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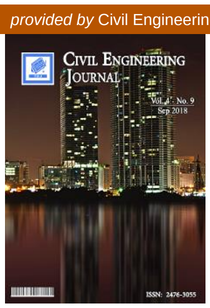
Civil Engineering Journal

Vol. 4, No. 9, September, 2018



# Evaluation of the Volume Measurement Optical Method Suitability for Determining the Relative Compaction of Soils

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Received 30 July 2018; Accepted 20 September 2018

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**Abstract**

The goal of this paper is evaluation of the volume measurement optical method suitability for determining relative compaction of soils. The Structure for Motion technique was utilized in order to achieve the goal by making the three-dimensional models (with Bentley ContextCapture software). Created models were used in volume measurement of the pit-holes. The results were compared with the basic methods: the sand cone test and the water method. The laboratory tests were carried out in two stages. In the first stage, the optical method was tested in similar to operating conditions. Ten holes were made in the soil and the volumes were measured with three different methods. The results were compared and submitted for statistical analysis. Statistical analysis showed the potential of optical method. The second laboratory test focused on repeatability and accuracy of measurement. The volume of the vessel imitating a pit-hole was obtained. The results of the second stage showed that the optical method has better accuracy and lower statistical dispersion compared with sand method. On this basis it can be concluded that optical method of volume measurement has great potential in soil compaction testing.

*Keywords:* Relative Compaction; Volume Measurement; Structure for Motion; Photogrammetry; Context Capture.

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## 1. Introduction

Relative compaction $I_s$ is one of the most important parameters influencing the performance of embankments, soils foundations and subbase layers. One of the part of the measurement procedure is determining the volume of the pit-hole formed after taking a sample. This measurement is carried out by filling the pit-hole with a certain volume of another medium (e.g. water or sand). The test procedure is described in the standard [1]. The test result is then used to calculate the relative compaction by applying the following formula:

$$I_s = \frac{\rho_d}{\rho_{ds}} \tag{1}$$

Where:

$\rho_d$: Dry bulk density of the tested soil [g/cm$^3$],

$\rho_{ds}$: Maximum dry bulk density of the soil obtained in Proctor compaction [2] [g/cm$^3$],

$$\rho_d = \frac{M}{V(\frac{100+w}{100})} \tag{2}$$

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http://dx.doi.org/10.28991/cej-03091138

M: Mass of the soil sample [g],

w: Moisture of the soil sample [%],

V: Pit-Hole volume [$cm^3$],

The development of technology allows to, look for new, more accurate, more convenient solutions replacing traditional measurement techniques. Currently, newer technologies of shape measurement are being developed, and hence allowing for volume measurement. Image analysis technology, such as digital image correlation, is used in science and industry to measure the surface shape and deformation of various objects. A simultaneous image from at least two cameras may be used. However, the shape of the element can also be captured on the basis of many images captured with at least one camera (image from different perspectives) – Structure for Motion (SfM). Such a solution is applied in both open and commercial software (eg Bentley ContextCapture [3]). Furthermore, there are also known solutions allowing for the shape measurement by analyzing a series of the images of the surface covered which the projected pattern (grid, line, stripes) using structural lighting or a laser beam [4].

This article describes the feasibility analysis of the optical volume measurement method (SfM based) in order to determine the state of soil compaction. Previous studies on the accuracy of this type of models used in ground volume determining gave promising results [5]. The insights presented in this paper shows the high potential of application of the optical method in innovative procedures of soil compaction testing.

### 1.1. Review of SfM Applications

In recent years, measurement techniques based on image analysis have become more and more popular. It is related to the increase of computing power of hardware, the availability of increasingly better photographic equipment and the development of data analysis techniques. The universality of the method is also very important, especially in the case of the structure for motion technique (SfM). This method allows create the three-dimensional shape model of the measured object based on a series of pictures captured from different perspectives. Its growing popularity can be explained by the fact that the preparation of measurement data does not require special equipment, lighting conditions etc. The methodology is very versatile and finds applications for objects of various sizes.

Westoby and colleagues [6] compare the SfM-derrived terrain model with model based on the terrestrial laser scanning. Their work proves that SFM is an inexpensive and effective method of capturing terrain very different landforms of different scales. For example topography of very large area may be modeled on the basis of the pictures captured from a aerial vehicle (plane or helicopter). Javernick et al. [7] in their work used photographs captured from Robinson R22 helicopter created digital elevation model (DEM). With resolution of 0.21 m they obtained vertical average errors about 0.1 m. The spatial resolution and accuracy depends on the camera resolution and measurement distance. So with smaller distance greater accuracy may be reached. Unmanned aerial vehicles (UAV) gives this possibility. Clapuyt et al. [8] during tests analyzing reproducibility of UAV-based earth reconstructions obtained mean absolute error about 0.06 m. However they emphasized that control points survey is very important issue that influences the results. Harwin et al. [9] noted that additional oblique photography may improve the results. Their models created with UAV acquired photographs was characterized by root-mean-square error (RMSE) of elevations about 5-20 mm.

Work of Slocum and Parrish [10] is an interesting example of verifying the accuracy of the method. The measured object was a computer model generated in a graphical environment. In this way, the authors avoided the problem of the accuracy of the reference method. At a measurement resolution of 1 cm - ground sampling distance (GSD) of 1.00 cm - a mean standard deviation between 2.6 and 32.3 mm was obtained.

The SfM method is also applicable under water. The study [11] assessed the usefulness of the method for monitoring coral reefs. The influence of various factors on the accuracy of results was analyzed, among others the influence of the observer was verified and proved to be irrelevant. The comparison of the ground-based SfM and the terrestrial laser scanning shows, that at the kilometer scale results of coastal erosion monitoring are comparable [12]. Furthermore Obanawa and Hayakawa [13] showed that volumetric erosion of bedrock cliffs may be measured efficiently on the basis of pictures captured by UAV.

There is also many potential applications in the infrastructural engineering. Bhatla et al. [14] investigated if the photogrammetry method with handheld camera is proper method of modeling an under-construction bridge. At that time it appeared to be unsuitable due to significant differences (about 2-5%) in observed dimensions. Research of Ruzgiene et al. [15] shows that UAV photogrammetry may be even applied in monitoring road pavement condition. Nassar and Jung [16] presented possibility of SfM application to the earthworks planning. They achieved good accuracy for earthwork quantity survey (error ranging from 3.2% to 5.9% depending on the soil type). However it should be noted, that in compaction testing (considered in our work), required volume assessment accuracy is higher. Another example of ground volume assessment using SfM is work of Wróżyński et al. [5]. They conduct different scale tests (small embankment - in laboratory and field embankment). In laboratory tests they achieved very good accuracy (volume error between 0.2% and 0.07%), which shows high potential of the method.

## 2. The Test Procedure

The carried tests consisted of two stages. In the first stage of the research, the volume of the cavity in the ground was measured by three different methods: sand volumeter (sand cone test), water and optical method. The optical method involves measuring the volume based on a three-dimensional model made with ContextCapture. This software generates 3D model of a static subject on the basis of a set of digital photographs taken from different viewpoints. Basically it is used in civil engineering for big sized objects shape reconstruction (e.g. buildings, earthworks). Despite the presented in this paper application of the software differs from usual, operating principle is the same. The 3D models of each pit-hole was created based on the analysis of 10 pictures. The pattern with scale was placed around the pit-hole (see Figure 1), allowing later scaling of the model to the appropriate units.

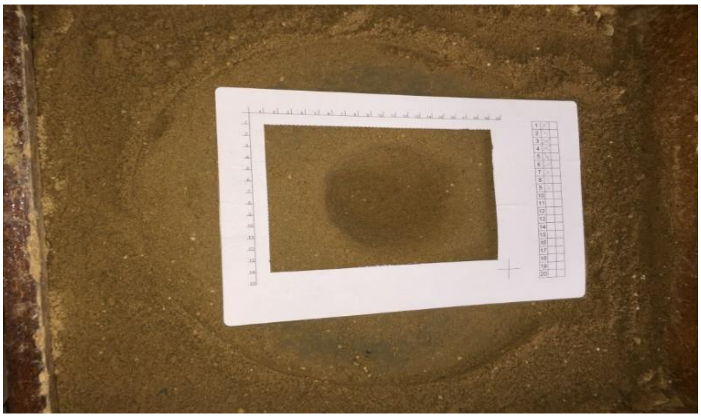

**Figure 1. Tested pit-hole with the scale used as ground control points**

The volume measurement was visualized in Figure 2.

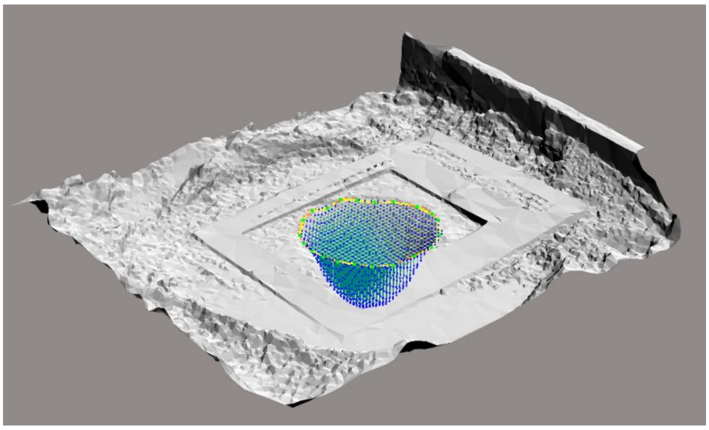

**Figure 2. Volume measurement using the ContextCapture software**

Traditional volume measurements were made according to the standard [1]. Ten pit-holes were measured in this way. There is no possibility to measure the pit-hole volume twice with the sand volumeter, so this kind of test does not provide full information about accuracy (especially repeatability) of the method. Therefore, in order to analyze the repeatability of individual methods, the second stage of the research was carried out. In the second stage, a multiple measurement of a vessel with a known volume imitating the pit-hole was performed.

At this stage, three series of photographs were taken, each of them consisting of 10 photographs. In order to more accurately reproduce the three-dimensional model, the irregular pattern was applied to the surface of the vessel, facilitating the identification of the points by the digital image correlation algorithm. The photographs were the input for the Context Capture software that was used for the volume calculation. Then, three series of measurements were made by water method, after earlier placing the plastic foil on the measured vessel, in order to protect the applied pattern (and also simulating film of water volumeter). Then ten measurements using the sand volumeter method were carried out. After all three tests, the water method was again used. This time without the use of the foil. Flow chart of the conducted tests is summarized in Figure 3.

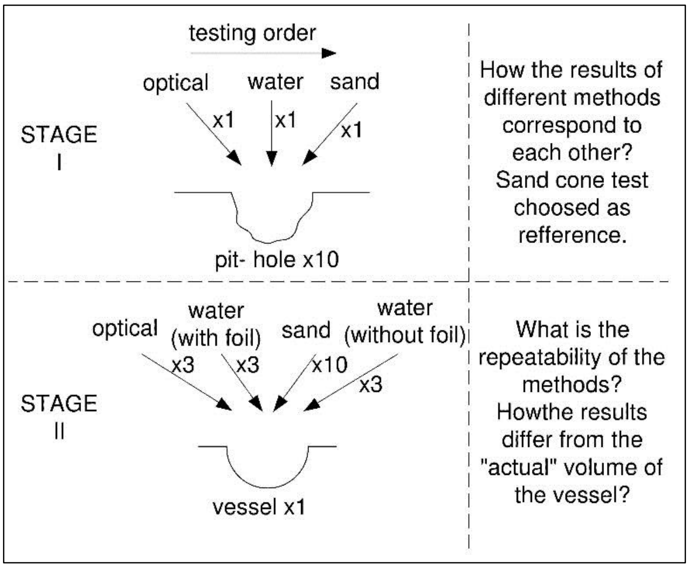

**Figure 3. Flow chart of conducted tests**

## 3. Results and Discussion

### 3.1. First Stage

The obtained results were analyzed statistically in accordance with the methodology presented in [17–19]. Because the volume of each pit-hole was measured by three methods, while comparing the results from the first stage, we have paired data. Each of the validated methods is compared with the reference method. It was initially assumed that the sand method will be the reference method, while the validated methods will be the optical and water method. For obvious reasons, it is not possible to test the same pit-hole several times using the sand volumetric method. Therefore, its accuracy or repeatability is unknown. One should be aware that the discrepancies between the results obtained with different methods are caused by both the errors of the reference and the validated method. The adopted methodology, however, requires the assumption that the refference method is completely accurate and assigns the whole error only to the validated method, which is a necessary simplification.

The basis for further analysis is the distribution of differences between methods. The differences between the results obtained from the sand volumemeter and the optical method were designated as DSO:

$$\mathrm{DSO_i} = \frac{\mathrm{VS_i} - \mathrm{VO_i}}{\mathrm{VS_i}} \tag{3}$$

Where:

$\mathrm{VS_i}$: Volume of the pit-hole number $i$ measured with sand volumeter method,

$\mathrm{VO_i}$: Volume of the pit-hole number $i$ measured with optical method,

While the differences between the results of the sand volumeter and water method were designated as DSW:

$$\mathrm{DSW_i} = \frac{\mathrm{VS_i} - \mathrm{VW_i}}{\mathrm{VS_i}} \tag{4}$$

Where:

$\mathrm{VW_i}$: Volume of the pit-hole number $i$ measured with water volume assessment method,

The analysis of the results was carried out in three stages: preliminary analysis, T-test and interval estimation. During the preliminary analysis, compliance with the assumptions was verified and outliers were rejected. The normality of the distribution was checked using the Shapiro-Wilk test, which in both cases gave a positive result. The results are presented in aggregated form in Figures 4 and 5 and in Table 1.

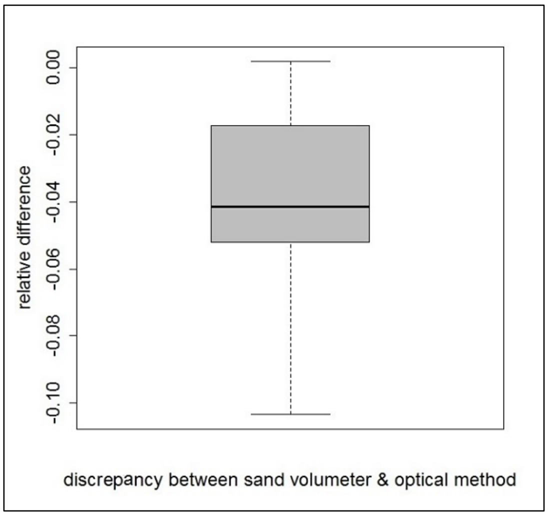

**Figure 4. Boxplot of DSO**

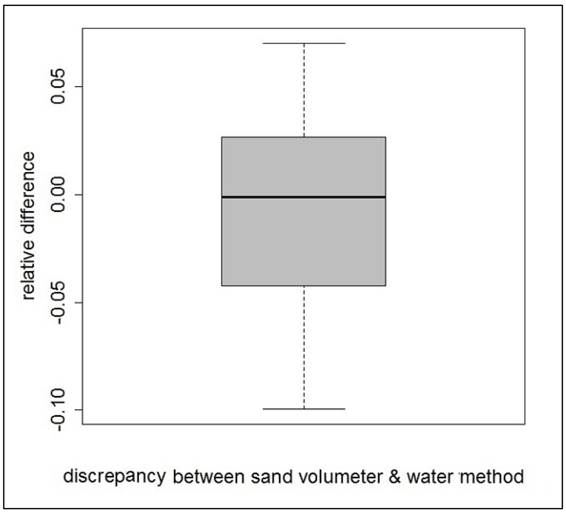

**Figure 5. Boxplot of DSW**

**Table 1. Aggregated information about population of differences between methods**

| | DSO | DSW |
|---|---|---|
| sample size (after rejecting outliers) | 9 | 10 |
| mean | -0.039 | -0.006 |
| standard deviation | 0.032 | 0.049 |
| Shapiro-Wilks p-value | 0.563 | 0.756 |
| T-test p-value | 0.006 | 0.704 |

In the next step of the analysis, Student's T-test was carried out, which aims to answer the question whether the results obtained by the method differ significantly from the results obtained by the reference method. As can be seen in Figure 3, the average DSO deviates from zero. Therefore, it can be expected that the average results obtained by the optical method will be significantly different from the results obtained by the sand volume measuring method. This is confirmed by the formally performed Student's T-test. The p-value was 0.006, so at the adopted significance level (5%), it should be considered that the optical method gives different results. However, in the case of DSW p-value was 0.704, so there is no reason to conclude that the average results between the sand and water method differ significantly.

It should be noted that the Student's T-test serves to compare the average results. Despite the fact that DSW scatter is larger than DSO, the water method seems to be better because in the case of a large number of measurements we can expect a result similar to the “real one” (obtained with sand cone test). The difference between the average result in the case of the optical method may be caused by a systematic error (which usually can be simply corrected). However, the method has a lot of potential because its results dispersion is much smaller (for example, measured by standard deviation). In order to illustrate this better, the interval estimation was carried out. In contrast to the previous approach, we infer directly from the distribution, therefore the confidence intervals concern the expected differences between individual measurement results. The results are, presented in Figures 6 and 7, applying confidence intervals to the probability density charts and in Table 2.

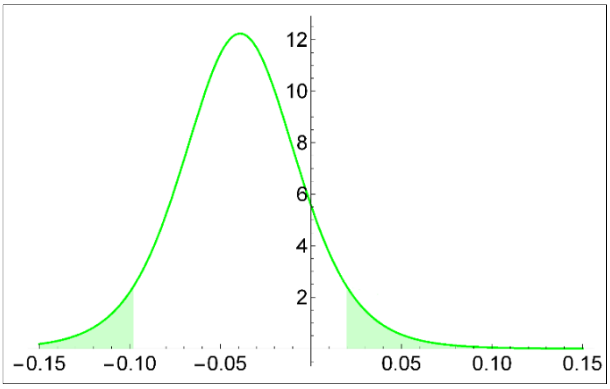

**Figure 6. Probability density function of DSO with 90% confidence interval**

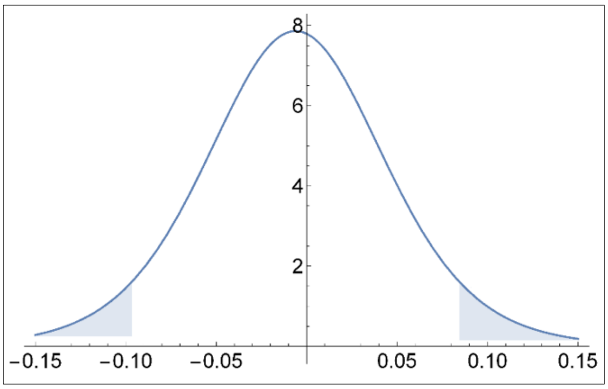

**Figure 7. Probability density function of DSW with 90% confidence interval**

**Table 2. Interval estimation results**

| | | **DSO** | **DSW** |
|---|---|---|---|
| 90% confidence interval | upper limit | -0.097 | -0.097 |
| | lower limit | 0.019 | 0.084 |
| | width | 0.116 | 0.181 |
| 95% confidence interval | upper limit | -0.111 | -0.118 |
| | lower limit | 0.032 | 0.106 |
| | width | 0.143 | 0.223 |

As previously noted, the optical method shows a certain systematic error (offset in relation to zero). However, it has a lot of potential because the spread of results and thus the confidence interval is smaller. The analysis of the results of the research carried out in the first stage still leaves doubts about which method is actually the most accurate. Hence it is necessary to analyze another series of tests consisting of a constant volume vessel measurements.

## 3.2. Second Stage

The results obtained in the second stage of the research are presented in an aggregated form in the Table 3. The greater number of measurements using the sand method were conducted because of the much larger spread of results.

**Table 3. Aggregated information about volume results obtained with different methods**

| | **Water method (with foil)** | **Water method (without foil)** | **Sand method** | **Optical method** |
|---|---|---|---|---|
| sample size (after rejecting outliers) | 3 | 3 | 10 | 3 |
| mean volume [cm3] | 634.13 | 642.37 | 678.17 | 654.66 |
| standard deviation [cm3] | 7.447 | 0.351 | 8.072 | 0.651 |

By analyzing the results obtained during the second laboratory test, it can be assumed that in this case the water method (without foil) should be assumed as the reference method, because the dispersion of results is the smallest. When comparing the two water methods, the difference between the measurements is around 8 $cm^3$. This difference is most likely caused by the air under the foil and the foil itself. At the vessel surface of approx. 150 $cm^2$, this error is due to the average difference in height measured of only 0.5 mm. The difference between the average volume measurements obtained using the water and optical method is approx. 12 $cm^3$.

The results obtained with the sand volumeter test are inflated by an average of 36 $cm^3$. This points to committing some systematic error, which may be based on an incorrect determination of the density of calibrated sand or the volume of the cone of the measuring device. Such an error can be easily eliminated by applying a correction during the calculations. However, the scatter of results is already a serious limitation of the method.

The optical method results compared to the reference method are also slightly overestimated. The difference may be due to the measurement of the distance between the characteristic points (ground control points) that were used in order to scale the ContextCapture models. On the other hand, the very small dispersion of the results indicates a good repeatability and potential of the method.

Comparing all obtained results, it can be concluded that in this case the optical method is more accurate than the sand method. A statistical analysis was carried out for confirmation. This time results were not paired because the same shape was captured during whole stage. The relative differences between the water method (without film) and the optical one were designated DWO, and between water and sand DWS.

**Table 4. Interval estimation results**

| | | **DWO** | **DWS** |
|---|---|---|---|
| 90% confidence interval | upper limit | 0.0221 | 0.0787 |
| | lower limit | 0.0162 | 0.0327 |
| | width | 0.0059 | 0.0461 |
| 95% confidence interval | upper limit | 0.0235 | 0.0841 |
| | lower limit | 0.0148 | 0.0273 |
| | width | 0.0087 | 0.0568 |

It can be concluded from above results that the dispersion of sand measurements is relatively large. This means that the result of a single measurement may differ significantly from the actual value. For example there is 10% probability that the error of randomly chosen result is greater than 2.3%. With the same probability the error of the optical method would be about eight times smaller. The optical method performs much better in this case.

## 4. Conclusion

On the basis of the results it can be concluded that the optical method of the volume measurement has a large potential. The spread of obtained results is much smaller than in the case of the sand volumetric method. The measurement uncertainty associated with the large spread of the results of the sand volumetric method can be reduced by performing more measurements, but this is associated with a greater labor intensity. The optical method allows for obtaining results with a narrower confidence interval, making the single result more reliable. In addition, the results obtained with this method are also closer to the actual volume of the vessel. An additional advantage of the optical method is the 3D visualization using the Context Capture software, which allows additional testing control in case of any doubts.

The practical usability analysis also indicates the superiority of the optical method. It is related to the width of the confidence interval, which is respectively: 4.6% for the sand method and 0.6% for the optical method. The results obtained in the sand volume will be in the range of ± 14 $cm^3$ (2.3%), and in the case of the optical method ± 2 $cm^3$ (0.3%). Analyzing the formula (1), one can easily come to the conclusion that the error of volume measurement transfer directly into the error of the determined relative compaction. The difference of 2% is an order of magnitude comparable with the differences between the requirements for road construction of different classes, so from a practical point of view it is very significant. Adaptation of the optical method to field measurements could bring great benefits. This would require automating measurements by developing easy to use hardware and dedicated software. Then, however, it should be noted that in 2012 a patent was issued describing the method and device used to determine the characteristics of the soil, i.e. volume, density [20]. In order to develop an optical volume measuring device, one must remember about the limitations associated with an existing patent.

## 5. Acknowledgements

We would like thank Bentley® Company for providing ContextCapture Software for research purposes.

## 6. Funding

This research was conducted by using funds from the Polish Government allocated to statutory aims of the Faculty of Civil Engineering.

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