and solid states, respectively. The boundary of water content for these states are unique for each soil. Similar water content for two soil with different originals may possess different consistency (Murthy 2002). Atterberg limits describe each soil state. Atterberg a century ago introduced consistency limits which were inherited by geotechnical studies. It refers to limits of consistency, usually liquid limit, plastic limit, and the shrinkage limit. Classification of fine-grained soil by Atterberg limits is defined as how water influences soil behavior. Conversion state from the liquid state to plastic state is called liquid limit, (LL), w_L . Liquid limit is a minimum water content that is enough for soil to remain in the liquid state. At this state the soil is weak enough, that it can flow like a fluid. Conversion state from a plastic state to semi-solid state is called plastic limit, (PL), w_p . The plastic limit is minimum water content that soil needs to behave like plastic material. In plastic limit moisture content, the soil state changes from plastic state to semi-solid state. Plasticity index is calculated by using plastic limit and liquid limit experiment results, calculated by the difference of liquid limit and plastic limit of soil.

For distinguishing the consistency, several methods have been proposed. According to Sridharan, et al. (1986), consistency limits method, proposed by Atterberg had uncertainty and were not easily reproducible. Casagrande developed a standard method to evaluate plastic and liquid limit values. For the measurement of the liquid limit of the soils Casagrande cup test and penetrometer based method have been introduced. These proposed two methods are performed on soil passes the sieve No.40 (425- μm). ASTM standards also offered Casagrande falling cup method as liquid limit test method (ASTMD 4318–17). The test results for this thesis can be seen in (APPENDIX_B).

3.2.3.1 Casagrande Cup test

The first process is providing the soil that passes from a 425- μm (No. 40) sieve. The indicated apparatus in standard is a brass cup, raised and dropped from a distance of 10 mm by a snail-shaped cam. A portion of the specimen is placed on this cup, after that, it is divided into two sides by a crossing a groove. By grooving tool, soil sample is separated two pieces having 8 mm deep, on the top in 11 mm wide and at the bottom in 2 mm wide. Repeatedly dropping of cup causes a shock on the specimen, which provides the specimen to flow. The liquid limit is defined as a water content that the two sides of groove in cup getting close as a distance of 13 mm by 25 drops of the cup. To obtain proper water content, numerous experiments should be applied to soil specimen. The number of drops that close the gap within a length of 13 mm is recorded as (N). The procedure should be repeated with increasing water content and it requires that the amount of the drops be between 20 and 30. On a semi-logarithmic graph water content versus number of drops should be plotted. A straight line should be fitted through the three or more plotted points. The liquid limit is evaluated as water content corresponding to the intersection of the line with the 25 drops.

3.2.3.2 Falling Cone Test

This method originally introduced by Geotechnical Commission of Swedish State railways in 1922. In different countries some developments were applied to standardize the method based on the first principles. Generally, BS 1377 (2010) standard method is preferred. Experts mostly consider this method more reliable than Casagrande cup method. Unlike the percussion method that highly depends on the operator, cone fall method results are more precise, because of independency from operator and not be influenced by dexterity. Cone penetration apparatus includes a dial to measure the penetration depth, a cone having a 30° angle and weighing 80 g, a metal mold with a 55 mm diameter and 40 mm height, in which the soil is placed. Liquid limit is defined as the moisture content that 20 mm penetration is achieved by releasing cone at the period of 5 seconds. In order to seize on this specific water content, numerous tests are applied in different water contents ranging from 15 mm to 25 mm of penetration. By plotting penetration height in perpendicular axis versus water contents in horizontal axis, liquid limit is defined as intercept of the 20 mm. It should be paid attention that cone edge should exactly held on surface of the soil before releasing the cone. During placing the soil into the can, there should not be any bubble remained in the soil.

3.2.3.3 Plastic limits

This test is conducted on the soil samples which passes 425- μm (No.40) sieve. This test can be performed both with hand or a rolling device which is introduced by ASTM-D4318. After selecting a portion of specimen, soil mass is rolled by one of the following procedures. These procedures are hand rolling and using rolling devices, over a glass plate. In the laboratory, plastic limit determined as the moist content when the soil begins to crack while it turns in diameter of 1/8 inch (about 3.2 millimeters) during rolling. This test depends on the operator and the results can be different depending on who is performing the experiment. However, by repeating the test procedure numerously, similar results can be approached by experienced hands.

3.2.4 Compaction Test

Soil compaction is required to approach an appropriate shear strength, permeability, and compressibility in geotechnical engineering constructions. To define the convenient soil mechanics properties, laboratory compaction test shall be applied. This test provides optimum water content (ω_{opt}) and maximum dry unit weight (γ_{dmax}), the compaction properties which can be evaluated to assure equable soil compaction. In the laboratory, the soil is compacted by falling weights with hammer or loading machine. A range of compaction values may be required during laboratory tests including shear strength, consolidation, permeability and shrinkage. Parameters in compaction include four variables, which are dry effective unit weight, water content, compactive effort and soil types. Compactive effort indicates as energy imposed on a soil mass. Compactive effort can easily be calculated by weight of rammer, drop height, number of drops and soil layer number. There are two prevalent standard compaction laboratory tests; the standard Proctor test and the modified Proctor test. The differences between these two tests are the number of drops, rammer weight and soil layer number. These disparities are the reason for different energy efforts. The process of compaction of soil is obtained from two test methods, Proctor standard effort (ASTM- D698) and Proctor modified effort test (ASTM- D1557). In these processes, various specimens are prepared. These specimens contain different water contents. The number of the drops and layers and also mold size are assigned according to the contemplated standard. The mold is filled with the specimen to form first layer. Then by rammer or loading machine, the soil is compacted. During compaction, soil loses the void and particles are densified. After compacting necessary soil layer, the surface of the specimen is flattened out by spatula, so specimen shaped exactly as same as mold dimension. Soil specimen is extracted from mold by the help of the jacking pressure. The specimen is weighed to determine the unit weight. Then to define water content, portion of the specimen is taken into the oven (102°). Dry weight and water content values illustrates compaction curve, and from that curve the maximum dry unit weight (γ_{dmax}) and optimum moisture content(ω_{opt}) can be found defined (See APPENDIX_C).

$$\gamma_d = \gamma / (1 + \omega / 100) \quad (3.1)$$

γ_d = dry unit weight
 γ = unit weight of compacted specimen
 ω = molding water content

3.2.5 Specific Gravity

In the calculation of phase relationships, the specific gravity is used to determine relationships such as void ratio and saturation degree. Also, specific gravity multiples by density of water for evaluation of the density of the soil. The specific gravity of the soil solids is the ratio of the mass of a unit volume of a soil particle to the mass of the same volume of de-aired distilled water. ASTM D854 introduced a test procedure to evaluate the specific gravity of soil particles. One pycnometer is necessary to pour the soil slurry in it. Passed soil through a No.40 sieve, is weighed 50 grams and be used. Soil particle slurry is prepared by using a mixer. Soil slurry is poured into the pycnometer. During the test process another pycnometer, filled with pure water is used to provide deaired water. Then for both pycnometers vacuum pressure is applied to extract the entrapped gasses from water and slurry. After the air outputting in the sample be stopped, deaired water was added and be filled until the calibration mark of the pycnometer. The same operation is performed again by placing only water on the same pycnometer and the specific gravity of soil solids (G_s) is calculated (See APPENDIX_D) by using the following equation:

$$G_s = \rho_s / \rho_w = M_s / (M_{p.w} - (M_{p.w.s} - M_s)) \quad (3.2)$$

ρ_s = the density of the soil solids
 ρ_w = the density of water
 M_s = the mass of the oven dry soil solids (g)
 $M_{p.w}$ = mass of the pycnometer and water
 $M_{p.w.s}$ = the mass of pycnometer, water, and soil solids

3.2.6 Free Swell Index Test

To estimate of swell potential soil specimen, free swell index test is a standard method. This method proposed to acquire accurate and precise measurements to predict swelling behavior; also, it is a quick method to assess the expansive behavior of the soil. To perform the test oven dry soil passing from 425- μm (No.40) sieve is needed. Initially, distilled water has to be poured into the cylinder to conduct this method. 2 gr dried soil needs to be transferred into a 100-mL graduated cylinder. This soil is added gradually to 0.1 gr per 10 minutes intervals. Then, the cylinder is closed down by a stretch film. After 24 hours rest swollen volume is measured by cylinder graduation. The free swell index can be calculated by the Eq. 3.3.

$$FS = (V_1 - V_2) / V * 100 \quad (3.3)$$

FS = the free swell, %

V_1 = the soil volume after swelling, cm^3

V_2 = the volume of dry soil, cm^3

V = the volume of soil specimen read from the graduated cylinder containing kerosene

3.3 Archimedes Method

The conventional methodology for the evaluation of soil bulk volume is waxing specimen with paraffin and weighing the specimen both in water and in air. The difference between two weighs is the buoyancy force of the liquid in which the specimen is soaked. According to Archimedes principle, the buoyancy force acting on a submerged specimen is equal to the multiply of the density of liquid and the volume of the specimen. However, this volume also includes the wax, which covers the soil specimen. Therefore, the weight of the paraffin and its corresponding volume has to be determined using the density of the wax. The purpose of using wax is to prevent the water to penetrate into the soil. For melting the solid paraffin, an electric powered metal pot device can be used. A laboratory electronic balance, having a hook mechanism, which allows to hang down the specimen in a water tank, is prepared for

the Archimedes method. Distilled water having 1 gr/cm³ density was used on the measurements.

$$V = (M_1 - M_2) / \rho_w \quad (3.4)$$

V = Volume of the specimens

M₁ = Mass of the specimen in air

M₂ = Mass of the submerged specimen in submerge

ρ_w = density of the water

3.4 Measurement of Volumetric Shrinkage using Vernier Caliper

The shrinkage curve was experimentally measured from initial water content condition to a dehydrated state. A digital caliper was used for the measurement of the volume at the various cycle of drying. In volume determination of specimens, the diameters of specimens were measured at two different points (0°-180° and 90°-270°), and heights of the samples were measured from four different positions (0°, 90°, 180°, 270°) as illustrated in Figure 3.3. Specimen diameters were beginning to decrease due to the shrinkage. During the drying process, crack initiation on the compacted specimens were observed. Cracking caused specimen shape to be the deformed. This case hampered the manual caliper readings due to the discontinuities observed on the surface of the specimen. Digital balance was used to measure the water content of the soil during drying for the shrinkage curve construction. Since the specimens were placed on rigid scaled basements, digital balance readings were made easily for all specimens. Drawing volume versus the water content presents Soil-Water Characteristic Curves. Compacted soil specimens were manually measured by Vernier Caliper after every photo acquisition.

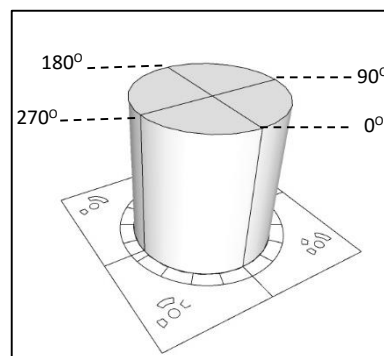


Figure 3.3 Locations of the manual caliper readings

3.5 Water Content Determination of Compacted Soil Specimens

During volume measurements, each compacted specimen was placed on a rigid plastic plate, which includes the scaled basement. This plate helped to move the specimens between acquisition setup and digital balance. Before putting specimens on the plate, each plate was weighed, so it could be possible to eliminate the plate weight. The specimen masses could be calculated in this manner. The initial water contents of the compacted soil specimens were determined at the end of the test. After placing the specimen on the plate, for each volume evaluation, the soil specimen was weighed. At the end of the shrinkage, when compacted soil didn't expose significant volume change, each specimen was taken in oven at 102⁰C. In this manner the dry weight of the soil specimen was determined, so water content for measurement intervals of soil specimen including the molding water content could be obtained.

3.6 Shrinkage Mechanism

The volume change of soil specimens occurs under wetting and drying cycles and according to this switching condition, shrinkage cracks appear. During drying, water gets out from pores and at the first stage, a slight decrease on the void ratio occurs. The water evaporation dries the soil particles at the surface, so it develops a curved interface at the edge of the soil specimen. In the inner side of the interface, a small magnitude of excess water pressure exists. The dry soil exerts influence on the excess water pressure of the surrounded soil and induce matric suction. Water content reduction progress cause matric suction to increase. Soil particle tensile resistance increases and void ratio scales down. This stage is called primary shrinkage stage. In the second stage, the void ratio decreases rapidly. As long as water content transition continues, insignificant changes in void ratio occur due to some fabric re-arrangement or bending of particles (Yong & Warkentin, 1975). In the third phase, marginal volume changes occur and this phase is called as residual shrinkage stage. In the first two shrinkage phases, as the soil volume is decreasing, the water content of the soil is also decreasing. On the other hand, in the residual phase, no volume changes occur (Berndt & Coughlan, 1977).

Shrinkage behavior of fine-grained soils is mostly described by the shrinkage limit and shrinkage ratio. Shrinkage limit is obtained by two methods: the mercury method and the wax method. Shrinkage limit is the lower water content in which soil volume does not change anymore. Shrinkage ratio describes the percentage of volume change during drying of the soil.

Shrinkage limit and shrinkage ratio are the parameters to classify the clay minerals in geotechnical engineering, but to accurately describe soil shrinkage behavior and predict three shrinkage stages, it is essential to measure the soil volume at varying water contents. Volumetric shrinkage curve can be expressed by drawing the corresponding between water content and void ratio. The conventional method for shrinkage monitoring of compacted laboratory specimens is the utilization of Vernier Caliper. However, in order to use Vernier caliper, the sample must be regularly shaped. Consequently, by plotting the shrinkage curve, the three shrinkage stages can be decomposed by evaluating the slopes of this curve.

3.7 Soil Shrinkage Characteristic Curve (SSCC)

Determination of the SSCC requires periodic measurement of the soil volume and the water content from an initial moisture content till oven dryness. The conventional method suggested by many authors to assess the bulk volume of soil is measuring the weight or volume of fluid, displaced by submerged soil samples by utilizing Archimedes law. Another approach for measuring the bulk soil volume is by measuring the dimensions of the soil sample directly by Vernier caliper, but this method is proper to measure volumetric shrinkage of the cylindrical shaped compacted soil specimens (Ören et al., 2006).

The accepted methods that have been developed to obtain SSCC are the paraffin and mercury methods. Lauritzen and Stewart (1941) suggested a coating approach for individual soil clods to determine the shrinkage of drying soils. Soil specimens in natural water content were coated by melted paraffin. The volume of soil clod, using the displacement method, was established by submerging sample into water. Until the

soil completely dried, periodical measurements had conducted. After drying ended, paraffin coating was peeled off to measure the weight of the dry soil. On the other hand, Brasher et al. (1966) proposed to use resin-coating to determine the SSCC of natural aggregates. In another study conducted by Berndt and Coughlan (1977), a core method was proposed for undisturbed soil samples to determine the volumetric shrinkage curve. In this study, soils transferred in plastic tubes from field to laboratory to prevent soil structure changes. In the laboratory, the soil was sliced in different sections and exposed to the atmosphere to dry slowly. During monitoring the volume and water content changes, the height of specimens was measured by dial gauge and the diameter of the core was measured by using a flexible ruler. By obtaining these values, curves for core bulk density versus water content were plotted.

3.8 3D Model Acquisition Procedure

3.8.1 Image Acquisition

The images were taken using the image acquisition setup in which the turntable, scaled base, and the specimen was located. Images are captured by rotating the turntable for every 20-degree, so one tour of the turntable corresponded to total of 18 photos. Since the camera was located on a height adjustable tripod in front of the specimen, appropriate elevation could be easily determined by adjusting the level of the tripod. For this study, three different levels of height were adapted as illustrated in Figure 3.4 Thus, 54 images in total were captured around the upper perspectives of the specimen (Figure 3.4).

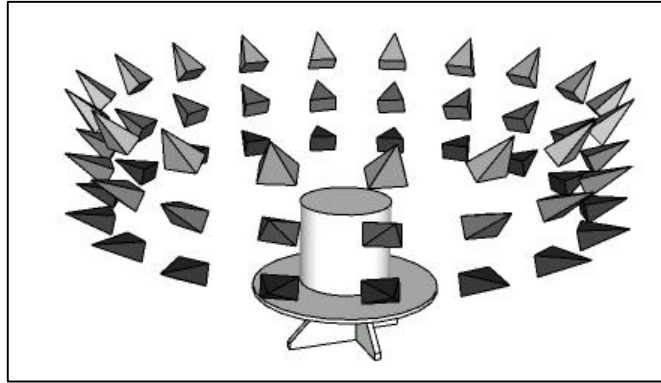


Figure 3.4 Turntable, specimen and camera positions

After the completion of the 54 images, another set of images were taken by lying the specimen upside down and imaging with the same procedure. This resulted another set of images that includes the unseen bottom part of the first set of images. By executing the adopted imaging procedure, 108 images in total were captured for the specimen (See Appendix F). This procedure employed for the bulk soil specimens. For the shrinkage monitoring of the compacted specimens only the upper perspective images were used (See Appendix G). This was necessary in order to not to disturb the compacted specimens. Otherwise any disturbance of the soil specimens would affect the measured volume.

A parametric study was conducted by eliminating the images, systematically for bulk soil specimens. The main purpose of the conducted parametric study is to determine the minimum number of images required for the determination of the volume of the specimens as accurate as possible. The following parameters were studied in this study (Table 3.4).

Table 3.4 Parameters investigated in this study and resulted number of images

	Action	Number of images processed
1	Full processing	108
2	Elimination of images taken from the first level of the camera	72
3	Elimination of images taken from the second level of the camera	72
4	Elimination of images taken from the third level of the camera	72
5	Elimination of intermediate angles	54

3.8.2 Photogrammetric Modeling of the Bulk Soil Specimens

In order to achieve accurate volumetric results, camera lens calibration have been performed by using the Agisoft Lens calibration tool. In this tool, a calibration pattern (i.e. checkerboard) is projected to the monitor for the acquisition of multiple images from different perspectives using the camera which will be calibrated. In this study, 15 images from different perspectives of the calibration pattern have been used for the calculation of the intrinsic parameters of the camera (See Appendix_E). The intrinsic parameters are focal length (f_x , f_y), principal point coordinates (c_x , c_y), radial distortion coefficients (K_1 , K_2 , K_3), tangential distortion coefficients (P_1 , P_2) and skew coefficient between the x and y axis (s). On the other hand, cameras extrinsic parameters describe camera location and orientation according to the real-world coordinates by estimation of camera matrix to form a linear equation.

For the 3D modeling of the soil bulk specimen, 108 images of the samples, taken from above and below perspectives have been transferred into two different chunks in Agisoft Metashape software. For each chunk, camera alignments are computed. This process contains both feature extraction and 3D points generation. During the feature extraction process, every distinct point in the images such as sharp edges or lines is

marked as key points. These key points are then targeted in each image during the image matching. In this step, SIFT algorithms are intensely used since changing perspectives resulted in slightly varying appearances in the sequential images. If the change in the perspective is significant, then the SIFT algorithm could not find enough key points to establish the connection between the images. So, the performance of the process is closely dependent on the number of images which are captured from close perspectives.

By identifying the key points, the geometry of the scene, camera positions, and orientation are solved by an iterative procedure using the camera intrinsic parameters. Thus, the 3D world scene points (i.e. sparse point cloud) and camera location and orientations have been obtained in this step (Figure 3.5). However, the established scene does not involve a scale unless calibration is performed.

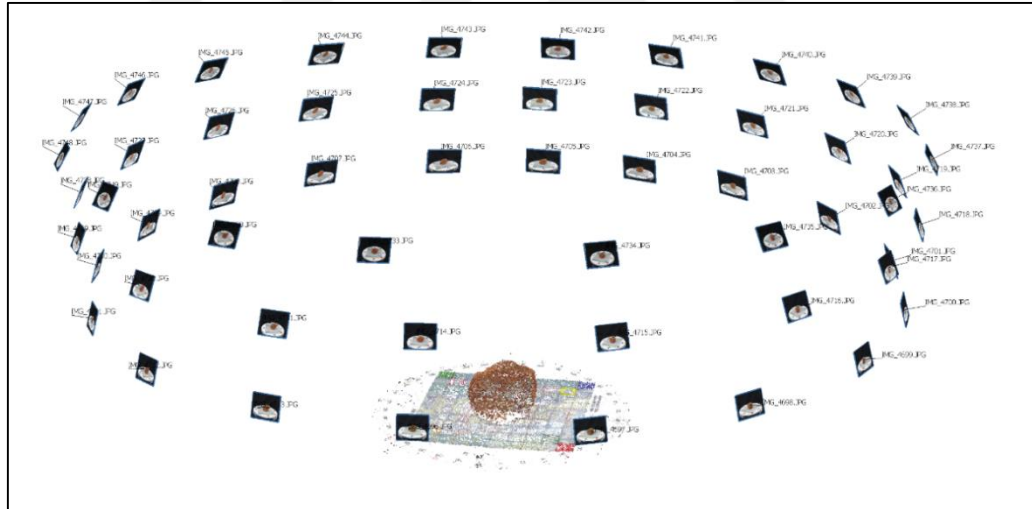


Figure 3.5 Camera alignments and sparse cloud of soil specimen

The calibration of the 3D scene has been established by markers in this study. For this purpose, 4 markers have been placed on the captured images at the reference points printed on the scaled basement shown in Figure 3.1b. The exact real-world coordinates have been assigned at these reference markers and calibration was made for two chunks by optimizing the reference coordinates and camera intrinsic and extrinsic parameters. Thus, two scaled 3D model of each specimen taken from different

perspectives including the scaled basement have been obtained. It should be noted that the mean errors for the reference points after the optimizations were in the range of 0.09 to 0.04 mm as can be seen in Table 3.5. Although, these mean errors were calculated as distances between the cloud point coordinates and real-world coordinates for the reference points, the same accuracy is acceptable for points belonging to soil specimen in the cloud.

Table 3.5 The mean errors for the reference points for soil specimens and calibration object

Soil	Chunk	Error (mm)	Error (Pixel)
Calibration Object	1	0.05299	0.121
	2	0.07132	0.056
CH-1s	1	0.08435	0.059
	2	0.07238	0.238
CH-1 _M	1	0.07102	0.073
	2	0.06419	0.184
SC-1s	1	0.03445	0.065
	2	0.06314	0.090
SC-1 _M	1	0.08450	0.015
	2	0.05859	0.023
SC-2s	1	0.04895	0.126
	2	0.06814	0.28
SC-2 _M	1	0.03759	0.039
	2	0.03853	0.328

Two 3D sparse cloud points belonging to the same soil specimen have been aligned to constitute 3D soil specimen. The alignment of the calibrated sparse clouds, presenting the upper and lower part of the bulk specimen, was established by placing 8 distinctive markers on each bulk specimen.

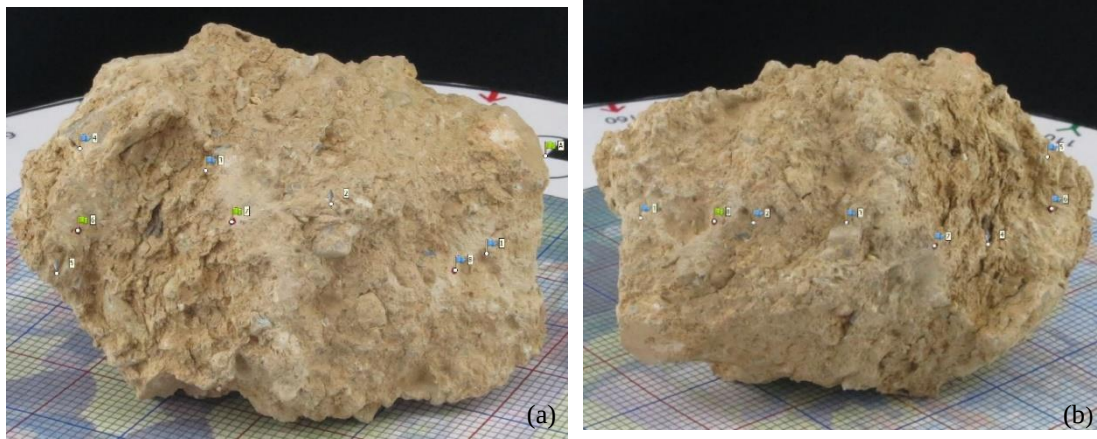


Figure 3.6 The presentation of the on-specimen markers for upper (a) and lower (b) perspective (Personal archive, 2019)

In order to track and find these distinctive points in the captured images, points have been marked with permanent ink on the specimens before image capturing process. Once on-specimen markers are placed in the captured images for two chunks, alignment of these chunks was performed by superposing two clouds based on on-specimen markers. In Figure 3.7a and b, two calibrated 3D models are shown in the orientation where on-specimen markers are aligned. Two aligned sparse cloud points have been overlapped together to form the full 3D soil specimen model (Figure 3.7c). However, since this model included two different oriented reference basements, it was not possible to calculate the volume with these references.

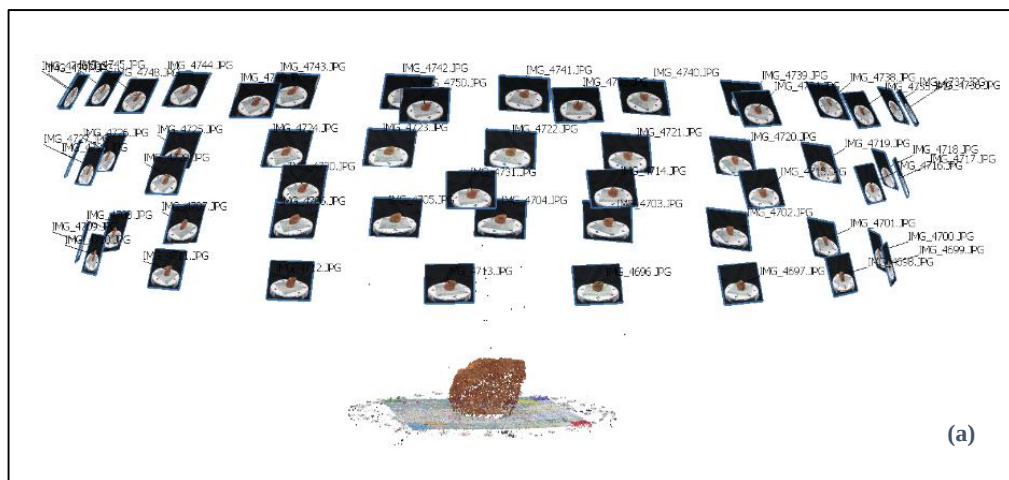


Figure 3.7 Two scaled (a-b) and aligned and overlapped (c) sparse clouds

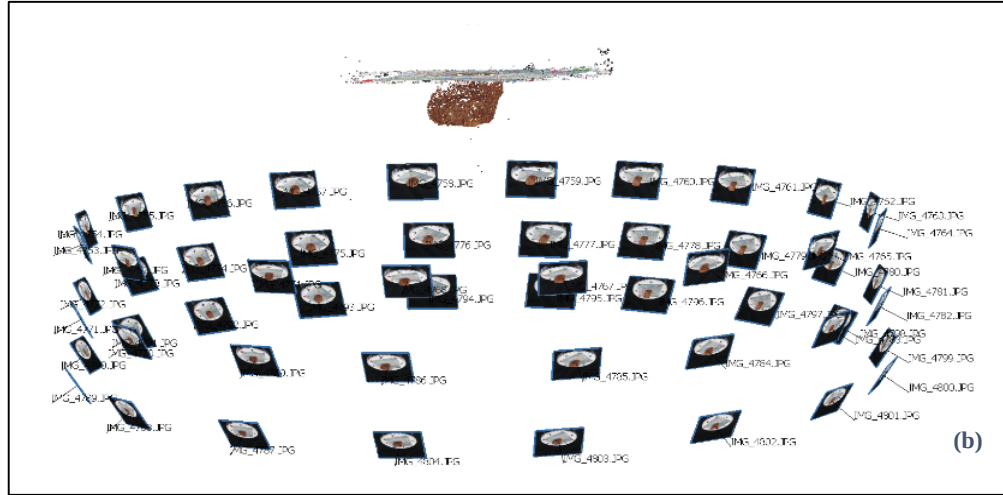


Figure 3.7 continues

Therefore, the reference basement and the partly seen lower part of the bulk specimen were cropped from sparse clouds for each separate chunk. However, the model based on sparse cloud lacks the detail required for the exact calculation of the volumetric quantities. Therefore, dense point clouds have been calculated by using depth maps for every image, resulting a cloud containing approximate million points for a bulk specimen. The cropped sections (i.e. reference basements and unseen lower parts) and their complemental parts obtained from the mate cloud were shown in Figure 3.8a and b with yellow and green marks, respectively. Two aligned and cropped

point clouds shown in Figure 3.8a and b have been merged together, in order to establish the complete 3D point cloud of the bulk specimen (Figure 3.8c). However, the determination of the exact volume requires a solid 3D object. Therefore, a 3D mesh was established based on the dense cloud point using screened Poisson surface reconstruction technique (Figure 3.8d). The volume calculation was made by choosing an arbitrary point in the specimen and summing up the volumes of all pyramids with mesh faces counted as bases of these pyramids. In this study, Poisson surface reconstruction and volume of bulk specimens were obtained by using the Agisoft Metashape software's built in functions.

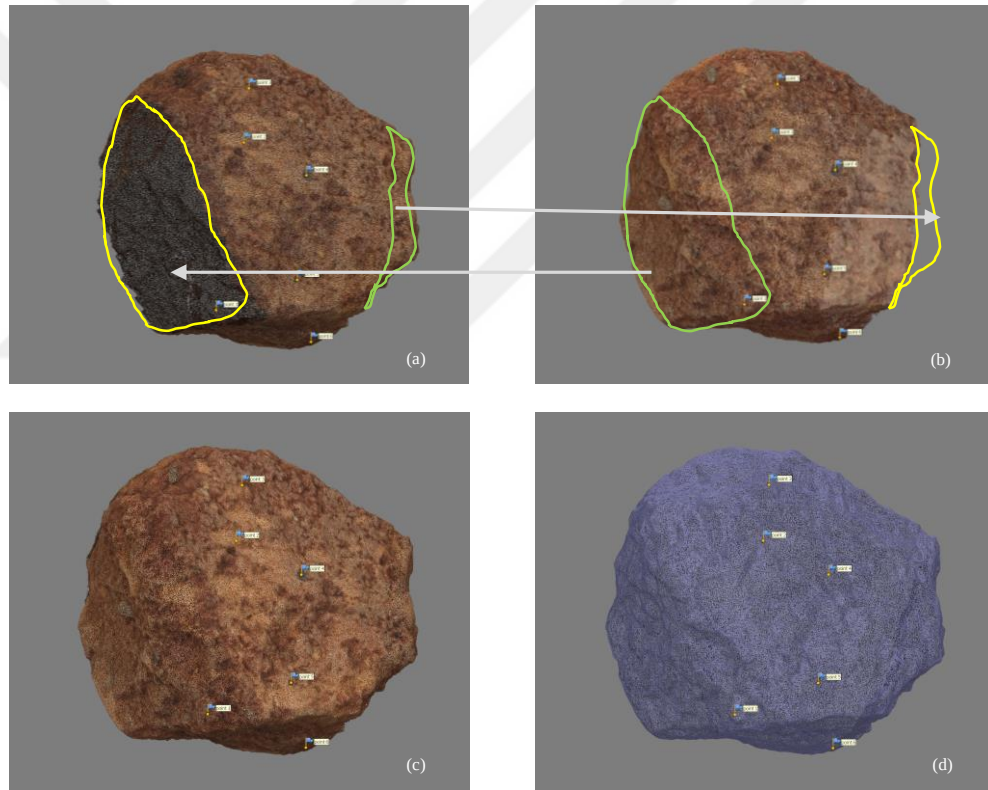


Figure 3.8 Alignment based on on-specimen markers

3.8.3 Photogrammetric Modeling of the Compacted Soil Specimens

Photogrammetry modeling includes camera calibration, image acquisition, image alignment, and mesh generation. Determining 3D coordinates on an object requires interior orientation parameters (i.e. focal distance, principal point coordinates, and

distortions) to be known. Automatic calibration maybe applied sequentially during 3D point cloud generation. However, this calibration does not provide the required precise accuracy. Model accuracy strongly depends on the calibration process. The camera calibration was performed by using the chessboard from Agisoft Lens tool. Images of the chessboard from different angles were captured, and imported images in Agisoft Metashape, so lens distortion was calculated. Figure 3.9a shows the Agisoft Lens tool and calculated camera parameters. In Figure 3.9b chessboard has been shown with red and blue circles that represent the detected corners of the cells.

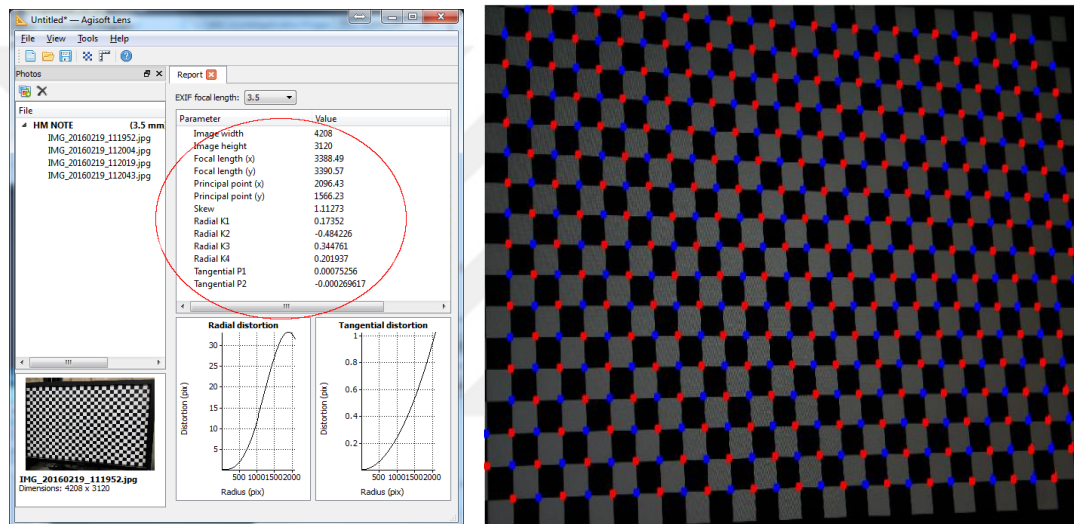


Figure 3.9 Agisoft Lens tool (a) and Chessboard with detected cells (b)

A scale-plate were used to assist the 3D model scaling. Automatically generated coded markers were plotted on this plate. Four markers were printed in each corner. These markers arranged as to have 12 cm distance from each other (Figure 3.10). The real-world distance between markers were used in the software to calibrate the 3D model to have the real-world dimensions.

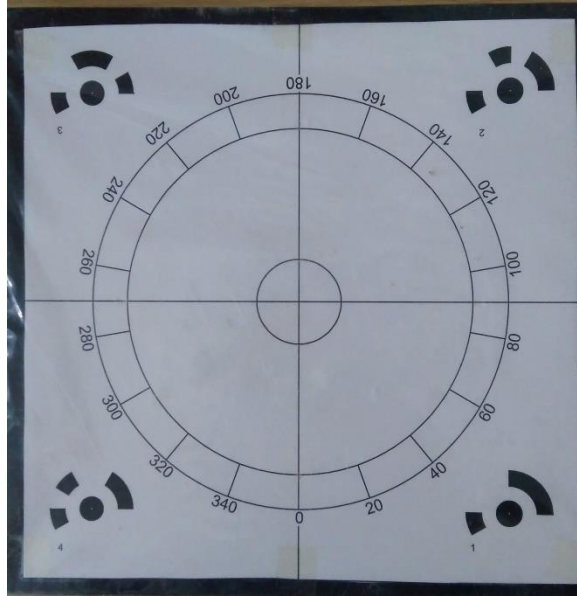


Figure 3.10 Scale-plate with four coded markers in corners (Personal archive, 2019)

To achieve multi-view perspective 54 images were taken by a camera mounted on a tripod. Images were captured from every 20 degrees rotations. This image acquisition process provides a full perspective view from the whole of the specimen because images should overlap and cover all specimen surfaces. Entire geometry of the soil specimen cannot reconstruct in this manner. In order to reconstruct the 3D soil specimen model, images were imported into photogrammetry software. The coded markers are detected by the software automatically and marked as reference points. After that, the real-world coordinates of the marker points were entered to calculate the solid models of the soil specimens.

The employed photogrammetry software uses structure from motion technique, in order to compute the point cloud using the 2D images of an object. For this purpose, alignment of 2D images has to be performed. In alignment process, feature detection and keypoint coordinates are determined. The detected features are searched in all images using the SIFT algorithm and located, which yields as matching point coordinates. These matching points are then used to tie the features and to calculate the camera positions, called as camera alignment. An initial point cloud based on estimation of the camera positions was built as a resulted alignment process as shown in Figure 3.11 by the software.

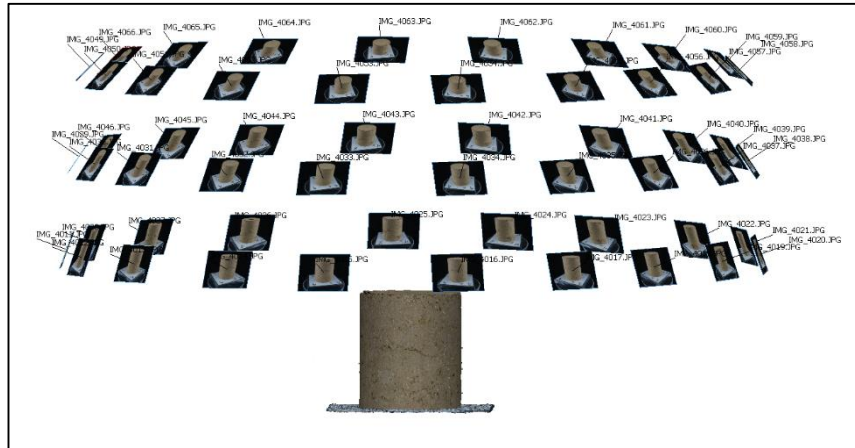


Figure 3.11 Camera alignments and sparse cloud of compacted soil specimen

In Figure 3.12, blue lines are connecting valid (used) matching points between the selected pair of images and red lines are connecting invalid (unused) matching points between these two images.

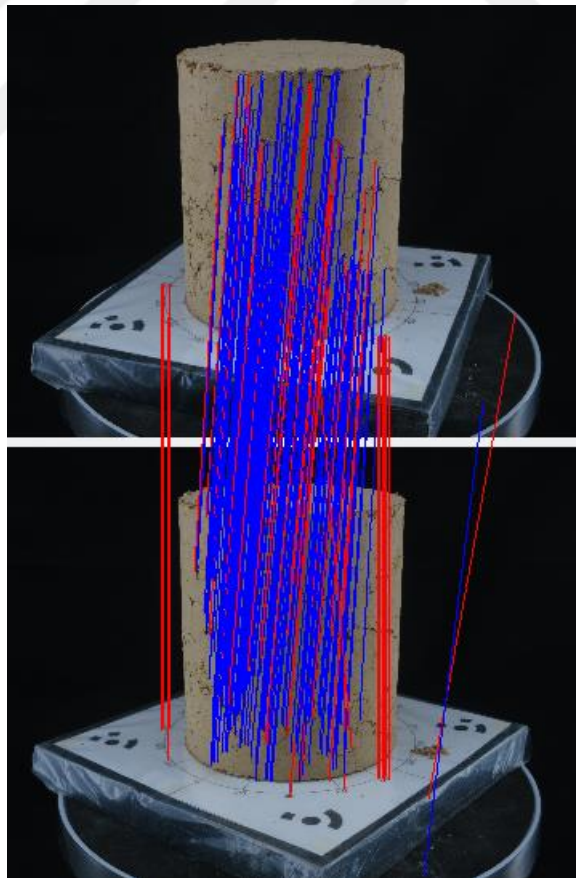


Figure 3.12 Two paired images matched points

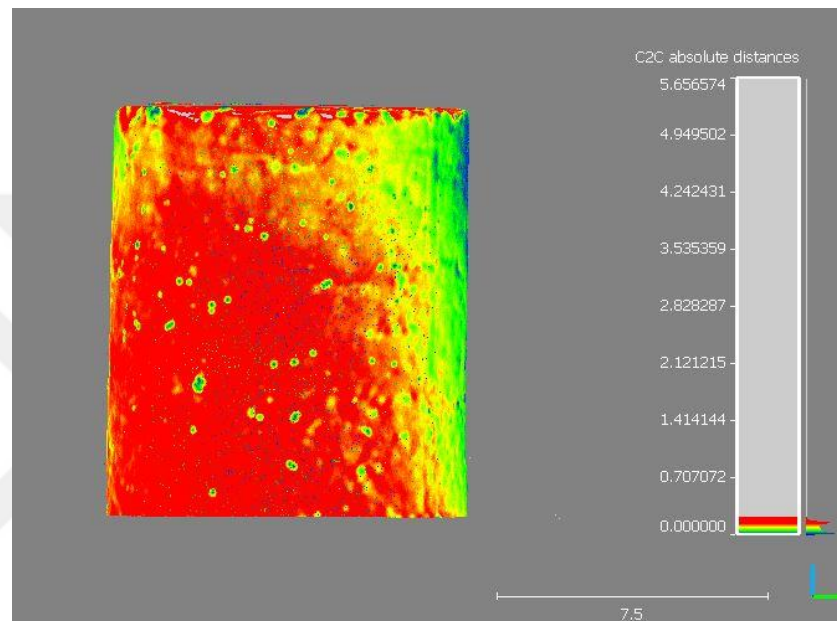
Geometrical mesh can be produced directly from point cloud. From trial and error experience it was observed that, a full detailed mesh cannot be directly generated from point cloud data for this soil specimens. To construct a mesh model with specific features, it is essential to extract a colorful model by building dense cloud. Generating dense cloud extracts essential details of the specimens. As the next step, a high detailed solid mesh should be interpolated from dense cloud data. Mesh model reconstructed is a triangulation process. The volume calculation principle for 3D meshes requires a complete closed triangulated mesh. Before calculating the volume of the specimen, meshing statistics should be checked and erroneous topologies should be fixed at that point. The calculation of the volume is a simple process which can be made by choosing an arbitrary point in the specimen and summing up the volumes of all pyramids with models faces counted as bases of these pyramids. These calculations were made by using the embedded function of the photogrammetry software.

3.8.4 Comparison of The Reconstructed 3D Models

CloudCompare software was used to compare the reconstructed 3D models. This software is reliable open source software to compare the obtained orientation and 3D coordinates extracted from an object. Several 3D clouds generated with high accuracy with millions of points can be imported into this software and compared in sub-millimeter accuracy. This software is a PhD thesis project that began in 2003 by Daniel Girardeau-Montaut in France. In order to determine the surface deformations between acquired models the dense clouds generated by Agisoft Metashape software were imported in this software.

To perform the comparison, clouds should fit in exactly the same coordinate system. The clouds which generated by Agisoft Metashape, contains the same coordinates as defined by reference points, so point clouds were located in circular areas in the XYZ plane with the same center and radius. Distance computation process was applied on to the imported 3D clouds by cloud-distance computational tool. The computational process can be applied by selecting the point clouds and then running the comparison algorithms. In the distance computation between two clouds, the

nearest point on the surface of the reference clouds was taken into account and the distance between these points are calculated. The distance between two clouds is visualized as different color plates according to the minimum and maximum obtained distances. As a comparison result, the deviation can be observed in color over the specimen. A sample comparison graph is shown in Figure 3.13. In this figure, red to blue color scheme represents the displacements magnitude.



3.13 Cloud compare surface deviation represented as colors

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Standard Compaction Test Results

The compaction characteristic of the soil used for shrinkage monitoring application, was presented in Figure 4.1. In this study, soil samples were compacted in standard Proctor energy. Bulk soil specimens also share the same standard compaction parameters.

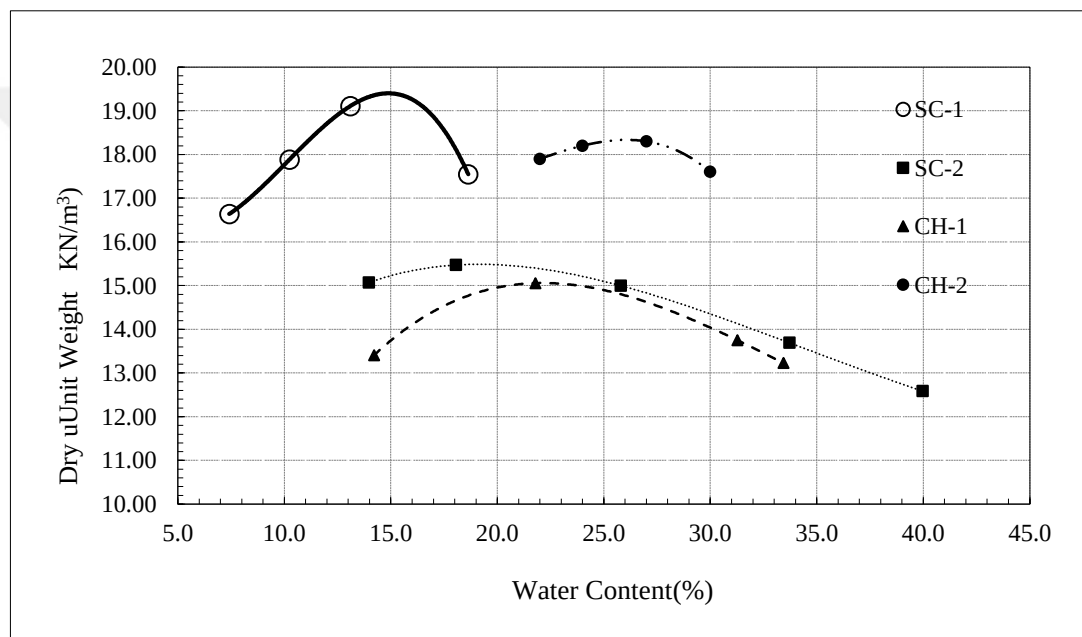


Figure 4.1 Compaction curve of the used soil classes

4.2 Parametric Image Elimination Study

In pursuance of the reducing the image acquisition and processing time length, a parametric photogrammetry study was performed, and the computationally determined volume was compared with the mechanically obtained volume. The number of images used for processing may have a negative effect both on image acquisition and processing steps. Therefore, the elimination of the images is important for the time, consumed for the methodology. On the other hand, the photogrammetry technique requires as many images as possible for the accuracy of the process.

A rock specimen was used to represent geotechnical laboratory specimens, in order to prevent volume changes due to drying (Figure 4.1). The volume of the specimen was determined by the Archimedes method as 294.58 cm^3 . This volume was referenced as base and comparisons are made according to the Archimedes method. The volume determined by SFM technique was obtained as 296.74 cm^3 by using 108 images, acquired as explained in the imaging procedure section (Table 4.1). The error calculated between the two methods is -0.73%, and the computational process required 13minute 22seconds. On the other hand, by eliminating the first, second, and third level of images resulted in volumes of 296.72 cm^3 , 292.72 cm^3 and 293.83 cm^3 , respectively. These calculations resulted as -0.72%, 0.62%, and 0.25% errors with the same order. By using all the available camera levels but eliminating the intermediate angles resulted a volume of 296.68 cm^3 , which represents an error of -0.71%.

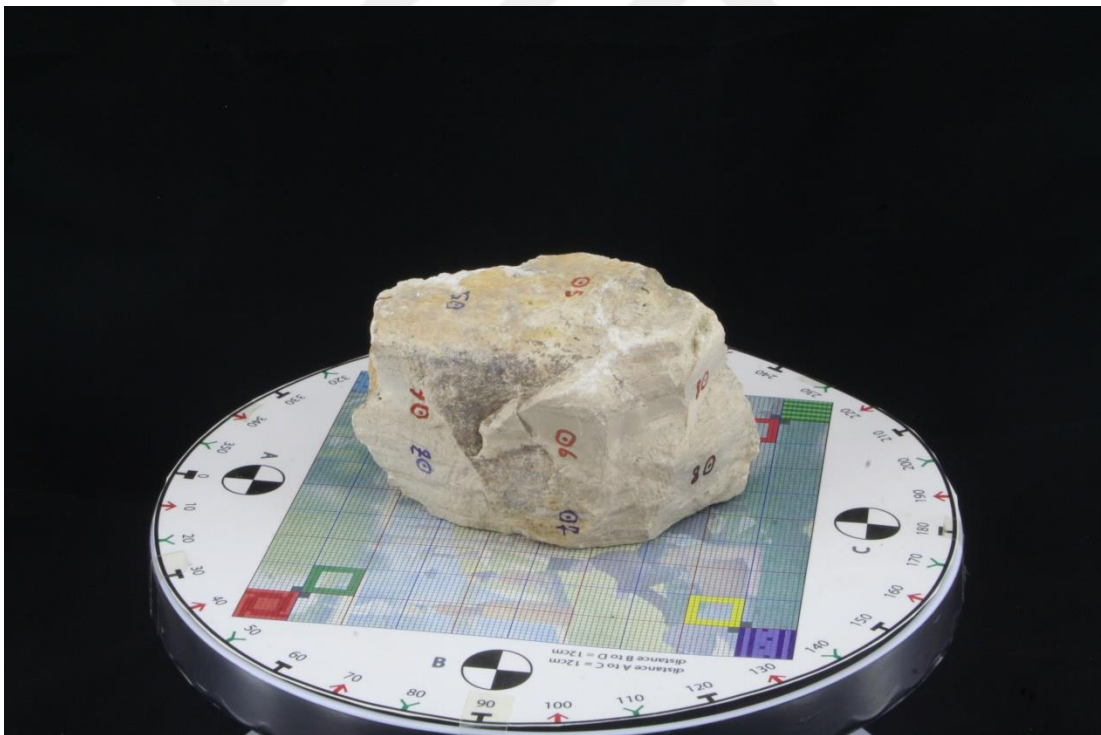


Figure 4.2 Rock specimen, used in the parametric image elimination study (Personal archive, 2019)

Table 4.1 Comparison of applied techniques and resulted in errors.

Procedure	Archimedes Method	SFM Method	Elimination of first level images	Elimination of second level images	Elimination of third level images	Elimination of intermediate angles
# of images	-	108	72	72	72	54
Volume (cm ³)	294.58	296.74	296.72	292.74	293.83	296.68
Error (%)	-	-0.73	-0.72	0.62	0.25	-0.71
Computational Time	-	13min 22s	4min 26s	4min 27s	5min 52s	3min 6s
Bulk Density (gr/cm ³)	2.429	2.411	2.411	2.444	2.435	2.412

By evaluating the volumes and bulk densities of the inspected specimen, strong correlation was found between Archimedes and all SFM methods. Although the elimination of the third level resulted in the minimum error, removal of intermediate angles was found more practical for the execution of the technique considering the time spend for the image acquisition, computational time and manual operator processes. The maximum variation on the bulk density was found as 0.018 gr/cm³. In this method, soil specimen was preserved for further laboratory tests. Usually, after coating with paraffin soil sample become unusable. So, if the quantity of the soil samples is inadequate, measurement with computer vision is recommended. However, it should be noticed that the duration of the process highly depends on the hardware of the computer and for most of the laboratories it may not be possible to provide enough processing power to perform this technique.

4.3 Volumetric Determination of Bulk Density

Since the cylindrical calibration object was produced with a high precision mechanical lathe tool, the exact volume of the object was easily calculated by using the dimensions of the cylinder. In order to test and verify the accuracy of the photogrammetric modeling technique, the volume of the calibration object was also obtained by using this technique. Furthermore, the volume of the calibration object was determined by using Archimedes method, in order to validate the Archimedes testing setup. The comparison of the volumes is shown in Table 4.2.

Table 4.2 The volumes of the calibration object based on methods

Method	Volume (cm ³)	Relative Error with Respect to Mech. Tool (%)
Mechanical Lathe Tool	943.69	-
SfM Method	943.496	0.020
Archimedes Method	944.17	-0.047

As can be seen in Table 4.2, relative errors concerning the mechanical tool were calculated as 0.020% and -0.047% for SfM method and Archimedes method, respectively. However, it should be mentioned that the Archimedes method was applied without using paraffin wax since the calibration object is made from a hard-solid material. By considering the low relative errors between the digital and conventional methods for regularly shaped calibration object, the same procedures were applied to the irregular shaped bulk specimens using wax.

Six irregular shaped soil specimens from three soil classes were weighed and imaged according to the proposed acquisition procedure. The volumes of the bulk specimens were obtained by performing the photogrammetric modeling technique. The statistics of the modeling and the calculated volumes were presented in Table 4.3.

Table 4.3 The appearances and the modeling statistics of the bulk soil specimens

Specimen	Appearance	Points	Faces	Vertices	Volume (cm ³)	Area (cm ²)
CH-1 _S		1207280	241456	120730	82.99	124.653
CH-1 _M		882128	180000	90002	56.41	87.709
SC-1 _S		1146479	229294	114649	87.079	124.653
SC-1 _M		1499168	299832	1499168	98.922	140.309
SC-2 _S		1618071	323614	161827	91.109	115.426
SC-2 _M		442520	60000	30002	155.887	167.774

S: standard Proctor; M: modified Proctor

Immediately after the image acquisition process, the specimens were covered with wax, and their volumes were determined by the Archimedes method. The volumes, corresponding bulk densities of the soil specimens and the relative errors between the testing methodologies are presented in Table 4.4. As can be seen in Table 4.4, the bulk densities of the specimens compacted with modified Proctor energy were determined slightly higher than those compacted with standard Proctor energy as expected. On the other hand, the errors between two methods appeared as negative values for standard Proctor specimens, as it was occurred positive for the modified Proctor specimens.

Table 4.4 The weights, volumes, and bulk densities of the soil specimens based on testing methods.

Specimen	Weight of the Specimen (gr)	Volume by Archimedes Method cm ³	Volume SfM Method cm ³	Bulk Density by Archimedes Method (gr/cm ³)	Bulk Density by SfM Method (gr/cm ³)	Compaction Energy	Error Between Methods (%)
CH-1 _S	154.08	83.74	82.99	1.84	1.85	Std. Proctor	-0.54
CH-1 _M	110.28	55.05	56.41	2.003	1.95	Md. Proctor	2.65
SC-1 _S	176.98	89.25	87.205	1.98	2.02	Std. Proctor	-2.02
SC-1 _M	208.38	97.52	98.92	2.13	2.106	Md. Proctor	1.13
SC-2 _S	170.70	92.75	91.11	1.84	1.87	Std. Proctor	-1.63
SC-2 _M	301.21	153.36	155.88	1.96	1.93	Md. Proctor	1.53

The volumes and bulk densities of the soil specimens obtained for both methods were compared on a 45° line in order to observe the variances in the measured quantities (Figure 4.3 a and b). Besides, the coefficients of determination for volume and bulk density measurements were calculated as 0.9973, 0.8919, respectively. Although both values indicate a good agreement between two methods, the relatively low value for bulk densities was originated by the differences between the weights of the soil specimens.

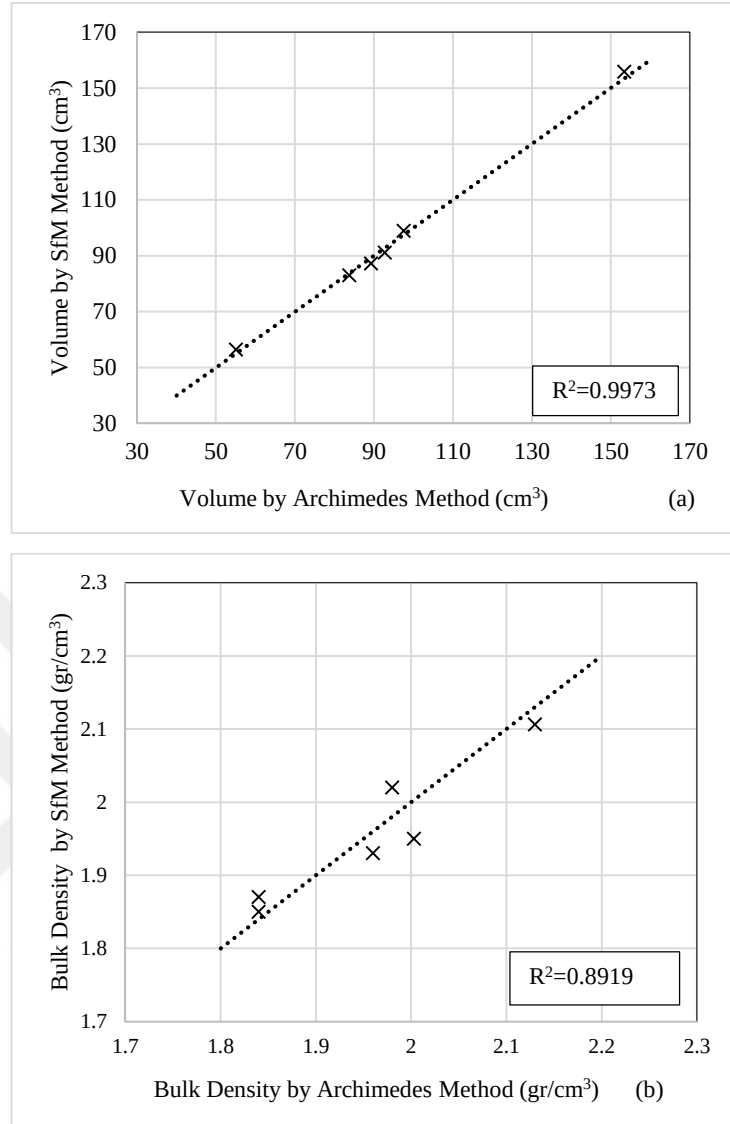


Figure 4.3 The comparison of volumes (a) and bulk densities (b) obtained by Archimedes and SfM methods

Very low relative errors between the SfM and the Archimedes methods were achieved with respect to precise mechanical production tool for the volume of the regular shaped calibration object. This result proved that, the SfM method is capable to make very accurate volumetric measurements, if used as proposed in this study. The low relative errors also indicated that the Archimedes setup employed in this study have a high precision in the volume measurements. It should be noted that, since the calibration object is made from hard solid material, paraffin wax coating was not necessary for the measurements using Archimedes method. On the other hand,

although using the same procedures, the relative errors for the bulk specimens appeared not in the same range compared to calibration object. This case is attributed to the deficiencies on the wax coating process and the wax itself in this study.

It is reported in the literature that the wax also has swell and shrink behavior due to the change in temperature (Freund, 1982; Riesen and Widmann, 1984; Ukrainczyk et al., 2010). Schimmelpfennig et al., (2007) studied volume expansion of nine paraffin wax samples on heating up from 30°C to the melting point (i.e. 51~72°C). Paraffin waxes tend to display differing expansion behavior according to their composition. It is reported that, volume expansions are determined in the range of 1 to approx. 4%. In current study, paraffin wax coated specimens were allowed to cool in the air at room temperature until the wax is hardened and the temperature of the coated wax during the measurements assumed as constant. Furthermore, while wax coating of some bulk specimens, bubbles were observed in the hardened paraffin. In such cases, a sharp knife was used to cut out the bubble and the specimen was recoated. It was observed that, high above the melting temperature of the paraffin wax, more bubbles were entrapped in the coating.

Previous studies showed that, the coated specimens may also include gaps in the coat layer. This results in penetration of water through the gap in to soil pore spaces and swelling of the bulk specimen due to increase in the water content (Stewart et al., 2012). As another drawback for using paraffin wax, it was observed in current study that, although paying attention, the hot wax loosened and plucked some grains from the surface of some bulk specimens.

Since the paraffin wax is in liquid state during coating, it could easily enter in the macro pores of the bulk specimens, which results slightly lower volumes in Archimedes method. Furthermore, hot wax may burn unprotected skin and overheated wax may burst in to flames.

It was observed that the volumes which were obtained by Archimedes method for modified Proctor compacted soil specimens were measured lower than SFM method.

In this study, the modified Proctor soil specimens were compacted in wet of optimum water contents. According to the researchers (Tinjum et al., 1997) the air entry suction in compacted specimens at wet of optimum water contents, were observed higher than the compacted specimens at optimum water contents. This is attributed to the broader unimodal pore-size distribution that primarily contains microscale pores for wet of optimum compacted specimens (Garcia-Bengochea et al., 1979; Acar and Oliveri, 1989; Benson and Daniel, 1990; Prapaharan et al., 1991) . Also, Tinjum et al. stated that for a given compaction water content, the air entry suction is higher for soils compacted with higher compaction effort. In this respect, it is considered that, since the paraffin wax was in liquid state by coating during the implementation of Archimedes method, higher paraffin penetration was occurred due to the increased suction for the modified Proctor specimens. On the other hand, higher suction values resulted increased water penetration into specimens if wax deficiencies were present at the coated surface. For both cases, the displaced water volume will decrease, which results lower volume measurements for the Archimedes method.

Coefficients of determinations between the SfM and Archimedes method for volume and bulk densities of soil specimens has been found as 0.9973 and 0.8919. Although variations occurred for the modified Proctor specimens due to the increased suction properties, the coefficients of determination values indicated a good relationship between the measured quantities. The relative low coefficients of determination value for bulk densities originated as a result of the differences between the weights of the soil specimens.

Consequently, by considering very low relative errors (0.02%) for the calibration object between the SfM method and the volume, calculated based on production dimensions, it was thought that the higher relative errors between SfM and Archimedes method were originated due to erroneous measurements occurred from the usage of paraffin wax.

4.4 Volumetric Shrinkage Monitoring of Compacted Specimens

The volumetric shrinkages of compacted soil specimens were monitored using the proposed technique. The water content of four specimens were also obtained using digital balance.

The following deductions can be made from the water content measurements. In Figure 4.4, water content versus time diagrams can be seen. In order to observe the possible crack patterns on the compacted soil specimens, the specimens were molded as to have 10% higher water content than optimum. One can observe that during drying each soil reached to an equilibrium condition. Between clay specimens, the highest water content loss was for soil CH-2, which started from 33.64% and dropped to 12.86%. Among the soil specimens, the SC-1 soil had minimum drying, of which water content altered by 13.05%. Soil CH-2 had rapid water content dropping among the soils. For 144 hours, clay lost 53.8% of its water.

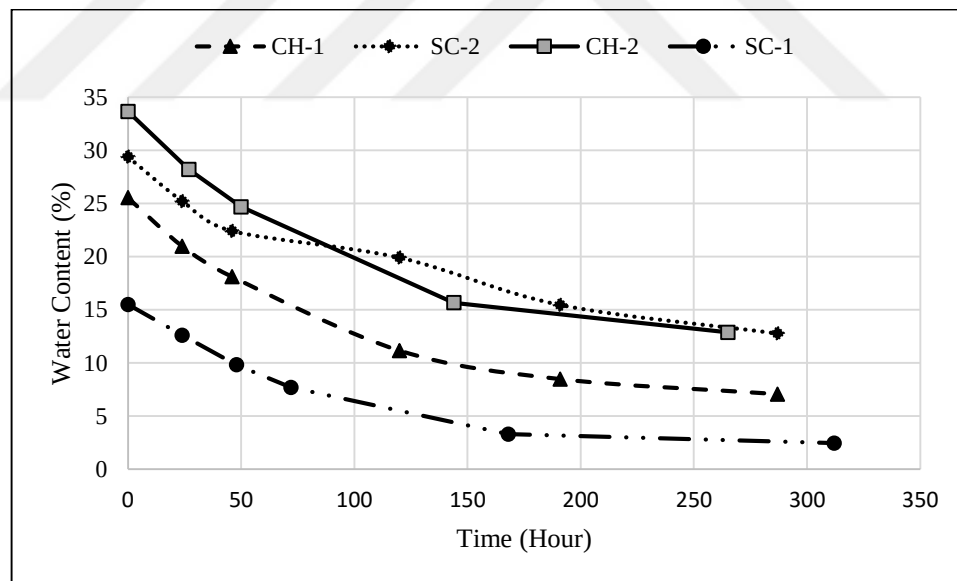


Figure 4.4 Water content vs time curve

In Figures 4.5 to 4.8 the volume change during drying were presented for both direct and digital method measurements. In Figure 4.5, the volume altering per time of soil CH-1 was plotted both for manual Caliper and digital measurements. Volume was decreased following a reduction in water content. Volume has decreased rapidly until

120 hours. The reduction was significant in 120 hours, where the difference between direct and digital measures is not obvious in this period. Close to equilibrium water content, volume changes continue but shows slight deviations. In this drying stage, there is a noticeable difference between the direct and digital method. This difference may be explained by cracks that was generated during drying. The maximum percentage difference for this soil sample is 1.37%.

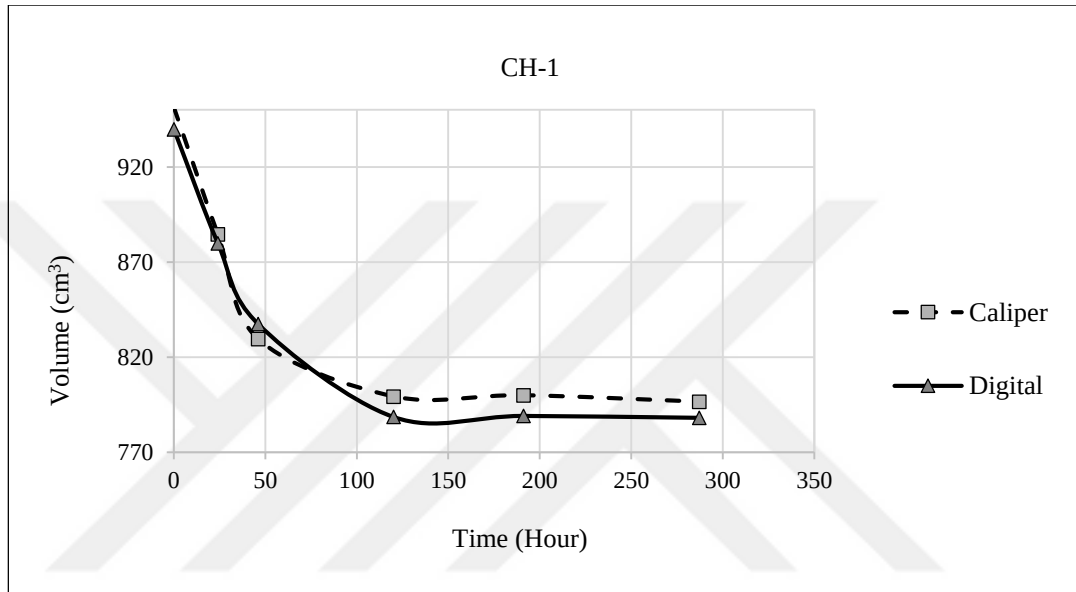


Figure 4.5 Volumes of Soil CH-1 during drying measured with a caliper and digital method.

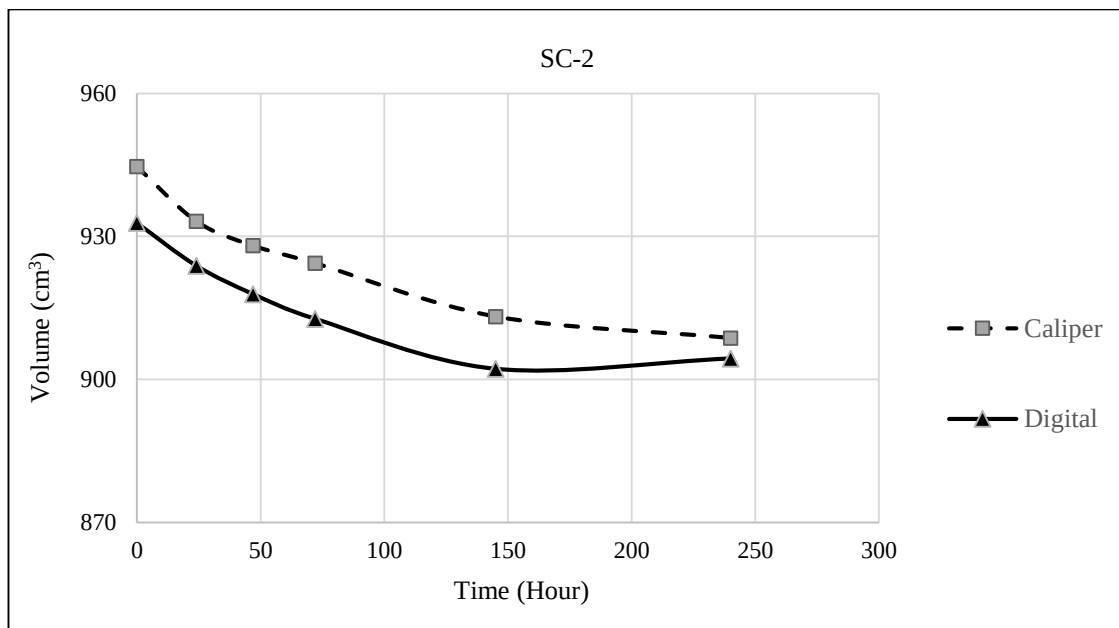


Figure 4.6 Volumes of Soil SC-2 during drying measured with a caliper and digital method

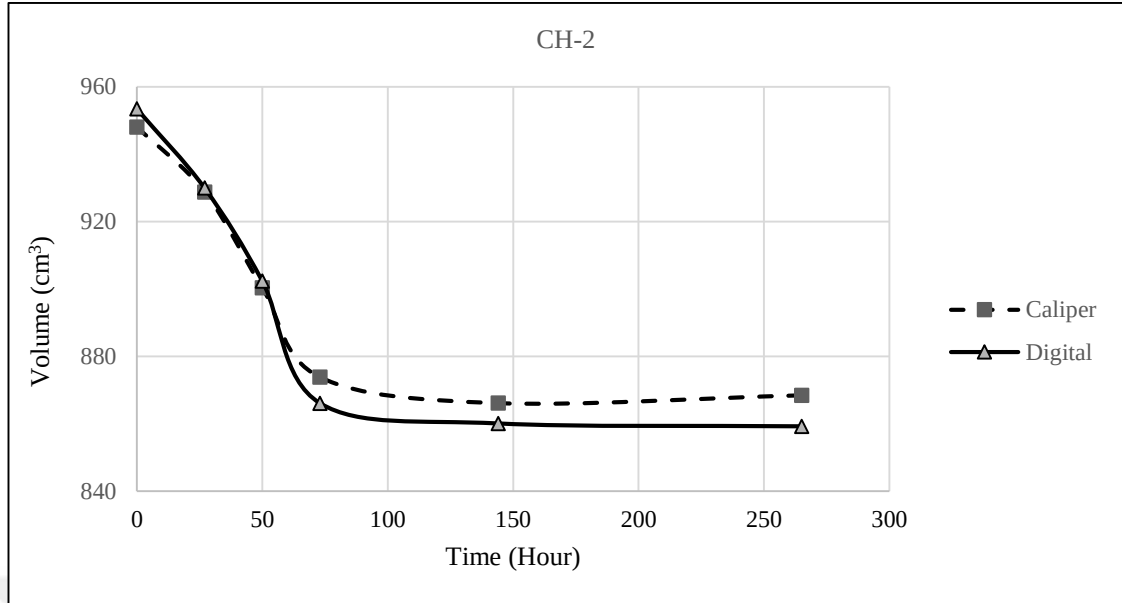


Figure 4.7 Volumes of Soil CH-2 during drying measured with a caliper and digital method.

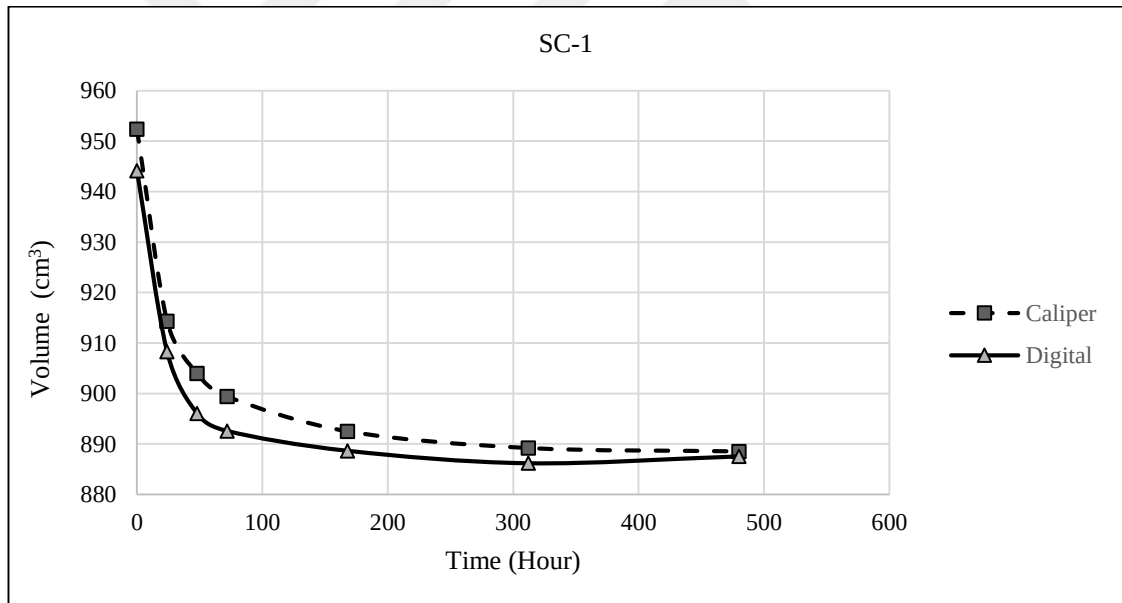


Figure 4.8 Volumes of Soil SC-1 during drying measured with caliper and digital method

In the proposed digital measurement method, the gaps originated by surficial cracks was taken into account on the volume quantification. Therefore, at dry stage of the monitoring process, the digital method shows lower values. The volume monitoring for soil SC-2 was illustrated in Figure 4.6. It can be seen in this figure that the acquired volume values from the direct and digital method are far from each other. There is a

considerable difference beginning from initial volume until volume equilibrium. By comparing two methods values, the maximum percentage variation was calculated as 1.26 %.

The volume changes due to drying of the soil CH-2 are showed in Figure 4.7. At first look it can be seen that rapid volume reduction occurred in the initial days, however, the volume changing was steady after 73 hours. During these periods, there is not a significant difference between manual and digital methods. It is obvious that the volume variation obtained by two methods happened after specimens are in dry stage. The maximum volume difference between method is 1.059%.

Figure 4.8 is the presentation of the volumes during drying of soil SC-1. In the first hour, there is a considerable difference between manual and digital method. The obtained result in digital technique was 944.14 cm^3 and for the manual approach it was 952.35 cm^3 . The volume which was obtained by digital method is close to the original mold volume. However, manual method resulted a higher volume than the mold volume. This may attribute an operator error or slight expansion of the soil specimen after extrusion of the rigid mold.

The following observations can be made from the volume determination test results that measurements with caliper provide higher values than digital methods. This difference could be originated from measuring the pores and cracks that were established during shrinkage. In caliper measurement void has been not measured. The differences between digital and manual volume measurements ranged between 0.2 % and 1.37 % for compacted specimens.

4.5 Soil Shrinkage Characteristic Curve

Soil shrinkage characteristic curves (SSCC) were shown in Figures 4.9 to 4.12 for four soil specimens based on values obtained from the digital method to present the shrinkage behavior. Figure 4.8 shows the soil CH-1 shrinkage diagram. The three stages of shrinkage can be seen in this diagram. It is obvious that the soil lost volume

until 15% water content, and then by water reduction, the volume has no significant changes and became stabilized.

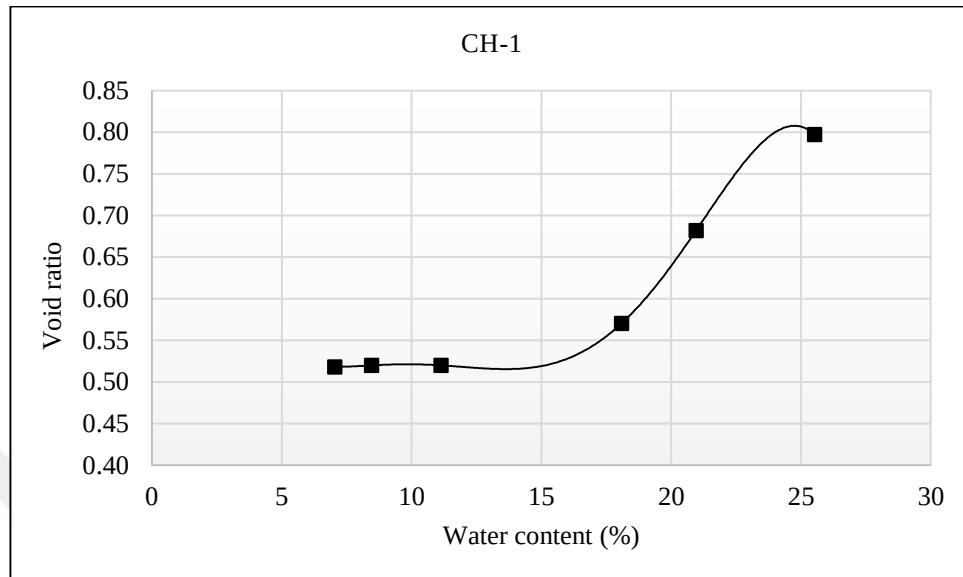


Figure 4.9 Soil CH-1 shrinkage characteristic curves determined with the digital method

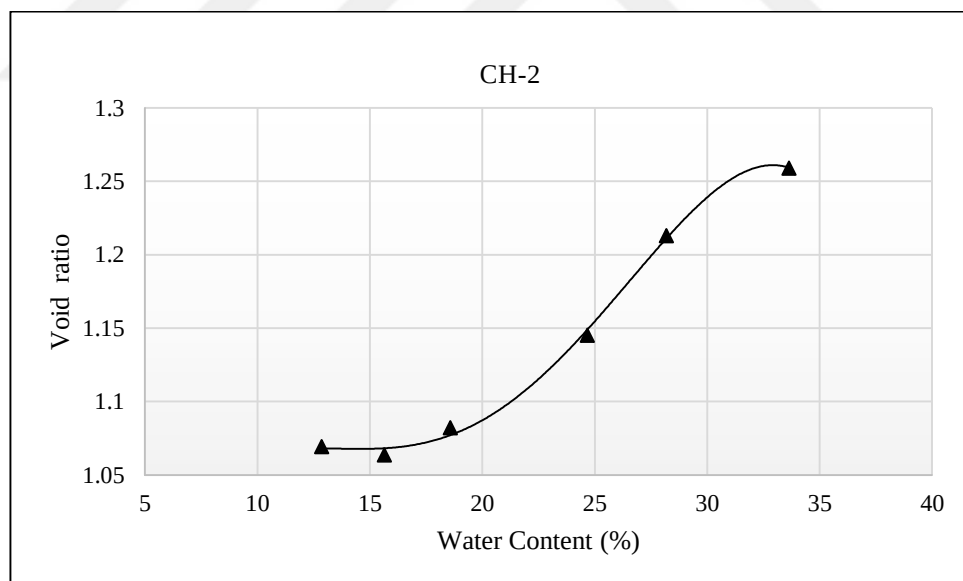


Figure 4.10 Soil CH-2 shrinkage characteristic curves determined with the digital method

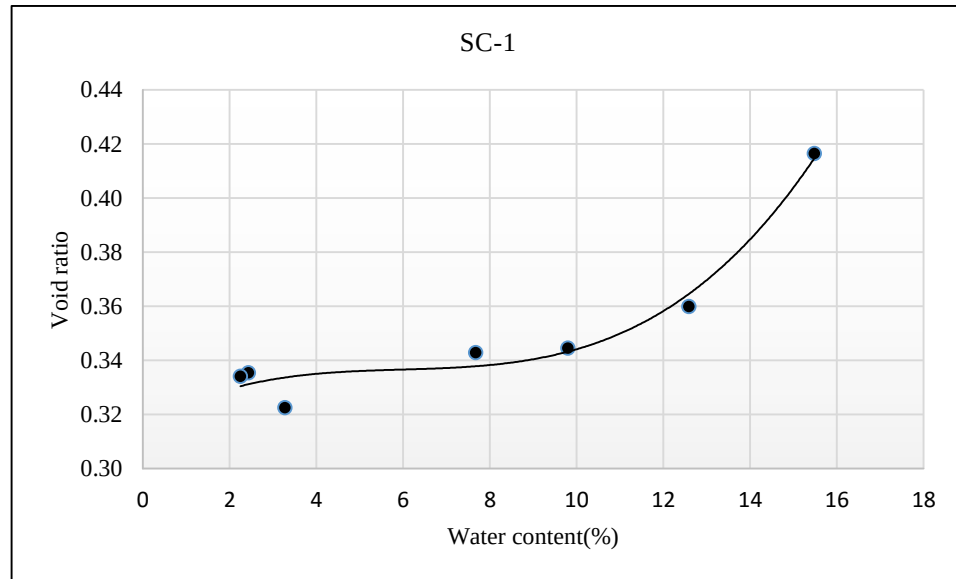


Figure 4.11 Soil SC-1 shrinkage characteristic curves determined with the digital method

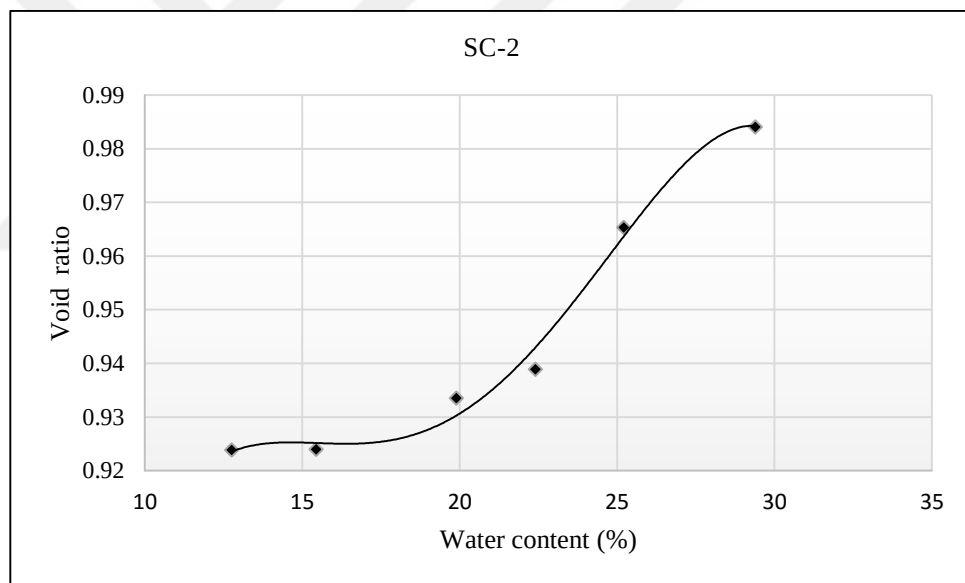


Figure 4.12 Soil SC-2 shrinkage characteristic curves determined with the digital method

Figure 4.10 indicated soil CH-2 shrinkage curve measurements. The obtained diagram shows the three shrinkage stages. From water content decreases from 33% to 28%, however the soil does not pose serious void reduction. In this first stage of shrinkage, the inner pores are emptied but, on the specimen, no significant volume changes were observed. In the second stage, soil volume decreases gradually as water

content reduces to 18.5%. In the third stage, as water disappearing from the pores, void reduction became stabilized.

Soil SC-1 shrinkage curve is illustrated in Figure 4.11. It shows that in this soil, volume changed immediately as water content is decreasing and by reaching to 10% volume remains un-altered while water content continues to decrease. In this soil, after nearly 3% water content reduction, volume change became steady and equilibrated to zero shrinkage stage.

For soil SC-2 the SSCC diagram was presented in Figure 4.12. Here is presented that volume of the specimens changed rapidly by losing water. The soil volume continuously decreased with decreasing water content until reaching to water content 20% and then the volume reduction became constant. The deviation in the void ratio of the tested soil mixtures during shrinkage was 0.99 to 0.92. No significant volume changes were observed in this specimen.

4.6 Volumetric Shrinkage Strain of Compacted Soil

Volumetric shrinkage strain results for both Caliper and digital measurements are expressed in Figure 4.13. Comparison of shrinkage strains for four compacted soil specimens were presented in percent.

At first glance, the observations that can be made from Figure 4.13 is that the obtained digital volumetric strains are higher than the manual volumetric measurement. It is obvious that the attained data are mostly above the line 1:1 that was drawn on the figure. It can be resulted that the digital volume evaluation provides accurate strain values. The volumetric strain values diverging from 1:1 line indicate that digital measurement method has successfully extracted the surficial anomalies arising from desiccation.

In a study that was conducted by Puppala et al. (2004), the obtained digital measurements strain results were observed higher than the manual measurements, similar to the achieved results in this study.

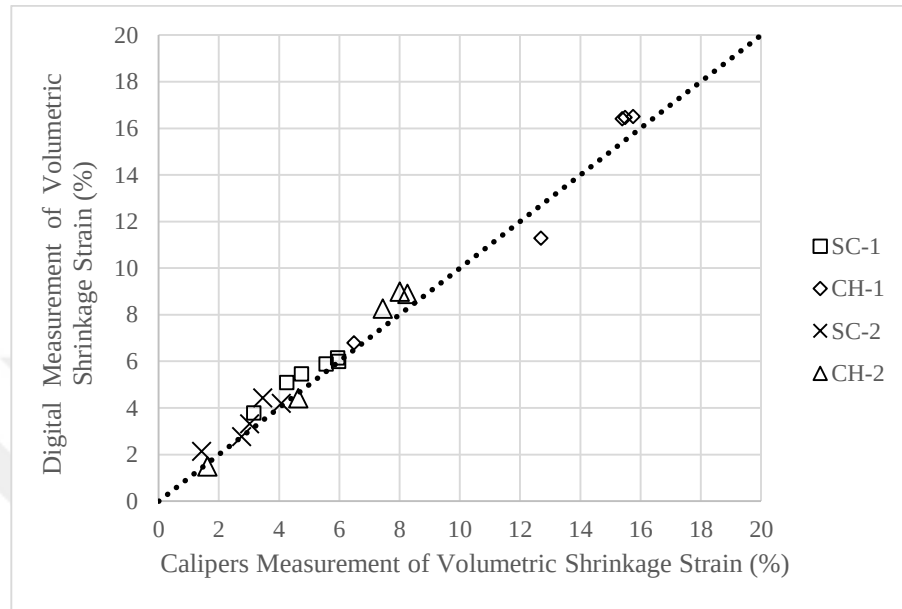


Figure 4.13 Comparisons between Calipers and digital volumetric shrinkage strains

It can be seen that the soil SC-2 has the best fit with the line 1:1. This indicates that both digital and manual methods have not significant distinction for this soil type. From the figure it can be noted that the clay soils have the higher strain magnitude. Soil CH-1 and CH-2 have wider strain value domains; acknowledge that due to the crack growing during desiccation there was significant void reduction in these soils.

One of the results that could be achieved is the soils, which shrank homogeneously have relatively similar results for both digital and manual measurements. However, because of the nonhomogeneous structure of some desiccated soils there is no significant correlation between digital and Vernier caliper measurements. According to this, manual measurements are not reliable for expansive and clay soils.

4.7 The Comparison of the Time Laps 3D Models of the Compacted Specimens

In order to quantify and visualize surficial changes occurred during drying stages, the comparison of the 3D cloud point models of the compacted soil specimens were made. To achieve this, the point clouds of the compacted soil specimens generated by Agisoft Metashape were imported in the CloudCompare software. CloudCompare is based on a PhD thesis and calculates the distances between two point clouds using complicated mathematical algorithms. Once distances are calculated, data can be visualized on the 3D point cloud in order to emphasize the variations between two clouds. For this purpose, several filters can be chosen such as RGB or grayscale presentation. After the calculation, data were presented over the cloud surfaces to visualize the differences. The software visualizes the high deviation with the color red in RGB color scheme. From Figure 4.13 through 4.31, the surface variation from the cloud comparison software were discussed. These figures of the soil specimens were illustrated from three different angles which are the top view, side view and isometric view.

The obtained cloud comparisons for soil SC-1 during the thirteen-day shrinkage are shown in Figures 4.14 through 4.18. Figure 4.14 shows the first-day shrinkage of the soil specimen. It can be observed that the height of the soil had decreased. Also, it appeared that the specimen had shrunk non-homogenously. The red color shows the higher deviation in comparison to other parts of the sample. The most considerable distance between the clouds is 0.34 cm (as seen in the red area), and the majority of the points are at a range lower than 0.0005 cm. The volume of the specimen was decreased 35.86 cm² in the first day of shrinkage process.

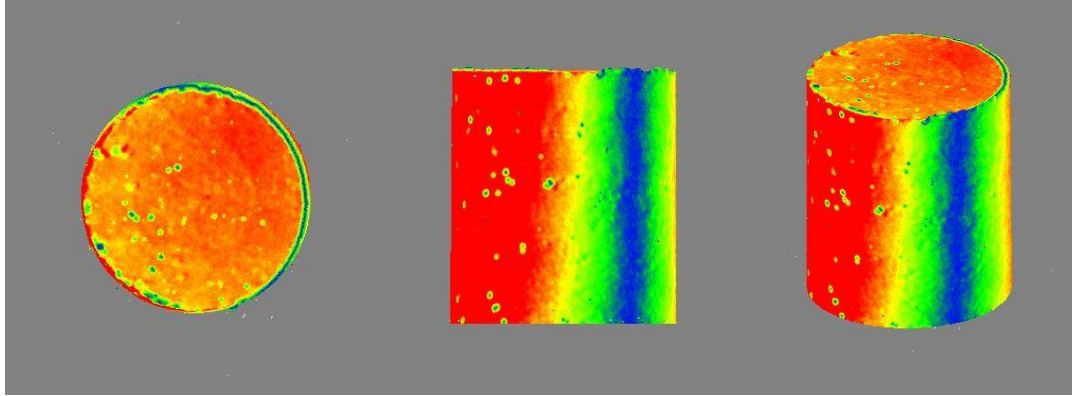


Figure 4.14 The cloud point comparison of specimen SC-1 for the first day of shrinkage

Cloud comparison for the second day of the shrinkage is presented in Figure 4.15. From the obtained graph, it can be observed that the specimen had shrunk mostly vertically. This can be easily noticed by the red area on the top of the specimen. There are not any significant changes in shrinkage compared from day two of the cloud with day three. The highest deviation value for this observation was 0.138 cm and the lowest was 0.00099945 cm. The volume was reduced 12.24 cm², respect to the previous day.

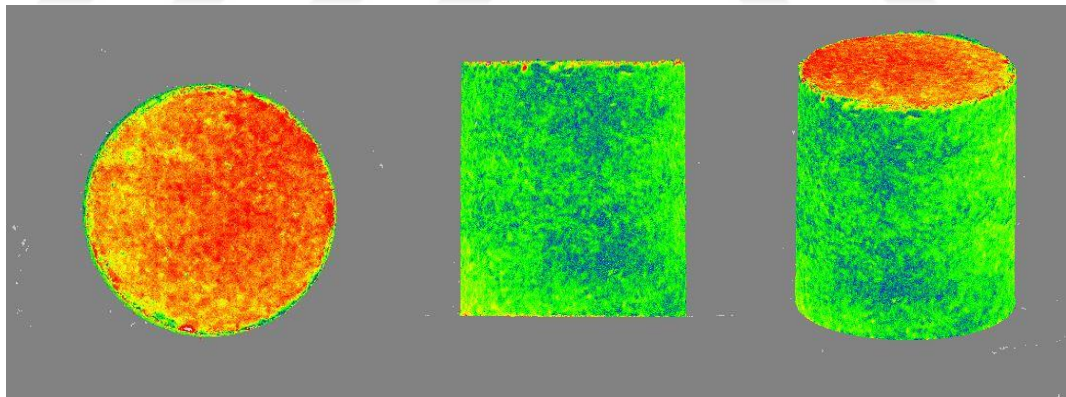


Figure 4.15 The cloud point comparison of specimen SC-1 for the second day of shrinkage

The cloud point comparison between second and the third days was illustrated in Figure 4.16. This figure shows that the specimen had barely shrunk but not from the height or from the sides. It has been already mentioned in Figure 4.8 that the volume of the soil did not have any significant change with respect to the previous day. The difference on the volume for this time period was only 3.46 cm². This deduction can

also be made by the grey color matrix shown in Figure 4.16. The maximum measured distance in this step is 0.075 cm.

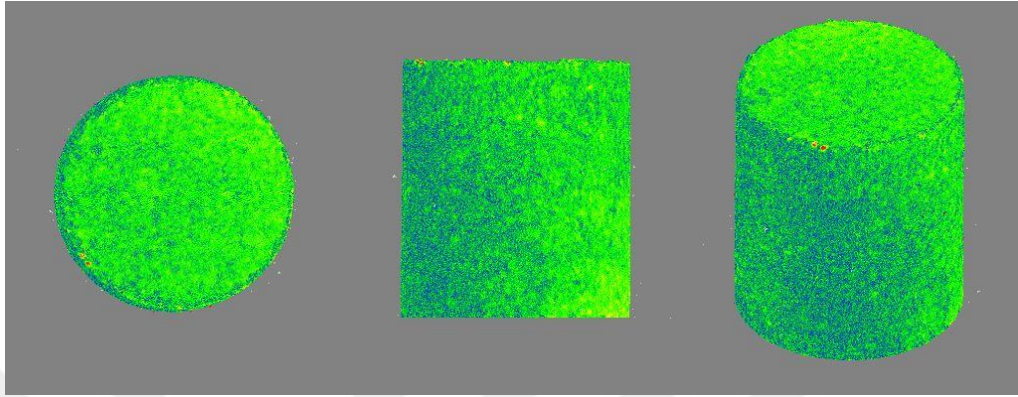


Figure 4.16 The cloud point comparison of specimen SC-1 for third day of shrinkage

Figure 4.17 and 4.18 shows the results obtained from a comparison analysis for the three to seven days and seven to thirteen days of shrinkage, respectively. The SSCC diagram for these soils indicates that they are in the residual phase. In this phase, the specimen does not pose meaningful volume changes. The volume differences obtained as 1.35 cm^2 . According to the acquired data from the cloud comparisons of the specimens and during the final hours of shrinkage, the maximum distance variation for day seven was 0.04 cm, and for day thirteen, the same value was 0.037 cm.

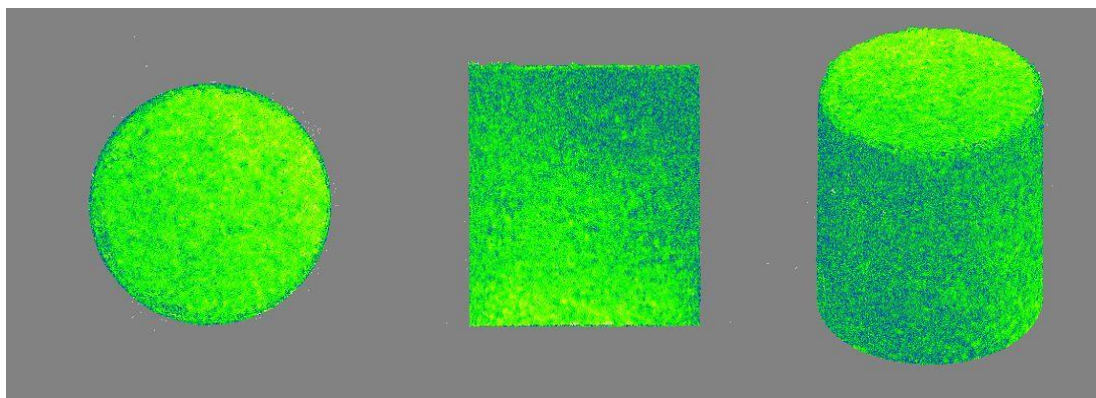


Figure 4.17 The cloud point comparison of specimen SC-1 for the third and seventh day of shrinkage

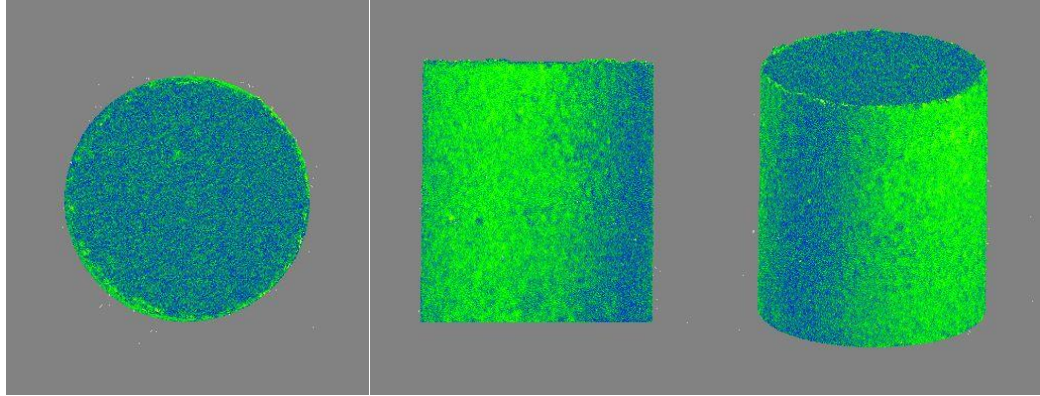


Figure 4.18 The cloud point comparison of specimen SC-1 for the seventh and thirteenth day of shrinkage

Cloud comparison observation for soil SC-2 is represented in Figures 4.19 through 4.23 for ten-days shrinkage period. In the first day of soil specimen desiccation, the highest distance variation, shown as red areas was observed in the height of the soil as shown in Figure 4.19. The maximum and minimum obtained deviation values are 0.17 cm and 0.009945 cm. At this stage the volume decreased by 8.97 cm³.

The deviations between the first and second day of drying can be seen in some areas of the specimen in Figure 4.20. According to the blue color on the cloud surface, one can deduce that no significant change was evident at this stage. The crack development of the specimen can be observed in green points on the surface of the 3D model cloud. The highest attained deflection value on the second and third day is 0.04 cm and 0.08 cm. The variation in volume is 5.96 cm³.

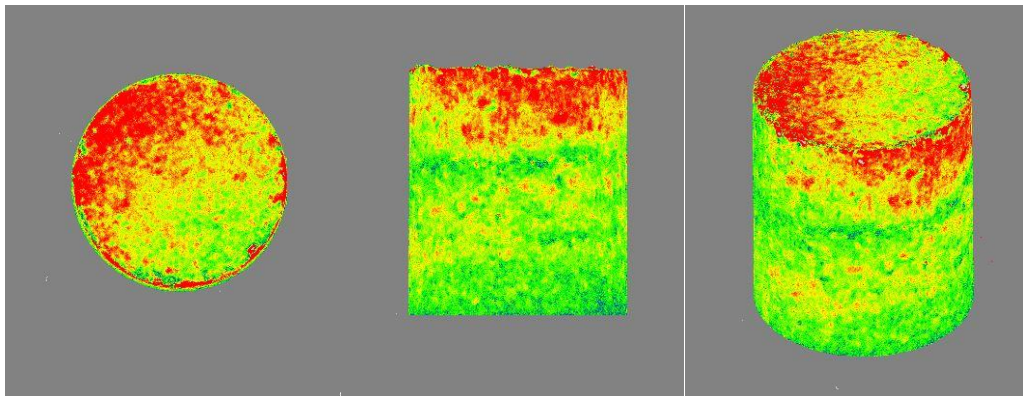


Figure 4.19 The cloud point comparison of specimen SC-2 for first day of shrinkage

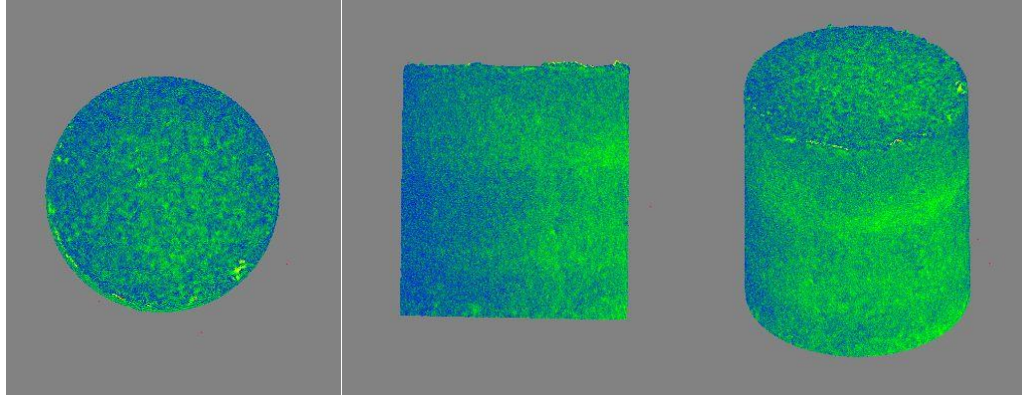


Figure 4.20 The cloud point comparison of specimen SC-2 for second day of shrinkage

On the other hand, the deviations between the second and third day of drying can be seen in some areas of the specimen in Figure 4.21. No significant deviation was observed also at this stage according to the green to blue areas on the surface of the soil specimen. The crack development was observed further in green points on the surface of the 3D model cloud. The highest attained deflection value on the second and third day is 0.04 cm and 0.08 cm. The volume variation is 5.96 cm² and 5.17.

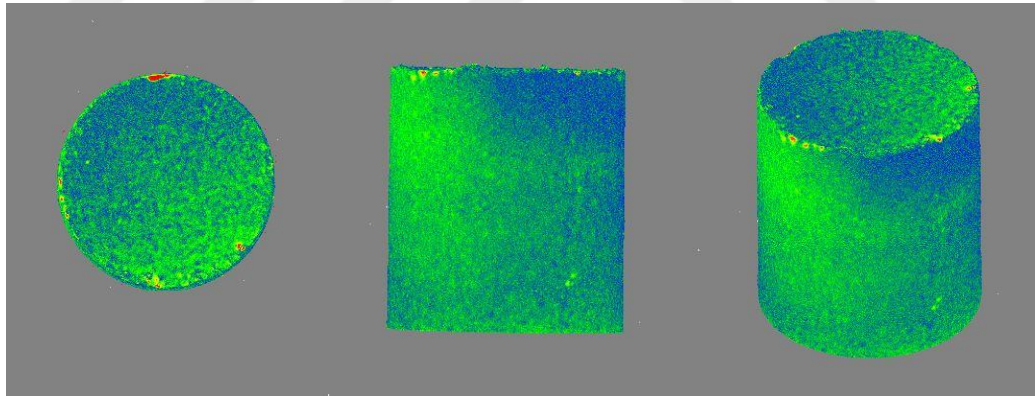


Figure 4.21 The cloud point comparison of specimen SC-2 for second and third day of shrinkage

The compacted soil specimen shrinkage process had been sustained until sixth desiccation day. At this stage, the specimen shrunk nonhomogeneous. In red color areas, the maximum attained distance is 0.18 cm. According to volume change versus time diagram (Figure 4.6), the specimen volume decreased by 10.51 cm². It can be seen that the height of the sample shortened non-homogeneously. In the final shrinkage monitoring day (10th day), soil height drops off according to Figure 4.23 and volume was reduced 2.18 cm².

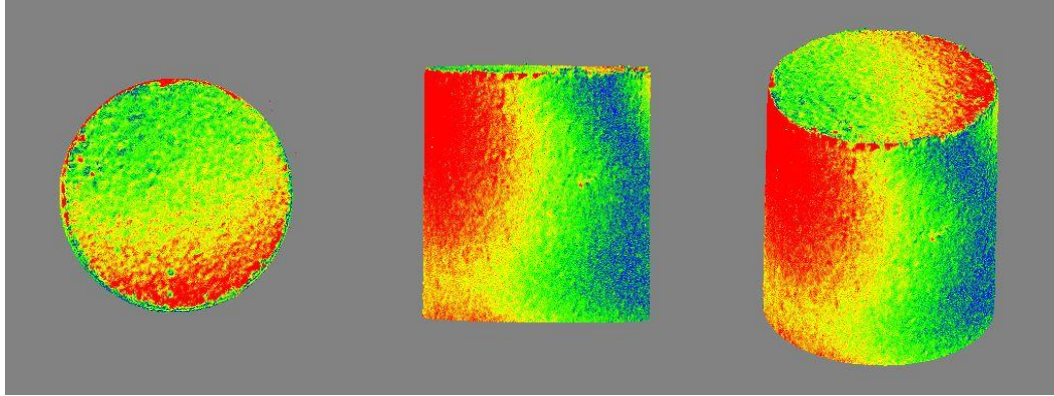


Figure 4.22 The cloud point comparison of specimen SC-2 for third and sixth day of shrinkage

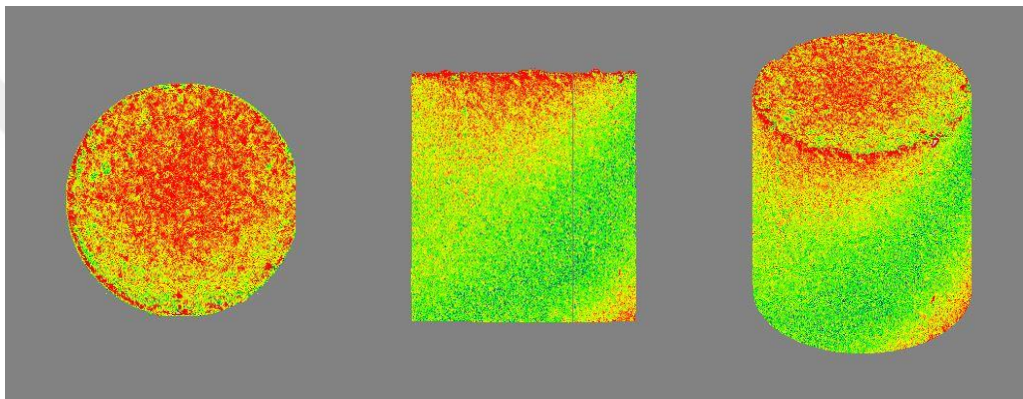


Figure 4.23 The cloud point comparison of specimen SC-2 for sixth and tenth day of shrinkage

Cloud comparisons for soil CH-1 were demonstrated in Figures 4.24 throw 4.28. After the initial day of shrinkage, the sample height decreased distinctly. The center of the sample barely shrunk, as represented by the green color on its surface. In comparison with the cylindrical mold and the initial day of cloud shrinkage, the lower part of the sample did not have a significant difference in distance. The highest decreased value for the first day is 0.36 cm. Through the second day of desiccation, the compacted specimen had not shrunk homogenously. The volume deduction was observed mostly at the top part of the specimen (Figure 4.24). The red surface color signifies the most surface variation and the yellow and green colors show a low amount of decrease in value, as mentioned before with the blue color representing minimal decrease in surface deviation value. The reduction in the specimen height had continued. The maximum surface difference was achieved as 0.22 cm. The volume differences are 59.84 cm² and 42.44 cm² respectively.

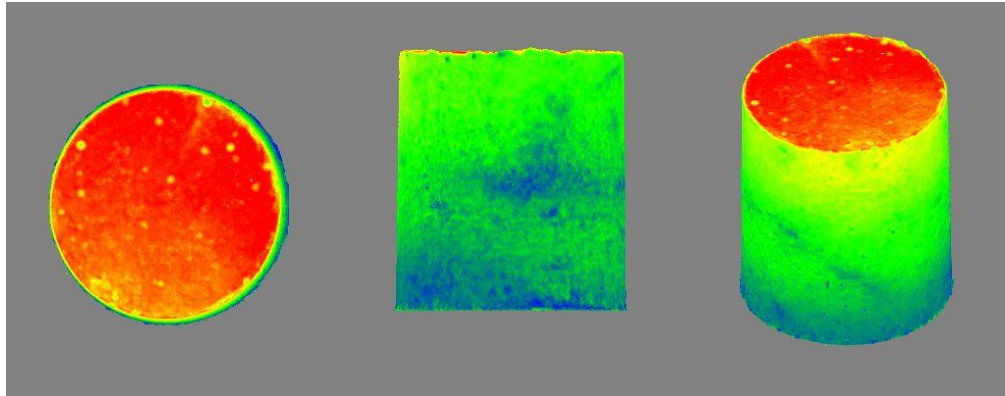


Figure 4.24 The cloud point comparison of specimen CH-1 for first day of shrinkage

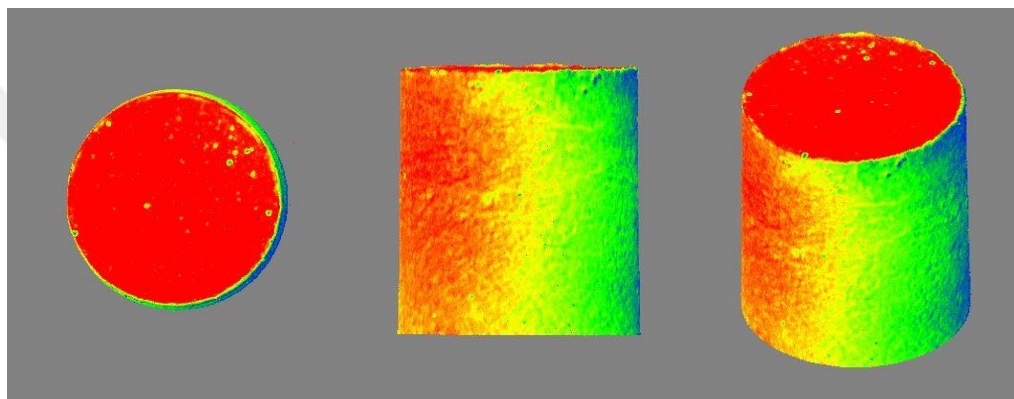


Figure 4.25 The cloud point comparison of specimen CH-1 for first and second day of shrinkage

As Figure 4.26 indicates, the shrinkage on the fifth day, the specimen shrinkage continued similarly through the second day of desiccation, the height of the specimen still continued to decrease. In this manner, the maximum cloud difference for the fifth-day desiccation is 0.25 cm, the volume reduction being recorded as 48.88 cm².

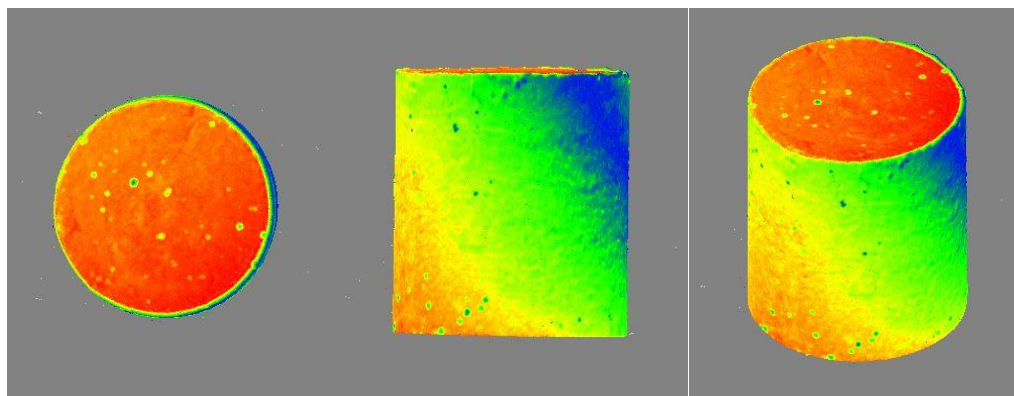


Figure 4.26 The cloud point comparison of specimen CH-1 for third and fifth day of shrinkage

Figure 4.27 and 4.28 show the cloud of the shrinkage process at the time of shrinkage on day eight and day eleven. The blue points indicate that there is no change in strain changes on those surfaces. The green color points indicate the constant change in surface strain. In both samples, the dimensions did not reduce homogeneously and shrinkage had continued on one side of the soil. Volume decreased as 0.54 cm^2 and 1 cm^2 in eighth and eleventh day of shrinkage respectively.

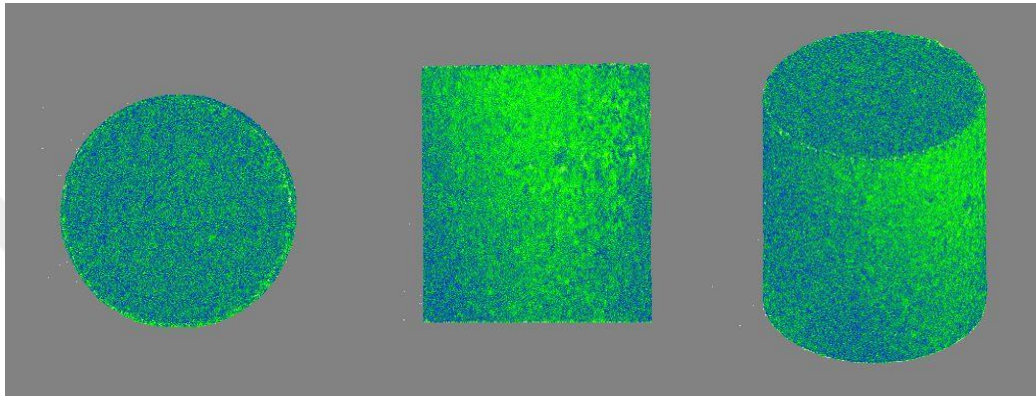


Figure 4.27 The cloud point comparison of specimen CH-1 for fifth and eighth day of shrinkage

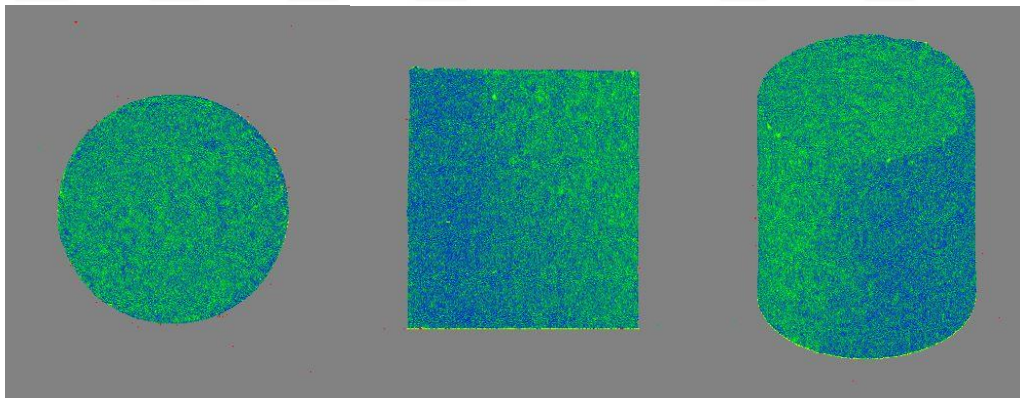


Figure 4.28 The cloud point comparison of specimen CH-1 for eighth and eleventh day of shrinkage

The cloud comparisons of the compacted soil CH-2 are presented in Figures 4.29 throw 4.33. Uniform dimension change could not be observed in Figure 4.29. One part of the specimen shrunk whereas another part of the sample including the top of the soil did not have significant changes. As it can be observed, the shrinkage cracks occurred after day one of the desiccation period. The maximum difference occurred as 0.24 cm . Volume reduction is 23.51 cm^2 .

Figure 4.30 shows that the crack development commenced in the second day of shrinkage. The crack took place in the lower part of the compacted soil. Sample elevation decreased. The maximum surface difference obtained at 0.11 cm. In Figure 4.31, it can be seen that soil specimen volume decreased mostly from the top of the sample, and the maximum elevation difference measured as 0.15 cm. On the final day of monitoring, the compacted soil did not particularly shrink. Figure 4.32 shows that the height had not stopped decreasing. Volume decreased by 27.64 cm². The highest surface distance was calculated as 0.17 cm by comparing the clouds.

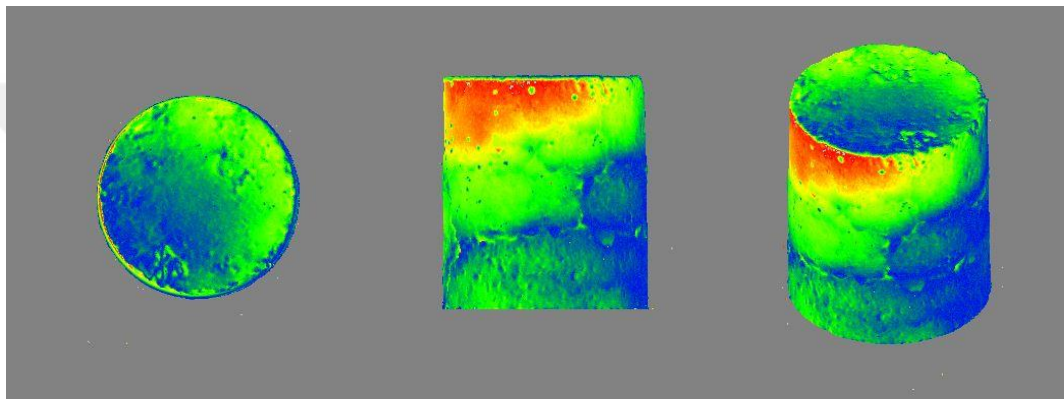


Figure 4.29 The cloud point comparison of specimen CH-2 for first day of shrinkage

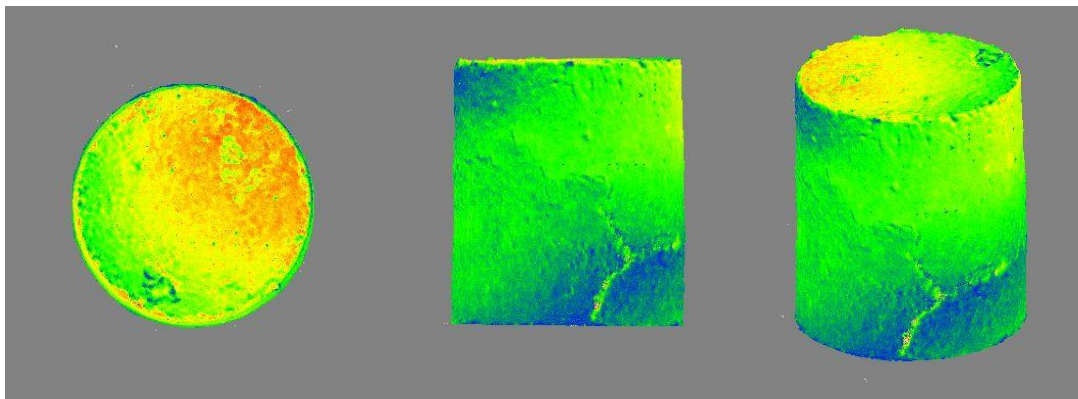


Figure 4.30 The cloud point comparison of specimen CH-2 for first and second day of shrinkage

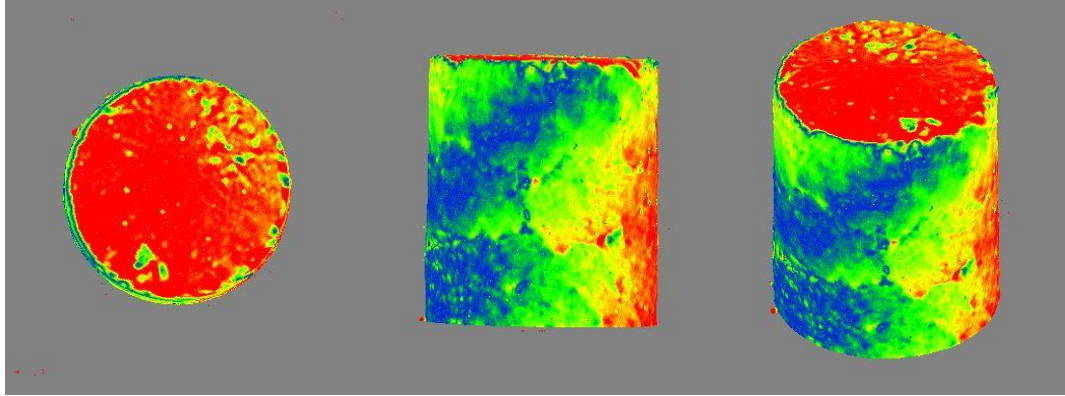


Figure 4.31 The cloud point comparison of specimen CH-2 for second and fifth day of shrinkage

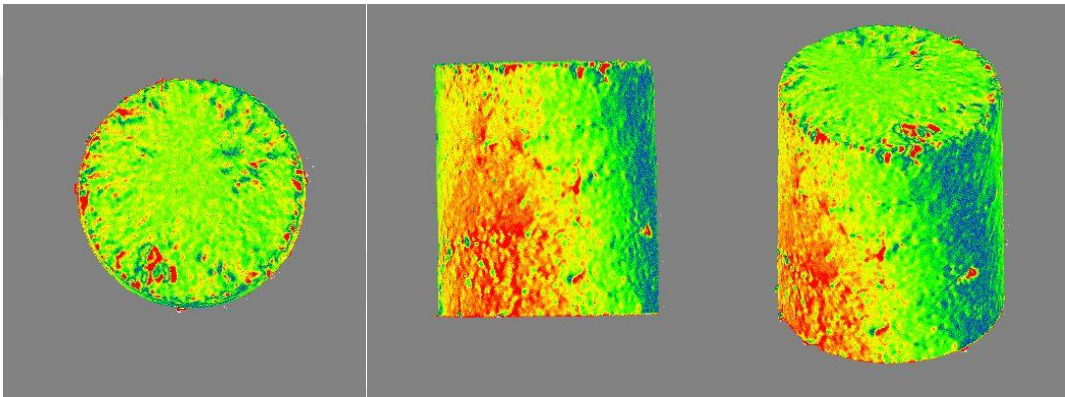


Figure 4.32 The cloud point comparison of specimen CH-2 for fifth and eighth day of shrinkage

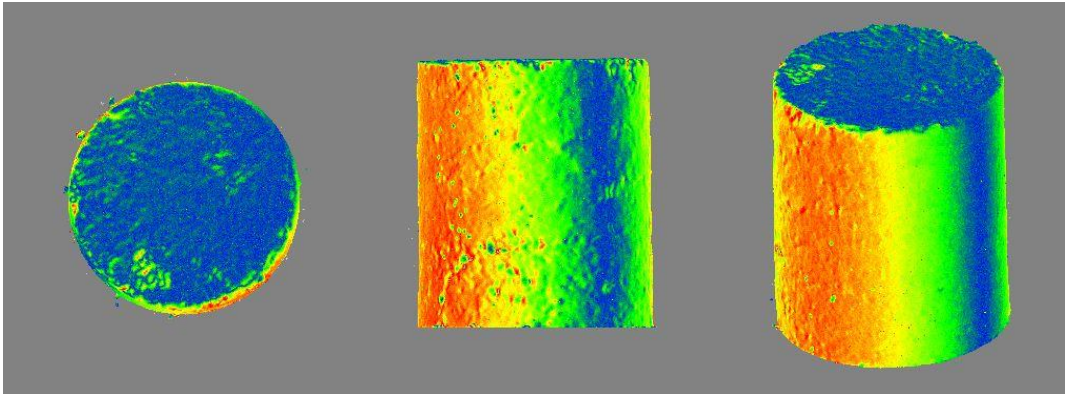


Figure 4.33 The cloud point comparison of specimen CH-2 for eighth and sixteenth day of shrinkage

Crack formation was observed in desiccated soils in Figures 4.20, 4.29, 4.30 and 4.31. Crack patterns typically appeared over the compacted layers. These crack formations on the compacted layers can be associated with the non-homogeneous distribution of the compaction effort in the vertical direction (Figure 4.34). In addition, Sánchez et al. in 2014 asserted that the crack formation emerged with an increase of

tensile stress during desiccation, and the soil cracks propagated whenever the stresses exceeded soil tensile strength.

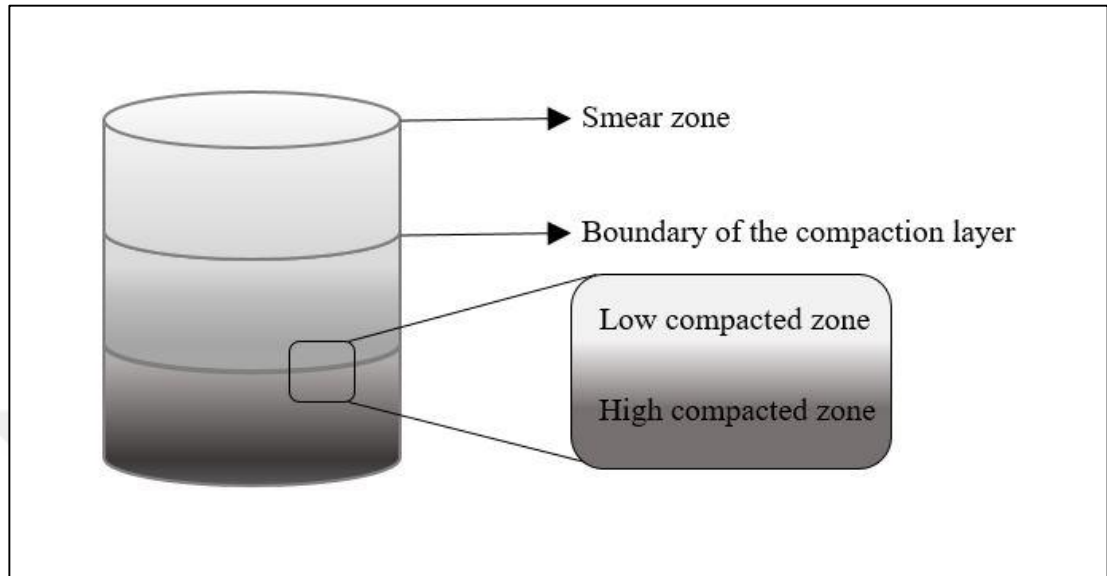


Figure 4.34 Distribution of the compaction effort in layers

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

As a result, the following conclusions can be summarized:

- Comparison of the digital measurements with those of the manual caliper readings for compacted soil specimens showed that operator error is highly possible during caliper readings.
- The volumetric shrinkages of the compacted specimens were successfully monitored by using the proposed technique.
- A significant difference between manual and digital evaluation method were observed for the soils that desiccated non-homogenously.
- It was observed that as the shrinkage progressed, in some soils the volume values for digital and manual methods become distant, this can be attributed to the irregular volumetric shrinkage and progressing cracks during desiccation.
- The volume of the soil specimens that were compacted with modified effort has lower value respect to the soils that were compacted with standard effort in Archimedes setup. In modified compacted soils, because of the increased matric suction, macro voids were prevalent. The wax penetration into these macro voids resulted a lower volume evaluation in Archimedes method.
- The non-homogenous shrinkage of the compacted specimens was successfully detected and quantified by point cloud comparisons. Also, the visualization of the shrinkage strains using coloring the distance magnitude, provided deeper understanding on the shrinkage progressing for the layered compacted specimens. These features are unique for the proposed methodology and was not possible using conventional methods.

- The implementation of the SfM method has found to be advantageous for the determination of the bulk densities of the irregular shaped bulk soil specimens in geotechnical laboratories.
- Conventional wax coating method contains health hazard and it is time consuming. The proposed method in this study results in a nondestructive way to obtain accurate volumetric properties of laboratory bulk specimens.
- In the determination of the bulk density both for rock specimen and bulk soils, the rock specimen has lower error than the bulk soils. The pore structure of the specimens affected the obtained errors.
- Wax also has expansive behavior, and it is observed that cohesive bounds between soil particles at the border of the specimen may subject to disturbance due to the hardening of the paraffin wax.
- The implemented technique was found to be promising for the nondestructive determination of the volumetric properties of soil specimens. Since the SFM technique is nondestructive, the implementation of this technique allows researchers to conduct further laboratory tests with the same specimen.
- In this digital measurement technique, images can be taken with an off the shelf low-cost camera with moderate pixel density.
- In order to process the images rapidly, proposed technique requires high-performance computer hardware. In various steps of the 3D construction process, software needed good cooperation between CPU and graphic cards. The graphic cards (GPU) processing capacity is a dominant factor for the duration of the process. Therefore, a computer, having 2 high-end graphics processors was chosen for this study. However, the same precision is achievable with moderate computer systems with a longer processing time.

- The cylindrical calibration object has the minimum error in the comparison of the digital and manual methods. This reason can be originated from the detailed surface and rigid structure of the object.

These recommendations can be considered for future studies:

- This technique may be utilized as an auxiliary tool in the development of a new laboratory compaction apparatus.
- By using this proposed methodology 3D surface of the soil samples can be generated and then numerical analysis can be applied.
- This technique can be used to monitor the triaxle test to the assessing failure modes of soil specimen and determine the progress of deformation

REFERENCES

- Acar, Y. B., & Olivieri, I. (1989). Pore fluid effects on the fabric and hydraulic conductivity of laboratory-compacted clay. *Transportation Research Record*, 1219,144-159.
- ASTM Committee D-18 on Soil and Rock. (2017). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*1. ASTM international.
- ASTM Committee D-18 on Soil and Rock. (2007). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 Ft-lbf/ft³ (600 KN-m/m³)* 1. ASTM international.
- ASTM Committee D-18 on Soil and Rock. (2009). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 Ft-lbf/ft³ (2,700 KN-m/m³))* 1. ASTM International.
- Benson, C. H., & Daniel, D. E. (1990). Influence of clods on the hydraulic conductivity of compacted clay. *Journal of Geotechnical Engineering*, 116(8), 1231-1248.
- Berndt, R. D., & Coughlan, K. J. (1977). The nature of changes in bulk density with water content in a cracking clay. *Australian Journal of Soil Research*, 15(1), 27–37.
- Brasher, B. R., Franzmeier, D. P., Valassis, V., & Davidson, S. E. (1966). Use of saran resin to coat natural soil clods for bulk-density and water-retention measurements. *Soil Science*, 101(2), 108.
- Fischler, M. A., & Bolles, R. C. (1981). Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM*, 24(6), 381-395.

- Förstner, W. (1993). Feature extraction in digital photogrammetry. *The photogrammetric record*, 14(82), 595–611.
- Freund, M. (1982). *Paraffin products: properties, technologies, applications*, 14. New York: Elsevier Science Limited.
- Garcia-Bengochea, I., Altschaeffl, A. G., & Lovell, C. W. (1979). Pore distribution and permeability of silty clays. *Journal of the Geotechnical Engineering Division*, 105(7), 839-856.
- Gonzalez, R. C., & Woods, R. E. (2002). *Digital image processing*, New Jersey: Prentice Hall.
- Gapak, Y., Das, G., Yerramshetty, U., & Bharat, T. V. (2017). Laboratory determination of volumetric shrinkage behavior of bentonites: A critical appraisal. *Applied Clay Science*, 135, 554–566.
- Lauritzen, C. W., & Stewart, A. J. (2010). Soil-volume changes and accompanying moisture and pore-space relationships1. *Soil Science Society of America Journal*, 6(C), 113.
- Li, L., & Zhang, X. (2018). A new approach to measure soil shrinkage curve. *Geotechnical Testing Journal*, 42(1), 1–18.
- Lowe, D. G. (1999). Object recognition from local scale-invariant features. In *International Conference on Computer Vision*, Corfu, Greece, 1150–1157.
- Lowe, D. G. (2004). Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision*, 60(2), 91-110.

- Moret-Fernández, D., Latorre, B., Peña, C., González-Cebollada, C., & López, M. V. (2016). Applicability of the photogrammetry technique to determine the volume and the bulk density of small soil aggregates. *Soil Research*, 54(3), 354–359.
- Matthews, N.A., 2008. *Aerial and close-range photogrammetric technology: providing resource documentation, interpretation, and preservation*. Technical Note, 428. Bureau of Land Management, Denver, Colorado.
- Note, M. (2014). Digital image basics. In *Managing Image Collections* 39–59. Oxford:Chandos Publishing.
- Ören, A. H., Önal, O., Özden, G., & Kaya, A. (2006). Nondestructive evaluation of volumetric shrinkage of compacted mixtures using digital image analysis. *Engineering Geology*, 85(3–4), 239–250.
- Porter, S. T., Roussel, M., & Soressi, M. (2016). A simple photogrammetry rig for the reliable creation of 3D artifact models in the field: lithic examples from the Early Upper Paleolithic sequence of Les Cottés (France). *Advances in Archaeological Practice*, 4(1), 71-86.
- Prapaharan, S., White, D. M., & Altschaeffl, A. G. (1991). Fabric of field-and laboratory-compacted clay. *Journal of Geotechnical Engineering*, 117(12), 1934-1940.
- Puppala, A. J., Katha, B., & Hoyos, L. R. (2004). Volumetric shrinkage strain measurements in expansive soils using digital imaging technology. *Geotechnical Testing Journal*, 27(6), 547-556.
- Riesen, R., & Widmann, G. (1984). Thermoanalyse Anwendungen, Begriffe, Methoden. *Food/Nahrung*, 29(8), 812-812.

- R.N. Yong, B.P. Warkentin (1975). *Soil properties and behaviour*. Amsterdam: Elsevier.
- Sánchez, M., Manzoli, O. L., & Guimarães, L. J. N. (2014). Modeling 3-D desiccation soil crack networks using a mesh fragmentation technique. *Computers and Geotechnics*, 62, 27–39.
- Sarıavcı, Ç. (2016). *Stabilizing meles delta soils and monitoring the bonding structures using SEM and XRD analyses*. M.Sc Thesis, Dokuz Eylül University, İzmir.
- Schimmelpfennig, M., Weber, K., Kalb, F., Feller, K. H., Butz, T., & Matthäi, M. (2007). Volume expansion of paraffins from dip tube measurements. *Jahrbuch fuer den Praktiker*, 417-429.
- Stewart, R. D., Abou Najm, M. R., Rupp, D. E., & Selker, J. S. (2012). An image-based method for determining bulk density and the soil shrinkage curve. *Soil Science Society of America Journal*, 76(4), 1217-1221.
- Tang, C. S., Shi, B., Liu, C., Suo, W. B., & Gao, L. (2011). Experimental characterization of shrinkage and desiccation cracking in thin clay layer. *Applied Clay Science*, 52(1-2), 69-77.
- Tariq, A.-U.-R., & Durnford, D. S. (2006). Soil volumetric shrinkage measurements. *Soil Science*, 155(5), 325–330.
- Tinjum, J. M., Benson, C. H., & Blotz, L. R. (1997). Soil-water characteristic curves for compacted clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(11), 1060-1069.

Ukrainczyk, N., Kurajica, S., & Šipušić, J. (2010). Thermophysical comparison of five commercial paraffin waxes as latent heat storage materials. *Chemical and Biochemical Engineering Quarterly*, 24(2), 129-137.

Westoby, M. J., J. Brasington, N. F. Glasser, M. J. Hambrey, and J. M. Reynolds. (2012) Structure-from-Motion photogrammetry: A low-cost, effective tool for geoscience applications *Geomorphology*, 179, 300- 314.

Yi, G., Jianxin, L., Hangping, Q., & Bo, W. (2014). Survey of structure from motion. In *Proceedings of 2014 International Conference on Cloud Computing and Internet of Things, CCIOT* 72–76. Institute of Electrical and Electronics Engineers Inc.

APPENDICES

Appendix _ A: Sieve analysis

Table A.1 SC-1 Sieve analysis

Initial Dry Weight (gr): 468					
(Sieve No)		(Weight Retained)	(Cumulative Wt. Retained)	(% Retained)	(% Passing)
	Sieve Size (mm)	gr	gr	%	%
1"	25	0.00	0.00	0.00	100.00
1/2"	12.5	50.25	50.25	10.75	89.25
No.4	4.75	80.48	130.73	27.96	72.04
No.10	2	55.85	186.58	39.91	60.09
No.16	1.18	26.60	213.18	45.59	54.41
No.40	0.425	45.37	258.55	55.30	44.70
No.80	0.18	37.51	296.06	63.32	36.68
No.200	0.076	35.65	331.71	70.94	29.06
Pan :		135.85	467.56	100.00	0.00

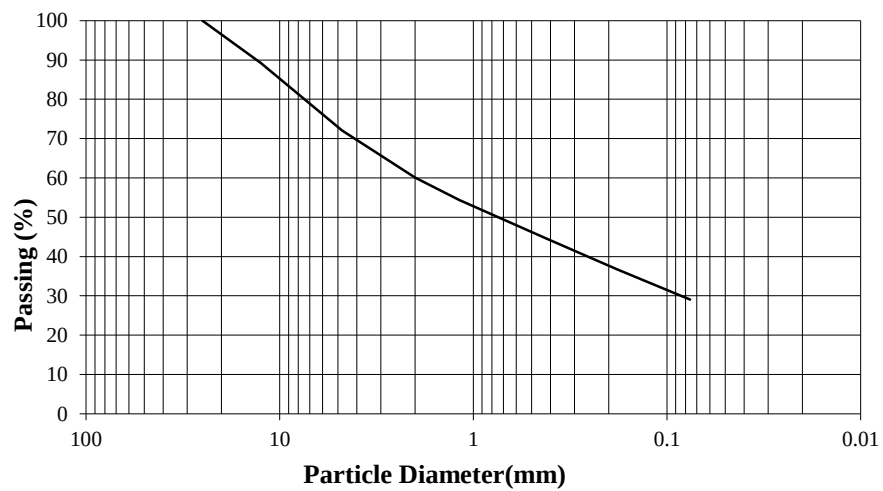


Figure A.1 Soil SC-1 sieve analysis diagram

Table A.2 SC-2 Sieve analysis

Initial Dry Weight (gr) : 352					
(Sieve No)		(Weight Retained)	(Cumulative Wt. Retained)	(% Retained)	(% Passing)
	Sieve Size (mm)	gr	gr	%	%
3"	63	0.00	0.00	0.00	100.00
2"	50	0.00	0.00	0.00	100.00
1"	25	0.00	0.00	0.00	100.00
1/2"	12.5	0.00	0.00	0.00	100.00
No.4	4.75	0.00	0.00	0.00	100.00
No.10	2	3.65	3.65	0.73	99.97
No.40	0.425	49.89	14.90	10.11	89.89
No.200	0.076	287.46	338	67.60	32.40
Pan :		162	500	100.00	0.00

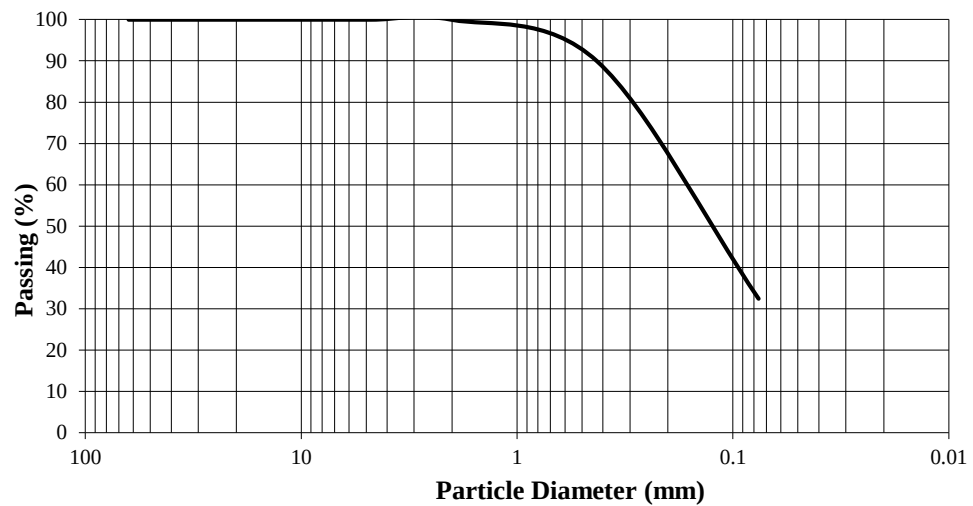


Figure A.2 Soil SC-2 sieve analysis diagram

Table A.3 CH-1 Sieve analysis

Initial Dry Weight (gr): 487					
(Sieve No)		(Weight Retained)	(Cumulative Wt. Retained)	(% Retained)	(% Passing)
	Sieve Size (mm)	gr	gr	%	%
3"	63	0.00	0.00	0.00	100.00
2"	50	0.00	0.00	0.00	100.00
1"	25	0.00	0.00	0.00	100.00
1/2"	12.5	0.00	0.00	0.00	100.00
No.4	4.75	0.85	0.85	0.17	99.83
No.10	2	6.89	7.74	1.59	98.41
No.40	0.425	13.61	21.35	4.39	95.61
No.200	0.076	29.30	50.65	10.40	89.60
Pan :		436.14	486.79	100.00	0.00

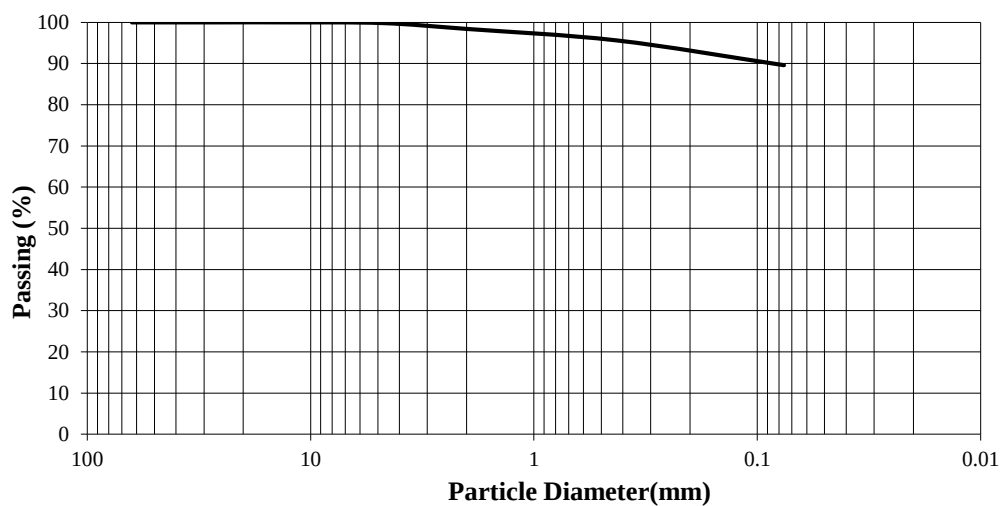


Figure A.3 Soil CH-1 sieve analysis diagram

Table A.4 CH-2 Sieve analysis

Initial Dry Weight (gr) : 352					
(Sieve No)		(Weight Retained)	(Cumulative Wt. Retained)	(% Retained)	(% Passing)
	Sieve Size (mm)	gr	gr	%	%
3"	63	0.00	0.00	0.00	100.00
2"	50	0.00	0.00	0.00	100.00
1"	25	0.00	0.00	0.00	100.00
1/2"	12.5	0.00	0.00	0.00	100.00
No.4	4.75	0.00	0.00	0.00	100
No.10	2	0.2	0.2	0.06	99.94
No.40	0.425	14.70	14.90	4.23	95.77
No.200	0.076	44.80	59.70	16.94	83.06
Pan :		292.72	352.42	100.00	0.00

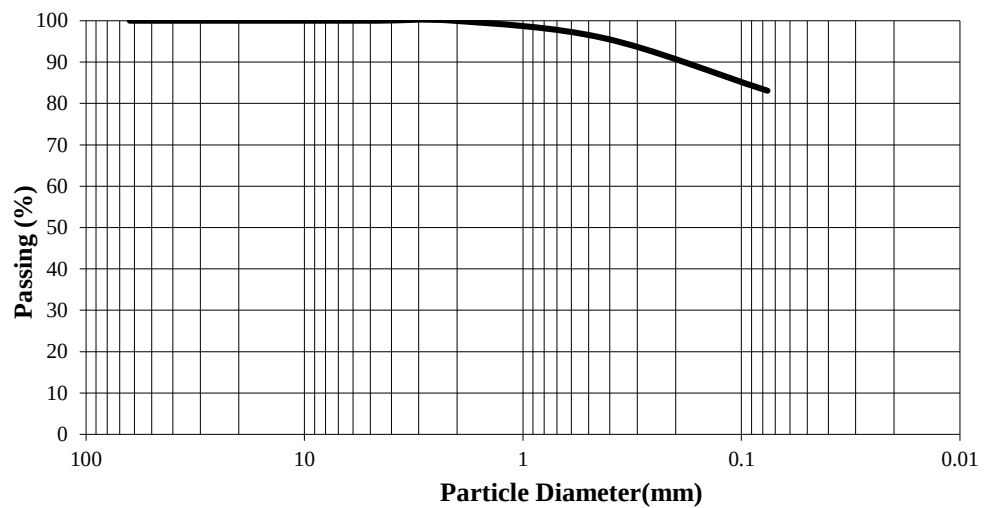


Figure A.4 Soil CH-2 sieve analysis diagram

APPENDIX_B: Consistency Limits

Table B.1 SC-1 Liquid limits

Liquid Limit Determination	1	2	3	4	5	6
Cup No	90	120	95	130	145	148
Cup + Wet Sample Weight (g)	44.23	42.52	45.74	42.95	49.33	42.12
Cup + Dry Sample Weight (g)	37.62	36.09	38.50	36.27	40.77	35.27
Water Weight (g)	6.61	6.43	7.24	6.68	8.56	6.85
Cup Weight (g)	17.84	17.73	18.12	18.15	18.54	17.79
Dry Sample Weight (g)	19.78	18.36	20.38	18.12	22.23	17.48
Water Content w (%)	0.33	0.35	0.36	0.37	0.39	0.39
Cone Penetration mm	14.30	16.80	17.50	19.70	21.50	25.30

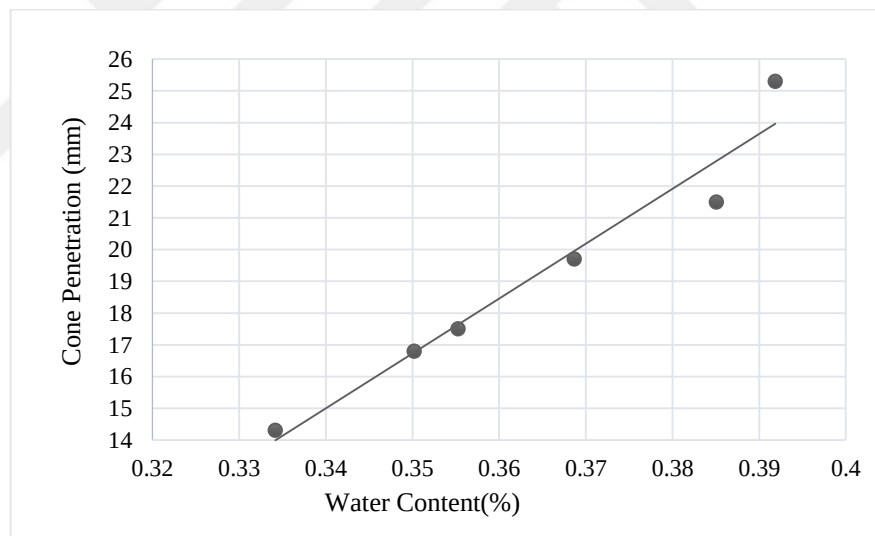


Figure B.1 Cone penetration

Table B.2 SC-1 Plastic limits

Determination of Plastic Limit	1	2	3
Cup No	43	61	93
Cup + Wet Sample Weight (g)	11.93	10.17	12.10
Cup + Dry Sample Weight (g)	11.54	9.99	11.57
Water Weight (g)	0.39	0.18	0.53
Cup Weight (g)	8.95	8.93	8.43
Dry Sample Weight (g)	2.59	1.06	3.14
Water Content w (%)	0.15	0.17	0.17

Table B.3 SC-2 Liquid limits

Liquid Limit Determination	1	2	3	4	5
Cup No	1	93	175	23	48
Cup + Wet Sample Weight (g)	35.27	41.83	35.84	38.48	46.52
Cup + Dry Sample Weight (g)	27.67	31.3	28.04	29.02	33.4
Water Weight (g)	7.60	10.53	7.80	9.46	13.12
Cup Weight (g)	18.39	18.58	19.26	18.47	18.87
Dry Sample Weight (g)	9.28	12.72	8.78	10.55	14.53
Water Content w (%)	0.82	0.83	0.89	0.90	0.90
Cone Penetration mm	15.50	17.40	19.80	22.20	24.10

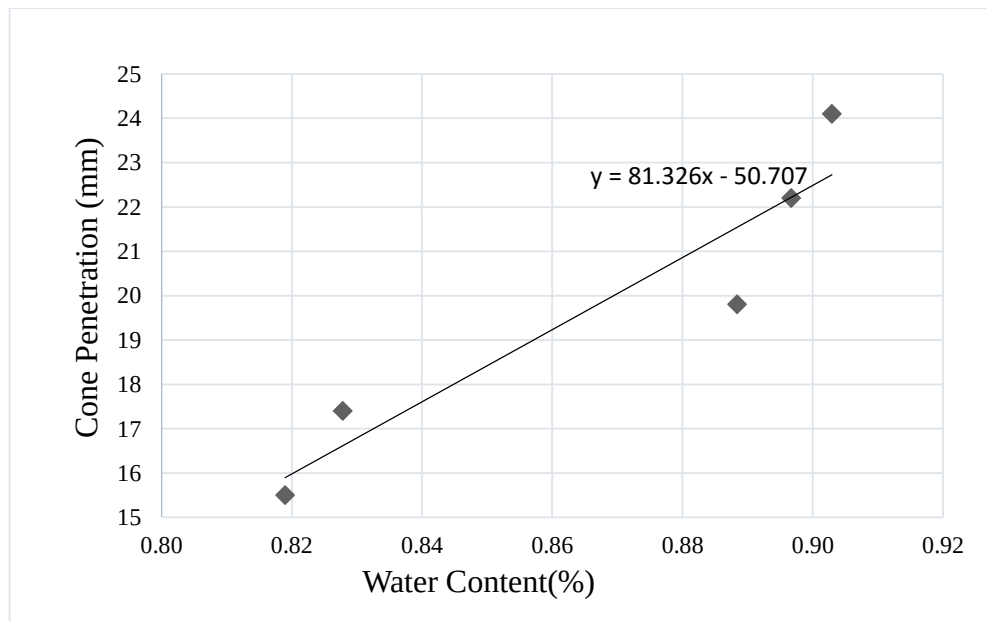


Figure B.2 SC-2 Cone penetration

Table B.4 SC-2 Plastic limit

Determination of Plastic Limit	1	2	3
Cup No	26	64	13
Cup + Wet Sample Weight (g)	9.80	9.32	9.60
Cup + Dry Sample Weight (g)	9.54	9.06	9.31
Water Weight (g)	0.26	0.26	0.29
Cup Weight (g)	8.70	8.32	8.48
Dry Sample Weight (g)	0.84	0.74	0.83
Water Content w (%)	0.31	0.35	0.35

Table B.5 CH-1 Liquid limits

Liquid Limit Determination	1	2	3	4	5	6
Cup No	101	75	137	144	36	18
Cup + Wet Sample Weight (g)	37.32	38.20	37.08	40.12	36.55	36.05
Cup + Dry Sample Weight (g)	30.91	30.73	30.11	31.64	29.58	29.05
Water Weight (g)	6.41	7.47	6.97	8.48	6.97	7.00
Cup Weight (g)	18.82	17.27	18.09	17.44	18.27	18.12
Dry Sample Weight (g)	12.09	13.46	12.02	14.20	11.31	10.93
Water Content w (%)	0.53	0.55	0.58	0.60	0.62	0.64
Cone Penetration mm	15.40	16.80	19.50	20.90	21.90	24.00

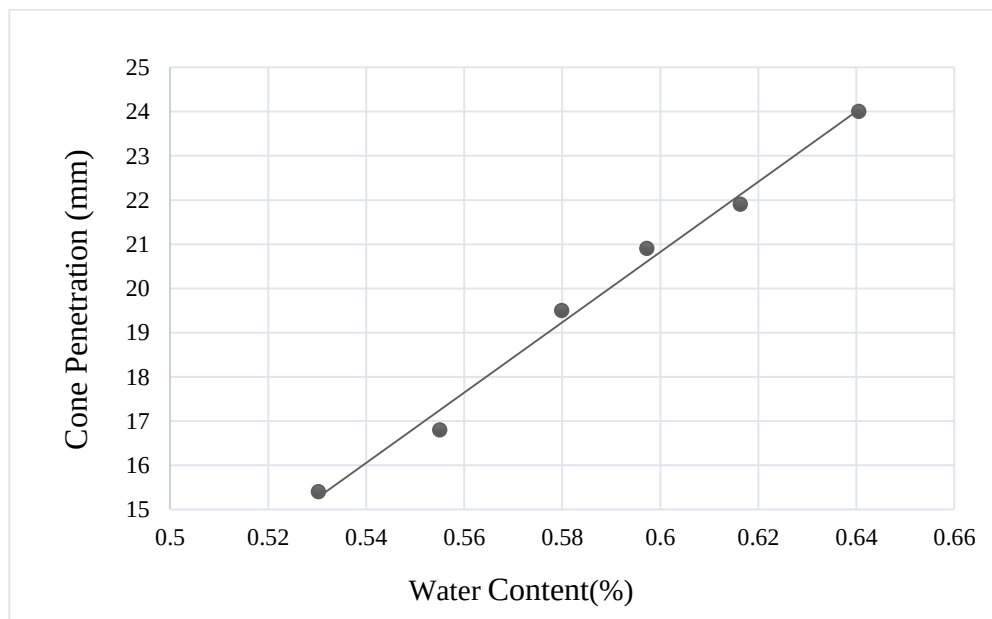


Figure B.3 CH-1 Cone penetration

Table B.6 CH-1 Plastic limits

Determination of Plastic Limit	1	2	3
Cup No	18	3	47
Cup + Wet Sample Weight (g)	12.28	11.01	13.94
Cup + Dry Sample Weight (g)	11.63	10.49	12.87
Water Weight (g)	0.65	0.52	1.07
Cup Weight (g)	8.89	8.47	8.64
Dry Sample Weight (g)	2.74	2.02	4.23
Water Content w (%)	23.72	25.74	25.30

Table B.7 CH-2 Liquid limits

Liquid Limit Determination	1	2	3	4
Cup No	N/A	N/A	N/A	N/A
Cup + Wet Sample Weight (g)	N/A	N/A	N/A	N/A
Cup + Dry Sample Weight (g)	N/A	N/A	N/A	N/A
Water Weight (g)	N/A	N/A	N/A	N/A
Cup Weight (g)	N/A	N/A	N/A	N/A
Dry Sample Weight (g)	N/A	N/A	N/A	N/A
Water Content w (%)	0.86	0.90	0.93	0.98
Cone Penetration (mm)	13.90	17.80	20.20	22.60

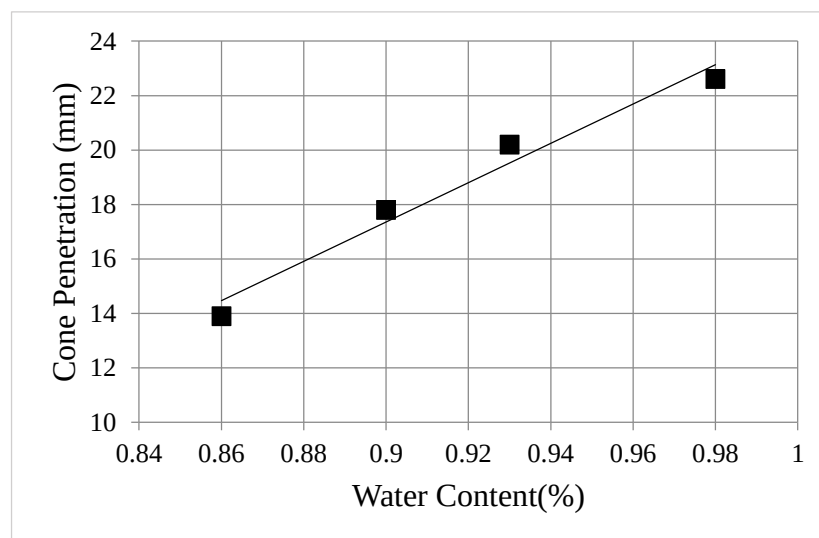


Figure B.4 CH-2 Cone penetration

Table B.8 CH-2 Plastic limits

Determination of Plastic Limit	1	2	3
Cup No	26	64	54
Cup + Wet Sample Weight (g)	10.59	9.43	14.75
Cup + Dry Sample Weight (g)	10.09	9.15	13.44
Water Weight (g)	0.50	0.28	1.31
Cup Weight (g)	8.69	8.31	8.97
Dry Sample Weight (g)	1.40	0.84	4.47
Water Content w (%)	0.36	0.33	0.29

APPENDIX_C: Compaction Test Results

Table C.1 SC-1 Standard Proctor Compaction Test

Cup No	10	11	12	13
Mold Weight	4296	4296	4296	4296
Compacted soil Weight (gr)	1687	1861	2040	1965
Mold + Comp.S Weight. (g)	5983	6157	6336	6261
Wet unit Weight (KN / m ³)	17.87	19.71	21.61	20.82
Water Content (%)	7.4	10.2	13.1	18.6
Dry unit Wt. (KN / m ³)	16.64	17.88	19.11	17.55

Cup No	1	2	3	4
Cup + Wet Sample (gr)	689.22	586.45	833.69	495.61
Cup + Dry Sample (gr)	647.17	539.14	747.41	431.02
Water Weight (gr)	42.05	47.31	86.28	64.59
Cup Weight (gr)	80.0	77.1	88.6	84.4
Dry Sample Weight (gr)	567.2	462.1	658.8	346.6
Water Content (%)	7.4	10.2	13.1	18.6

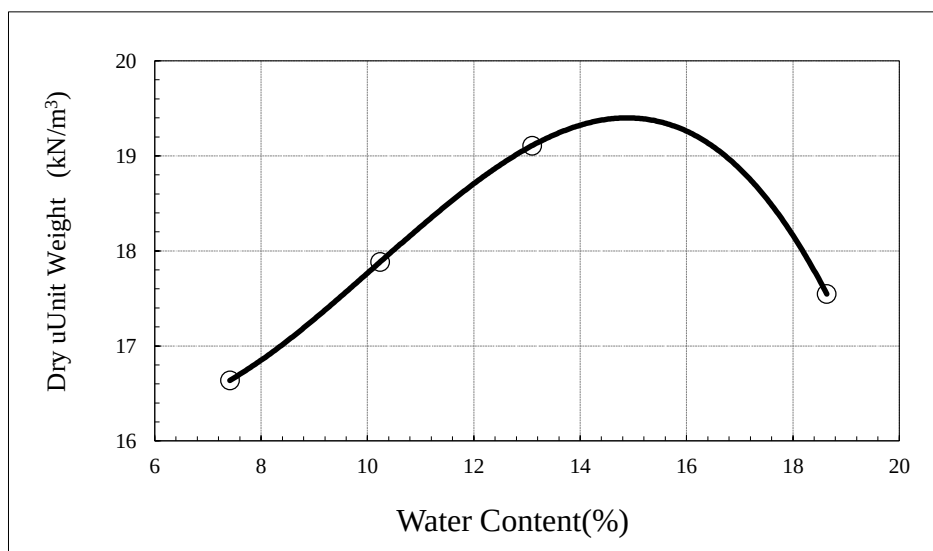


Figure C.1 SC-1 Soil compaction curve

Table C.2 SC-2 Standard Proctor Compaction Test

Cup No					
Mold Weight	4296	4296	4296	4296	4296
Compacted soil Weight (gr)	1621	1724	1781	1728	1663
Mold + Comp.S Weight. (g)	5917	6020	6077	6024	5959
Wet unit Weight (kN/m ³)	17.17	18.26	18.87	18.31	17.62
Water Content (%)	14.0	18.1	25.8	33.7	40.0
Dry unit Wt. (kN/m ³)	15.07	15.47	15.00	13.69	12.59

Cup No	1	2	3	4	4
Cup + Wet Sample (gr)	507.73	903.22	391.79	724.35	617.29
Cup + Dry Sample (gr)	456.38	790.77	341.43	565.13	469.69
Water Weight (gr)	51.35	112.45	50.36	159.22	147.6
Cup Weight (gr)	88.7	167.9	146.2	92.9	100.4
Dry Sample Weight (gr)	367.7	622.9	195.2	472.2	369.3
Water Content (%)	14.0	18.1	25.8	33.7	40.0

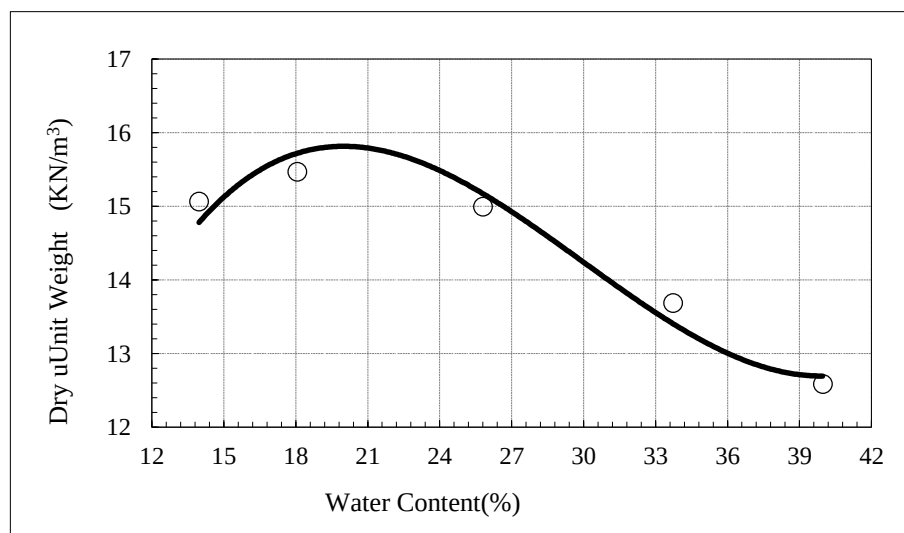


Figure C.2 Soil SC-2 compaction curve

Table C.3 CH-1 Standard Proctor Compaction Test

Cup No				
Mold Weight	4276	4276	4276	4276
Compacted soil Weight (gr)	1499	1795	1767	1728
Mold + Comp.S Weight. (g)	5775	6071	6043	6004
Wet unit Weight (KN/ m ³)	15.31	18.34	18.05	17.65
Water Content (%)	14.2	21.8	31.3	33.4
Dry unit Wt. (KN / m ³)	13.41	15.06	13.75	13.23

Cup No	1	2	3	4
Cup + Wet Sample (gr)	725.44	445.91	644.19	787.24
Cup + Dry Sample (gr)	653.7	384.35	512.28	627.67
Water Weight (gr)	71.74	61.56	131.91	159.57
Cup Weight (gr)	149.0	101.7	90.4	150.5
Dry Sample Weight (gr)	504.7	282.7	421.9	477.2
Water Content (%)	14.2	21.8	31.3	33.4

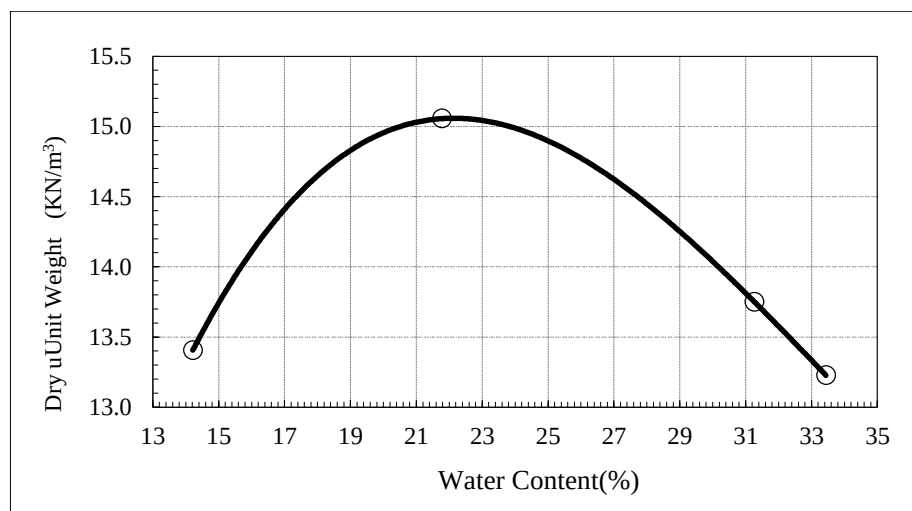


Figure C.3 Soil CH-1 compaction curve

Table C.4 CH-2 Standard Proctor compaction test

Cup No	1	2	3	4
Mold Weight	N/A	N/A	N/A	N/A
Compacted soil Weight (gr)	N/A	N/A	N/A	N/A
Mold + Comp.S Weight. (g)	N/A	N/A	N/A	N/A
Wet unit Weight (KN /m ³)	N/A	N/A	N/A	N/A
Water Content (%)	22	24	27	30
Dry unit Wt. (KN / m ³)	17.90	18.20	18.30	17.60

Cup No	1	2	3	4
Cup + Wet Sample (gr)	N/A	N/A	N/A	N/A
Cup + Dry Sample (gr)	N/A	N/A	N/A	N/A
Water Weight (gr)	N/A	N/A	N/A	N/A
Cup Weight (gr)	N/A	N/A	N/A	N/A
Dry Sample Weight (gr)	N/A	N/A	N/A	N/A
Water Content (%)	22.00	24.00	27.00	30.00

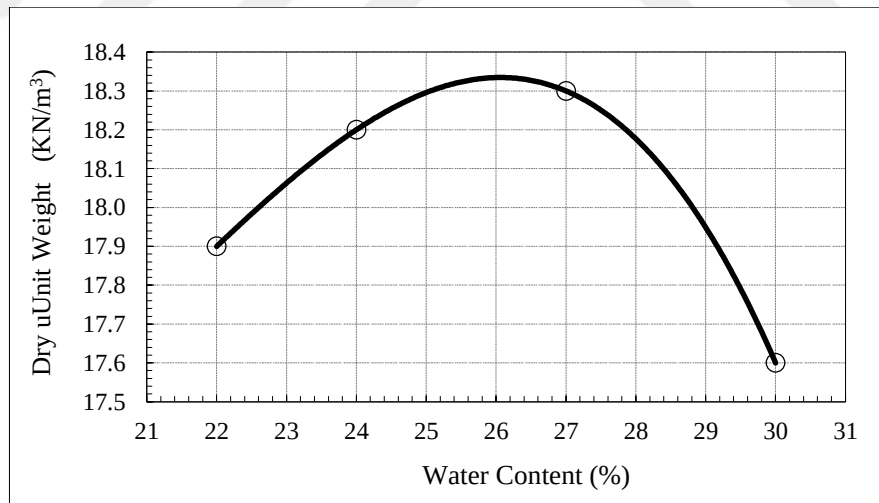


Figure C.4 CH-2 Soil compaction curve

APPENDIX_D: Specific Gravity Test Results

SC-1:

$$W_{\text{pyc}}=176.73 \text{ g}$$

$$W_{\text{dry}}=49.99 \text{ g}$$

$$G=49.99/ (49.99+672.43-703.28)$$

$$W_{\text{pyc+water+dry}}=703.28 \text{ g}$$

$$G=2.61$$

$$W_{\text{pyc+water}}=672.43 \text{ g}$$

SC-2:

$$W_{\text{pyc}}=164.92 \text{ g}$$

$$W_{\text{dry}}=50.10 \text{ g}$$

$$G=50.10/ (50.10+662.58-694.34)$$

$$W_{\text{pyc+water+dry}}=694.34 \text{ g}$$

$$G=2.73$$

$$W_{\text{pyc+water}}=662.58 \text{ g}$$

CH-1:

$$W_{\text{pyc}}=164.92 \text{ g}$$

$$W_{\text{dry}}=50.36 \text{ g}$$

$$G=50.36/ (50.36+661.67-694.08)$$

$$W_{\text{pyc+water+dry}}=694.08 \text{ g}$$

$$G=2.80$$

$$W_{\text{pik+su}}=661.67 \text{ g}$$

CH-2:

$$W_{\text{pyc}}=165.83 \text{ g}$$

$$W_{\text{dry}}=45.60 \text{ g}$$

$$G=45.6/ (45.6+662.91-692.24)$$

$$W_{\text{pyc+water+dry}}=692.24 \text{ g}$$

$$G=2.72$$

$$W_{\text{pyc+dry}}=662.91 \text{ g}$$

APPENDIX_E: Camera Calibration Values

Parameter	Value	Std Error
Image width	4000	
Image height	3000	
Focal length	5888.95	0.426286
Principal point (x)	5.52806	0.501575
Principal point (y)	-3.13475	0.598761
Affinity B1	-0.130419	0.119045
Skew B2	-2.7432	0.121321
Radial K1	-0.153689	0.00313855
Radial K2	0.0636745	0.0652631
Radial K3	-0.388844	0.535096
Radial K4	1.14055	1.4984
Tangential P1	5.13649e-05	2.40831e-05
Tangential P2	0.000199253	9.13604e-05

Figure E.1 Camera parameters

APPENDIX_F: Displaying Multiple Image of Bulk Specimens



Figure F.1 54 images that were taken from upper side of the bulk soil

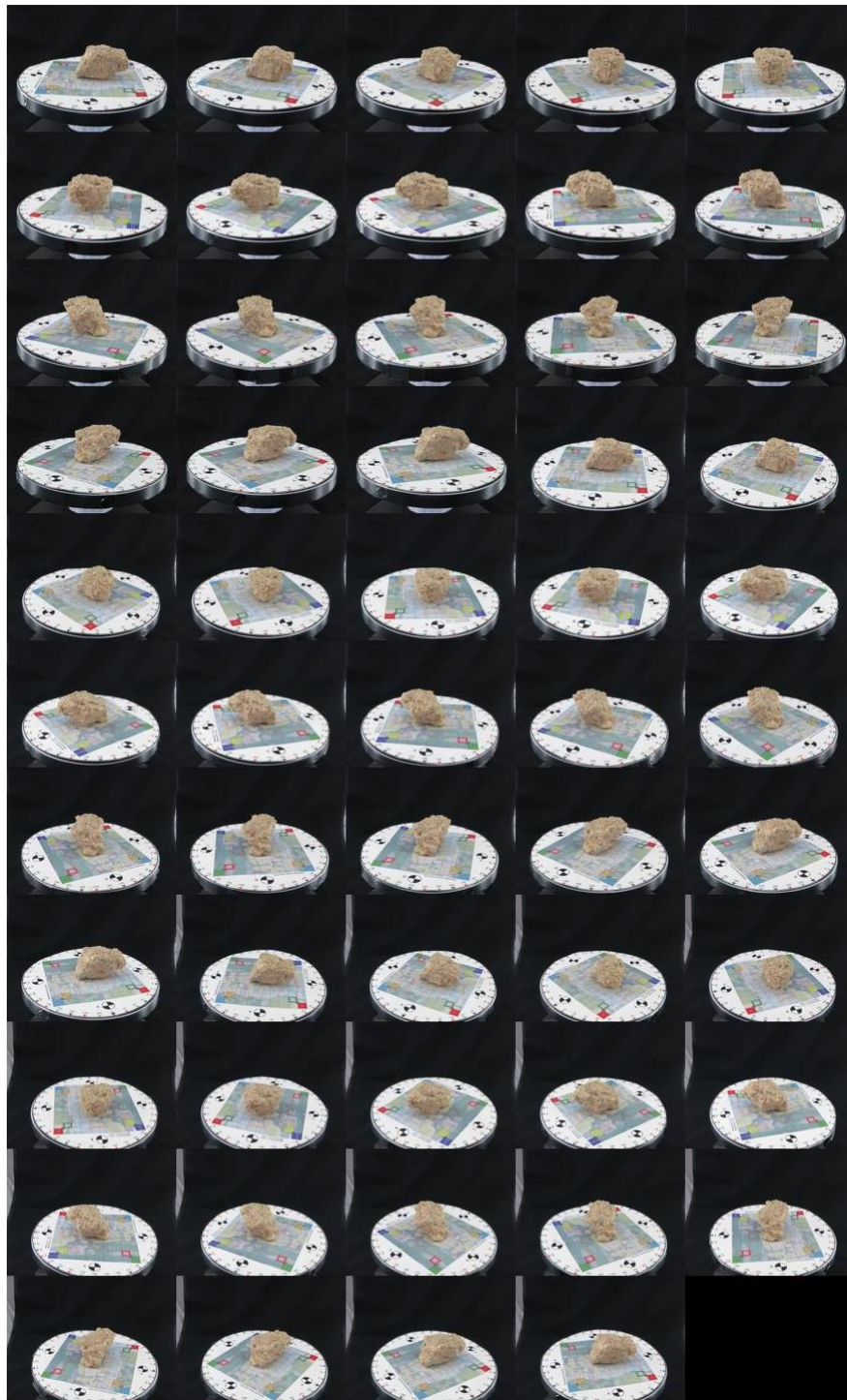


Figure F.2 54 images that were taken from bottom side of the bulk soil

APPENDIX_G: Displaying Multiple Image of Compacted Specimens

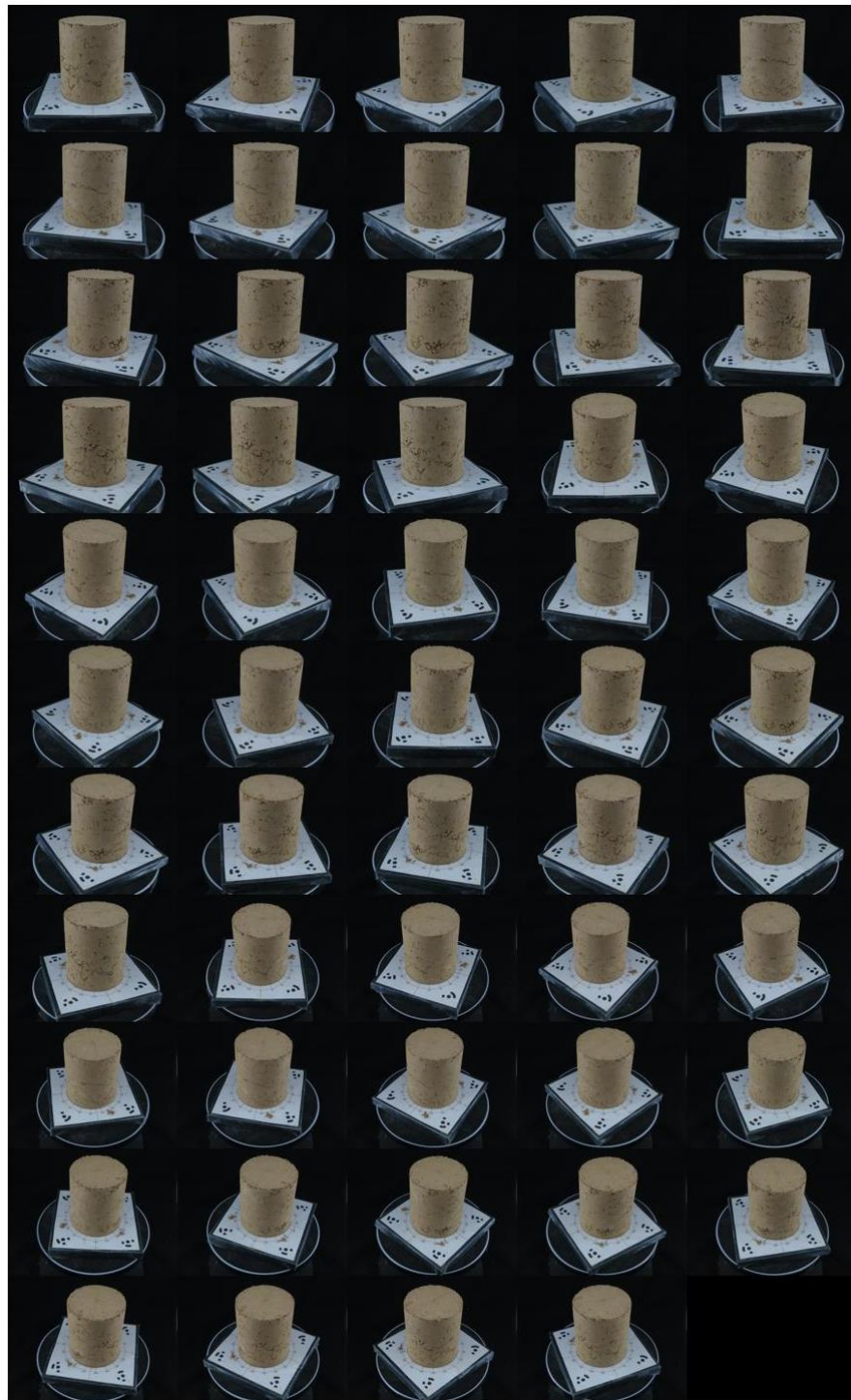


Figure G.1 54 images that were taken from Compacted soil