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Application of digital image processing in the determination of soil consolidation coefficient

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Abstract

In geotechnical engineering, in order to perform analyzes related to consolidation settlement, appropriate values of the consolidation coefficient should be available. In this research, the digital image processing (DIP) technique has been used to determine the deformation of the consolidation sample during the consolidation process. Due to the limitations of the conventional consolidation machine in terms of sample dimensions and also the lack of visibility of the sample, and as a result, the inability to take pictures, a new large-scale consolidation machine has been made. In order to ensure the proper functioning of the new device, 3 series of consolidation tests have been performed on Tabriz saturated clay samples with the new consolidation device as well as the conventional consolidation device. The comparison of the results shows that the consolidation parameters measured by the new device are comparable to the conventional odometer device. Then, by performing 4 series of consolidation tests with a new consolidation device and taking pictures of the sample during the consolidation process, the information related to the deformation of the sample was recorded and with the help of the DIP technique, the deformation of the consolidation sample, and as a result, the load-deformation information was measured and the consolidation coefficient of the samples has been determined based on them. The results show the accuracy and efficiency of the DIP technique in determining soil consolidation parameters. The valuable conclusion of this research is that the image processing technique can be a cost-effective and suitable method for determining the consolidation coefficient, because it does not require measuring devices and eliminates human errors in reading and recording data.

Keywords: Soil consolidation, digital image processing, consolidation coefficient, large consolidation odometer
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1 Introduction

Compression displacement, aggregate movements and expulsion of water from the soil pores cause settlement in mass soil; this process is called soil consolidation. Because of the low permeability of fine-grade soils such as clayey soil, consolidation is a time-dependent process that takes place over a long period of time, so consolidation settlement in saturated fine-grade soil has great importance. In studying one-dimensional consolidation done by the odometer

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apparatus, by applying a static load to a saturated (or nearly saturated) clayey soil, the amount of excess pore water pressure in the soil specimen changes and finally transfers from water to soil particles as effective pressure and settlement of soil take place. Studying the settlement behavior of soil is one of the first goals in geotechnical engineering and a major problem in the design of safe structures that are to be constructed. In order to develop field conditions, the consolidation test is performed in a Casagrande odometer in which the settlement of soil samples is noted at different time intervals. This test is performed in according with IS: 2720 (part xv) - 1965.

Although the rational Casagrande odometer is suitable for determining the consolidation specification of homogenous fine-graded soil, it is not suitable for coarse aggregate soils because of the scale factor [12]. Investigations show that sample size has a strong effect on deformation characteristics of homogenous fine-graded soil, such as Compression Index, Swelling index and coefficient of consolidation [9]. During the loading and unloading process in one-dimensional consolidation, the results of vertical deformations of the soil sample will be read by an analogue gauge or LVDT sensors installed on top of the specimen at different times. Actually, it may be said that this method is a contact method that, in addition to spending a high cost to preparation of preparing tools, because of human errors, the reliability of the results may be affected.

Nowadays, we can see that great development has been made in digital image techniques in many engineering fields, such as geotechnical engineering, and many researchers have used digital images to investigate soil deformation characteristics. Digital image processing technique has been successfully used in analyzing the gradation curve of fine-grained soils [18]. They analyzed the granulation curve of fine-grained soils with the help of a dynamic image processing technique and compared the results with the traditional method. By analyzing the digital images taken from the solid particles of fine-grained soil with a plasticity index of 30, they analyzed the particle size distribution of the sample and compared the results with the analysis of the hydrometric method and showed that this method can be used for all types of fine-grained soils much more easily than the hydrometric method. Nihat [2] with the help of digital image processing technique, analyzed the soil granulation curve and by comparing the results with the sieve method, observed that both methods have the same results. T. Prabaharan et al. [14] studied the applications of image processing in different fields. In their research, they focused on the applications of image processing techniques in different fields such as construction, fluid flow, thermal imaging, medical industries, fruit and vegetable industries, and showed that the use of image processing techniques leads to quality products that can reduce time and costs. Snehal [1] determined the shape characteristics of aggregates such as elongation, flakiness and sieve analysis with the help of image processing and compared the results with other conventional methods. He showed that the image processing method can provide a rapid and accurate method with minimum interference from the operator to determine the shape characteristics of aggregates. João et al. [17] showed that the images from common digital cameras and adequate processing can be used to estimate the moisture content of different soils. Kim et al. [8] used digital image analysis to evaluate the consolidation behavior of soils under the conditions of radial drainage and to measure the consolidation deformation of the sample. Digital image processing techniques can be used in three-dimensional tests to measure sample volume changes [4]. They developed a new imagery technique and used it for measuring the volumetric deformation of multistage shearing specimens in saturated and unsaturated conditions. Amir Hassan et al. [11] investigated the effects of internal erosion of discrete-grained soil samples on deformation behavior and stress-strain relationship with the help of an image processing technique. Erica Ellice et al. [16] used an image processing technique to determine the displacement and volume change of soil samples in three-dimensional devices and developed a non-contact measurement system with the help of image processing. In their study, Elena et al. [6] used digital imaging and image processing to determine strains and failure mechanisms in slope models during different loadings. Shao et al. [10] used the image processing technique in their research work "Digital Image Processing Application in the three-dimensional soil dynamic test" to measure the dynamic deformation of the samples. Sorin et al. [13] based on the processing of images taken from the in-situ rock mass; they presented a new method to determine the resistance index (GSI) of the rock mass and showed that this method can be easily used in engineering activities for underground and surface mining. Ramegowda et al. [7] developed the application of image processing in the field of engineering. In this research work, they adopted digital image processing to extract image features and laboratory tests to estimate the physical properties of the same sample then the correlation between image features and physical soil features is developed. Eichhorn et al. [3] introduced a low-cost system consisting of 4 computers and four related cameras to measure soil displacement and strain, and showed the efficiency of the system by conducting centrifuge modeling of slope failure test. Ajata et al. [15] by conducting a series of three axial tests on cylindrical samples of clay soils and using digital image analysis, they investigated the initiation and expansion of strain concentration inside the clay sample caused by the non-uniformity of the soil mass and the hardness of the material.

As mentioned above, the digital image processing technique has been widely used in various fields of engineering, especially in the determination of deformations. However, none of them have focused on determining the soil consolidation coefficient. Image processing technique has the ability to determine the deformation without any direct contact with the target of measurement [10]. In this research, an image processing technique has been used to determine the consolidation coefficient of clay soils, and its efficiency has been shown.

Results show that the digital image processing technique can be used as a suitable and powerful tool to determine deformation characteristics of soil and, hence, the analysis of soil settlement.

2 Theoretical foundations

2.1 Consolidation coefficient CV

After the consolidation test using one-dimensional consolidation devices, the results related to the deformation of the sample at different times and under the effect of applied loading are obtained. Various methods have been presented by researchers to determine the consolidation coefficient; among these methods, we can mention the time logarithm method and the time square root method. In this research, the time logarithm method was used to determine the soil consolidation coefficient. Based on this method, using the consolidation test results, the settlement-time logarithm curve is drawn, and the time related to 50% consolidation is determined; then, the consolidation coefficient is determined from the following equation:

$$C_v = \frac{0.197 * H_d^2}{t_{50}} \tag{2.1}$$

where H_d^2 is the time related to 50% consolidation, MATLAB is the software for image processing, and MATLAB is a programming platform designed specifically for engineers and scientists to analyse and design systems and products that transform our world. The heart of MATLAB is the MATLAB language, a matrix-based language allowing the most natural expression of computational mathematics. One of the reasons that MATLAB has become such an important tool is through the use of sets of MATLAB programs designed to support a particular task. These sets of programs are called toolboxes, and the particular toolbox of interest to us is the image processing toolbox [1].

2.2 Image processing and its benefit in geotechnical engineering

Image processing is the technique of converting an image into a digital format and performing operations on it to obtain an advanced image or extract some useful information from it. The changes that take place in the images are usually done automatically, relying on carefully designed algorithms. Image processing is a multidisciplinary field, drawing on the help of various branches of science, including mathematics, physics, optics, and electrical engineering. Image processing also overlaps with other areas such as pattern recognition, machine learning, artificial intelligence, and human vision research. The various steps involved in image processing include inputting the image through an optical scanner or digital camera, analyzing and working on the image (data compression, image enhancement, and filtering), and producing the desired output image. The need to extract information from images and interpret their content has been an effective factor in the development of image processing.

In the physical modelling of geotechnical phenomena, in order to observe soil behavior and simulate its real structure, deformations must be measured. The smallness of deformations on the one hand and the small scale of geotechnical models on the other hand have made it difficult to measure these deformations. Due to practical limitations and a small number of measurement points, conventional methods cannot fully show the deformation pattern inside the soil. Using an image processing technique can solve these limitations. With the help of image processing, displacements can be measured in any position and at any time.

In the normal consolidation test, which is a contact method, apart from the high cost to prepare measuring instruments, conducting the test requires spending a long time, and also due to the presence of human errors, the reliability of the results is affected. In addition, it is not possible to measure soil deformation at a specific point or surface, and it is not possible to determine the complete pattern of deformation. Therefore, in this research, in order to solve these limitations and access complete information about the deformation behavior of the consolidation sample, an image processing technique has been used. Figure 1 shows the image processing algorithm used in this research.

3 Methodology

First, a large consolidation apparatus based on a Casagrande-type odometer and similar to one that was used in David Igbinedion's work [5], has been fabricated, and its reliability has been shown by comparing acquired results with those obtained from a common odometer. Then, by conducting several condition tests with the new device and

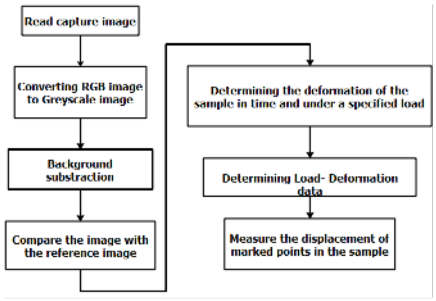

Figure 1: Image processing flow chart

processing of digital images that were taken from the sample during the consolidation period, time deformation data has been gathered and consolidation coefficient of specimen has been determined. The work process is shown in Figure 2.

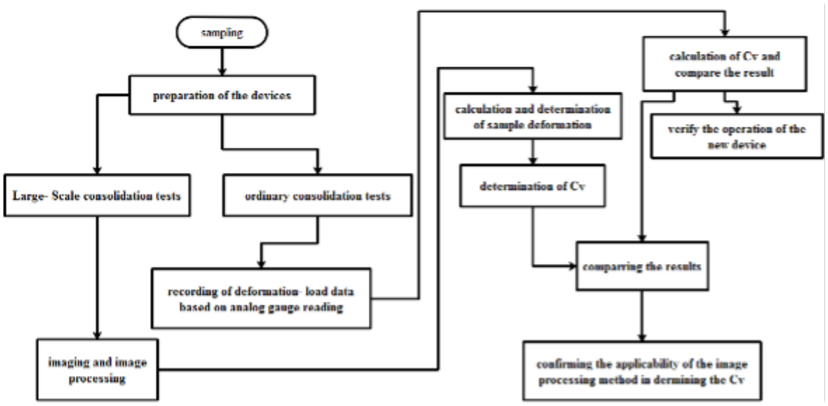

Figure 2: Work flow chart

Mathematical Formulations for Soil Consolidation Analysis Using Digital Image Processing

1. Governing Equation of Soil Consolidation

The consolidation process of soil under a constant load is governed by Terzaghi's one-dimensional consolidation equation:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2}$$

where u is the excess pore water pressure (kPa), t v time (s), z is the depth (m), and c_v is the coefficient of consolidation (m^2/s).

2. Coefficient of Consolidation Calculation

The coefficient of consolidation, , can be determined using laboratory test data. Two common methods are the Log-Time and Square-Root-Time methods:

2.1. Log-Time Method (Casagrande Method)

The coefficient of consolidation is calculated by:

$$c_v = \frac{T_{90} \cdot H^2}{t_{90}}$$

where T_{90} is the theoretical time factor for 90% consolidation (= 0.848), H is the drainage path length (m) (for double drainage: $H = \frac{H_s}{2}$) t_{90} is the time to reach 90% consolidation (s).

2.2 Square-Root-Time Method (Taylor Method)

$$c_v = \frac{T_{50} \cdot H^2}{t_{50}}$$

where, T_{50} is the theoretical time factor for 50% consolidation (= 0.197), and t_{50} is the time to reach 50% consolidation (s).

3. Digital Image Processing (DIP) Technique

To measure deformation using DIP, image sequences are analyzed to track displacement of markers on the soil sample surface. The displacement is obtained by comparing the pixel coordinates over time. The deformation Δh is calculated as:

$$\Delta h = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \times S$$

where, (x_1, y_1) and (x_2, y_2) = pixel coordinates of the target point before and after deformation, and S = scale factor (mm/pixel) determined by calibration.

4. Load-Deformation Analysis

The deformation data obtained through DIP is used to calculate the consolidation coefficient by applying it to the load-deformation curve.

$$e = \frac{\Delta h}{h_0}$$

where, e is the strain, Δh is the change in height (mm), and h_0 is the initial height (mm). The void ratio change with time is tracked to verify the consolidation progress.

5. Statistical Analysis

The Pearson correlation coefficient is applied to compare DIP results with conventional test data.

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

where x_i = consolidation coefficient from DIP, and y_i = consolidation coefficient from conventional tests. A high correlation ($R > 0.9$) indicates the reliability of DIP for soil consolidation analysis. The mathematical formulations presented validate the application of DIP in determining soil consolidation parameters. The derived values from DIP closely align with those obtained from conventional oedometer tests, demonstrating the method's accuracy and efficiency in geotechnical investigations. These formulations can be seamlessly integrated into the methodology section of the article to provide a clear and systematic explanation of the analytical framework used for determining the soil consolidation coefficient using DIP.

3.1 Large-scale odometer apparatus

The apparatus consists of a Plexiglas odometer cell with an internal diameter of 110mm and a height of 300mm, a loading arm, two Purus plates made up of Steel that are used for drainage from the top and bottom of the specimen, a steel piston to transfer load to the top of the specimen and a steel table to fix the cell on it. In Figure 3, the components of the apparatus and complete setup are shown. The weights were attached to the loading arm at 300cm from the fulcrum point. The mechanical advantage of the apparatus is 30.

3.2 Materials

In this research, experiments will be conducted on the clay of Tabriz metropolis, West Azerbaijan province, Iran. In order to collect samples, two boreholes were drilled (Figure 4) and a 127 mm drill bit was used to collect samples.

A total of 7 samples have been collected from the place. Due to the high level of underground water, all the samples are in the state of natural saturation. The investigations show that all the samples have almost the same conditions and have similar characteristics. The results of X-ray tests on all samples, as well as the results of granulation tests and Atterberg limits, confirm this issue. In Table 1, as an example, the results of the X-ray test on samples No. 7 and No. 8 are presented. Also, the results of the aggregation and Atterberg tests of sample 7 are presented in Figure 5. Other specifications related to these samples are presented in Table 2.

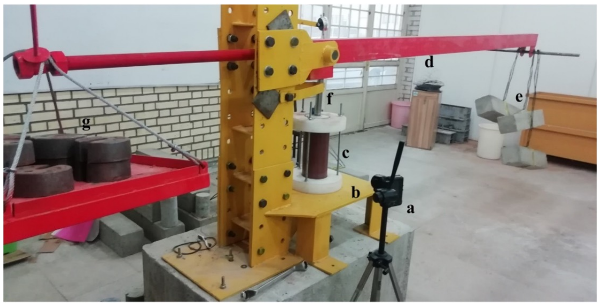

Figure 3: Components of apparatus and complete setup of new large consolidation device. a) camera, b) fix plate, c) Plexiglas cell, d) loading arm, e) loading weights, f) transfer load piston, g) balance weights.

Figure 4: Studding area location and drilling borehole.

Table 1: X- Ray results of sample NO. 7 and No.8

Soil sample structure	
No.7	**No.8**
Quartz sio2	**Quartz sio2**
Calcite caco3	**Calcite caco3**
Clay mineral (chlorite, montmorilonite)	**Clay mineral (chlorite, montmorilonite)**
Dolomite	**Dolomite**
Feldspar	**Feldspar**
muscovite	**muscovite**

Table 2: Aggregation and Atterberg test results.

USCS Classification		**% Gravel**	**% Sand**	**% Silt & Clay**	**Hydrometer Results**	
CL, Lean Clay		0.0%	0.8%	99.2%	Size, mm	% Passing
		% Silt	% Clay		0.074	99.1%
D_{10} =	0.01	45.2%	53.9%		0.050	96.6%
D_{30} =	0.02				0.020	86.3%
D_{60} =	0.05	Liquid Limit=		45.9%	0.005	53.9%
C_C =	1.50	Plastic Limit=		21.4%	0.002	42.6%
C_U =	6.00	Plasticity Index=		24.5%	0.001	30.8%

3.3 Test procedure

In this paper, two different sets of tests were done: ordinary consolidation tests and consolidation tests with a large-scale consolidation odometer. The odometer cell is made of transparent Plexiglas, which enables monitoring the internal movement of the soil sample during consolidation. The photo images on the front side of the specimen are used for digital image processing to find out the soil deformation during the consolidation process. Clay soils, unlike the Sandy soils, don't have a colourful texture and image processing can't give clear results about sample deformation to determine whether the clay sample has sufficient texture for the application of digital image processing. Small colored bullets (diameter of about 1mm) were inserted on the surface of the clay. Figure 6 shows a marked soil sample placed in a Plexiglas cell.

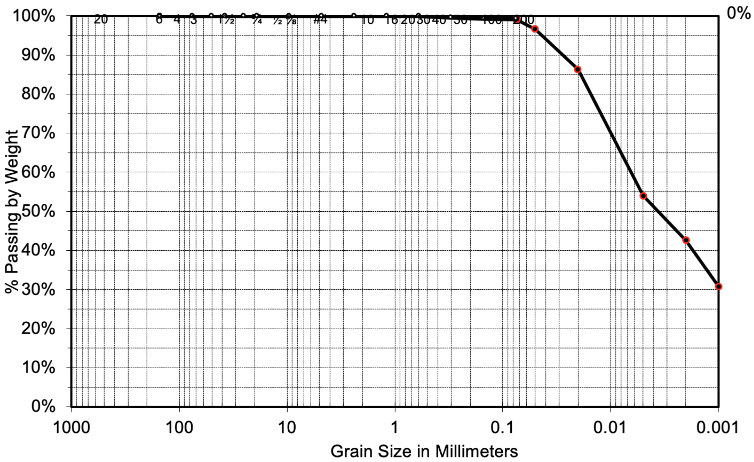

Figure 5: Grading chart of sample No.7.

Generally, 10 serious consolidation tests are done. 3 Serious by ordinary consolidation tests and 7 series by a new large-scale consolidation odometer. In 3 of the consolidation tests that were done by the new large-scale consolidation odometer, an analogue gauge is used for recording and determining of load-time deformation of the soil sample, and for the 4 remaining tests, a digital image processing technique is used.

Figure 6: Reference picture and Marked soil sample placed in Plexiglas cell.

4 Results

4.1 Performance of large- scale odometer

At this stage, by conducting one-dimensional consolidation tests on soil samples and comparing the results, the performance of the large-scale consolidation device is investigated. The results of three consolidation tests with the new device and two consolidation tests with the conventional Casagrande device are presented in the form of the porosity-logp diagram in Figure 7. It can be seen that in both cases, the change trend of the porosity ratio is decreasing with the continuation of external loading, and the two sets of graphs are comparable in terms of the change process, so that the new device has a similar performance to that of the standard one. The reason for the non-overlapping of the graphs is the level of applied stresses in the two groups of tests. In the new consolidation machine, due to the large dimensions of the sample, the applied stress values are higher (40- 375 N/cm2) and as a result, the graphs have shifted to the right.

4.2 Digital Image Processing

As earlier noted, to provide appropriate texture on the soil sample and take pictures, small colored bullets were inserted on the surface of the clay samples as shown in Figure 6. A Canon 7-megapixel camera fixed in front of the marked side of the soil sample, that placed in the transparent Plexiglas cell. Early photos that were captured before

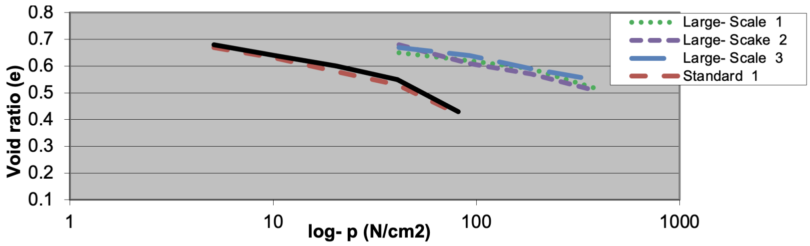

Figure 7: Load time deformation data (e- log p).

loading were saved as a reference photo. The digital images were gained during all 4 consolidation tests at different times after each loading step. Image processing will be done by comparing the images taken during the period of loading with reference one, in the Matlab software. By changing the position of inserted bullets in samples can be obtained, so vertical deformation of the soil sample in each test is determined, and load-time deformation data is obtained. The middle of the sample is selected to measure deformation.

The e-logp curves obtained from the large- scale odometer that plotted according to reading deformation data by analog gauge (a-g) and digital image processing (DIP) are illustrated in figure 8. As can be seen, as a result of consolidation, the void ratio of the sample decreases. The intensity of this reduction is mild in the initial stages of consolidation, and gradually its slope and, as a result, the amount of reduction increase. Based on the graphs of e-logp, it can be concluded that the results of the image processing method are comparable to the results of the normal gauge reading method, and the reason for the small difference between the results is that in the gauge reading method, deformations are measured at the top of the sample, but in the image processing method in the present research, the middle point of the sample is considered to calculate deformations. Considering that the deformation values of the sample in the central points of the sample, which have a greater length of the pore water drainage path, are less than the top of the sample, the complete lack of overlap between the graphs obtained from the two methods can be justified.

Time-dependent compression process under different loads is shown in Figure 9. A to 8.d. It can be seen that in all of the tests under different loads, the deformation of the soil sample increases with time, and gradually it will decrease.

4.3 Analysis of coefficient of consolidation

The results of the CV calculation are summarised in the table 3. Based on the deformation reading by the analogue gauge, the consolidation coefficient has been calculated in the range of 0.08 to 0.1cm2' sec, and in the method of image processing technique, it has been calculated in the range of 0.09 to 0.11cm2' sec. Comparing the results shows that with a very close approximation, both methods have the same answers. So, it can be concluded that the results obtained from the DIP technique are comparable with the results obtained from the ordinary method. This suggests that the DIP technique can be successfully used in determining the consolidation parameters.

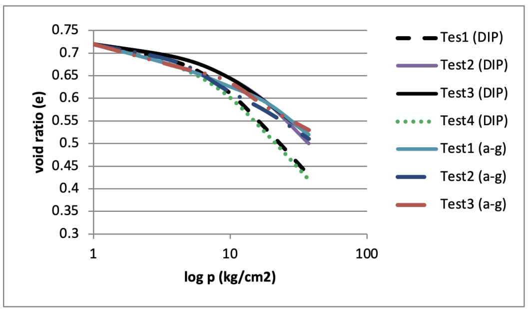

Figure 8: The e- logp curves obtained by new device

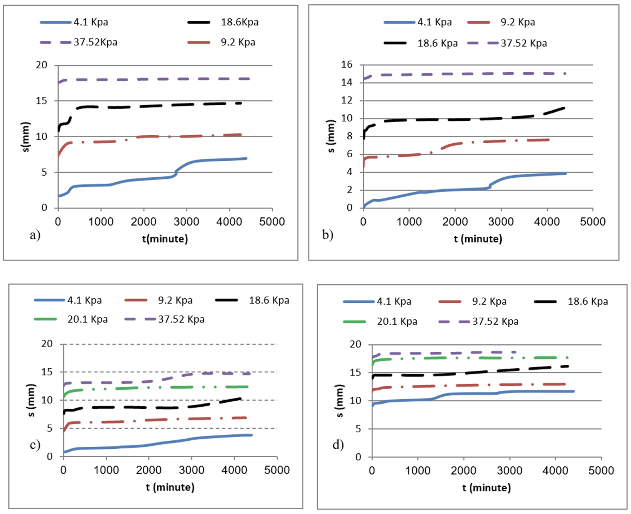

Figure 9: Time- deformation curves of soil samples under different vertical loads. a) Test No.1, b) test No.2, c) test No.3 and d) test No.4.

Table 3: The results of consolidation coefficient (cm2/sec) obtained by new device

TEST NO.	CACULATION METHOD	CONSOLIDATION COEFFICIENT- Cv
test 1	DIP	0.11
test 2	DIP	0.10
test 3	DIP	0.09
test 4	DIP	0.10
test 1 (a-g)	Analog gauge	0.09
test 2 (a-g)	Analog gauge	0.1
test 3 (a-g)	Analog gauge	0.08

5 Conclusion

In this research, digital image processing technique is used to evaluate the consolidation coefficient of saturated clay samples. In order to do this and provide the possibility of taking a picture of the consolidation sample, a large-scale consolidation device has been built. Based on the obtained results, it can be concluded that:

- The built large-scale consolidation device has a good performance and the results are comparable to the results obtained with a normal one-dimensional consolidation device.
- Due to the fact that clay soils, unlike sandy soils, do not have a colored texture, image processing cannot give clear results regarding sample deformation. In this research, the method of placing small colored ballets with a diameter of about 1 millimeter on the external surface of the sample has been successfully used to create a suitable surface texture.
- The image processing technique can be a cost-effective and suitable method for determining the consolidation coefficient due to the lack of need for measuring devices and the elimination of human errors for reading and recording data.

The limitations of this study include several factors that may affect the accuracy of the results. First, limitations related to the quality of the images captured during the consolidation process, such as lighting conditions and image resolution, might influence the analysis of sample deformation. Additionally, the use of the new consolidation device, despite producing comparable results with the Casagrande device, requires further validation under diverse soil conditions and varying load scenarios. Moreover, this study focuses solely on saturated clay samples from Tabriz, and generalizing the findings to other soil types necessitates additional investigations. Another limitation is associated with the digital image processing (DIP) technique, which relies heavily on the accurate calibration of the device and image analysis software, as minor variations in settings could impact the results.

Declarations

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