

## Article

# Quantifying Soil Particle Settlement Characteristics through Machine Vision Analysis Utilizing an RGB Camera

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**Abstract:** Soil particle size distribution is a crucial factor in determining soil properties and classifying soil types. Traditional methods, such as hydrometer tests, have limitations in terms of time required, labor, and operator dependency. In this paper, we propose a novel approach to quantify soil particle size analysis using machine vision analysis with an RGB camera. The method aims to overcome the limitations of traditional techniques by providing an efficient and automated analysis of fine-grained soils. It utilizes a digital camera to capture the settling properties of soil particles, eliminating the need for a hydrometer. Experimental results demonstrate the effectiveness of the machine vision-based approach in accurately determining soil particle size distribution. The comparison between the proposed method and traditional hydrometer tests reveals strong agreement, with an average deviation of only 2.3% in particle size measurements. This validates the reliability and accuracy of the machine vision-based approach. The proposed machine vision-based analysis offers a promising alternative to traditional techniques for assessing soil particle size distribution. The experimental results highlight its potential to revolutionize soil particle size analysis, providing precise, efficient, and cost-effective analysis for fine-grained soils.

**Keywords:** soil particle size analysis; machine vision; RGB camera; settling characteristic; image analysis



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## 1. Introduction

Soil is composed of particles with varying sizes [1], and its properties vary depending on the particle size distribution. Soil texture is determined by its sand, silt, and clay content, and it is divided into coarse- and fine-grained soils based on the particle size distribution. These soil classifications are crucial because they facilitate the easy identification of general soil characteristics.

Particle size analysis separates soil by size to determine the particle size distribution [1]. Particle size analysis is one of the most basic and important soil property tests because soils can be classified according to their particle size distributions [2–4]. Using this method, the particle size distribution curve, which is the relationship curve of the percent finer (P) as a function of the particle size (D) of the soil, can be obtained. In addition to soil classification, the results of particle size analysis can be used for purposes such as index testing, profiling, and compliance [5]. They can also be used to estimate various soil properties such as permeability, shear strength, compressibility, conductivity, and consolidation [2,3].

In the particle size analysis tests, the particles with a diameter of 0.075 mm or more are analyzed via sieve analysis, and those with smaller diameters are analyzed using hydrometer testing [1–4,6–8]. Hydrometer testing is a test method for determining the particle size distribution of soil particles by measuring the change in density in a soil–water suspension over time as the soil particles settle in the suspension [2].

Hydrometer tests are widely used but have some limitations [9]. For example, they can be time- and labor-consuming [10] and exhibits operator and instrument dependency [3].

The hydrometer test involves multiple steps, including soil dispersion, sedimentation, and reading the hydrometer scale at specific time intervals. This makes it difficult to analyze a multitude of soil samples within a short period. Moreover, the accuracy of the hydrometer test depends on the skills and experience of the operator. Appropriate sample preparation, handling, and accurate hydrometer scale are critical for obtaining reliable results. Reading the hydrometer scale can be challenging because of several factors. The scale is often small and requires precise measurement. Variations in technique between different operators may introduce inconsistencies and affect the accuracy of the analysis. Despite these drawbacks, hydrometer testing is widely used for particle size analysis of fine-grained soils owing to its moderate cost, wide availability, and extensive existing references [5].

There are many alternatives to hydrometer testing, including laser diffraction (LD), X-ray absorption, and gamma-ray attenuation methods [8]. The aforementioned methods afford faster analysis and higher accuracy compared to hydrometer tests. However, they require specialized equipment for experimentation, which can be expensive to purchase, operate, and maintain. In particular, compared to experimental methods such as sieve analysis or pipette method, the test cost per sample is approximately 3 to 10 times more expensive, and the equipment cost is approximately 10 to 25 times more expensive [5]. As a result, these alternative methods have limitations that make them difficult to use except in specialized labs. It is also worth noting that hydrometer tests typically use 50 g of sample, whereas the aforementioned methods use much smaller amounts of sample; this can lead to problems concerning the representativeness of the test results [8]. In this regard, the sieve-hydrometer method is still widely used as the most representative method of soil particle size analysis.

Digital image analysis essentially entails analysis based on features found in a digital image of an object [11,12]. The process of analyzing digital images to quickly make a desired decision is referred to as machine vision. Digital image analysis is fast, inexpensive, and repeatable and has a wide range of applications [13–17]. As regards soils, digital image analysis is also being used to predict various soil properties such as water content [12,18–20], density [12,20], soil cracks [21,22], permeability [23,24], settling velocity [25,26] and strength [27,28].

Analyzing particle size distribution is also possible via digital image analysis. Soil particle size analysis through digital image analysis can be divided into two methods: measuring the size of individual particles in images and predicting the particle size distribution based on the features in the images. Measuring the size of individual particles is a widely used method for aggregates. Mora et al. [29] performed particle size analysis of coarse aggregates from 6.3 to 28 mm with high accuracy by digital image analysis. Ohm and Hryciw [16] developed a new image-based test called “sedimaging” to analyze particle sizes in the range of 0.075–2.0 mm, which has been typically performed by sieve analysis. Sudarsan et al. [30] characterized soil particle sizes using image analysis of microscope images. Bittelli et al. [31] conducted a comparative analysis of the pipette method, SediGraph method, LD method, and automated digital image analysis to determine the appropriate test method for particle size analysis of fine-graded soil and recommended the LD method as the standard method. Sun et al. [32] proposed a minimum image quality to obtain reliable results in image-based soil particle shape characterization. However, in the case of fine-grained soils with particle sizes of 0.075 mm or less, the size distribution is difficult to predict with typical digital image analysis because of the extremely small size of the particles and the difficulty of separating individual particles. As a result, the particle size analysis of fine-grained soils using digital image analysis is still limited. Thus, it is necessary to develop a particle size analysis method based on digital image analysis to analyze the particle size of fine-grained soil affordably and quickly.

Therefore, this study devised a machine vision-based analysis method to replace the hydrometer test to perform particle size analysis of fine-grained soil. The test method was developed by applying the principles of the hydrometer test. To reduce operator dependency and errors in the readings, an experimental method that does not use a

hydrometer was proposed. A digital camera was used to analyze the settling properties of the soil, replacing the hydrometer. In particular, the analysis was performed based on digital images acquired using a conventional digital camera meant for general use. This enables efficient soil particle size analysis and affords the advantage of real-time analysis and automation.

This paper follows a structured approach to introduce a machine vision-based method for analyzing fine-grained soil particle sizes, aimed at replacing traditional hydrometer testing. It begins by outlining the rationale for the study and the development of the experimental technique, which eliminates the need for a hydrometer reading. The soil properties under investigation are detailed, and the methodology for particle size analysis, including sieve analysis and a particle size analyzer, is explained. The image acquisition process using a specially designed settling tank and digital camera is then elucidated. The core of the paper focuses on image analysis, establishing relationships between settling distance, particle size, and average image intensity, which replaces hydrometer readings. Results showcase the method's success in predicting particle size distribution across various soil types, followed by a discussion of practical considerations and limitations.

## 2. Hydrometer Test

The hydrometer test is a test method for obtaining the particle size distribution by measuring the density of soil–water suspension over time and obtaining the percent finer ( $P$ ) by particle diameter ( $D$ ) of the soil sample [7,33]. The hydrometer test calculates the diameter of a soil particle based on Stoke's law [3,4,34]. The settling velocity ( $v$ ) of a particle having diameter  $D$ , according to Stoke's law, is as follows:

$$v = \frac{g(\rho_s - \rho_w)}{18\mu} D^2, \quad (1)$$

where  $g$  is the gravitational acceleration,  $\rho_s$  is the density of the soil particle,  $\rho_w$  is the density of water, and  $\mu$  is the viscosity of water at  $T$  ( $^{\circ}\text{C}$ ). A particle having diameter  $D$  settles at a distance equal to the settling distance ( $L$ ) in an elapsed time ( $t$ ); therefore,  $v = L/t$ . Therefore,  $D$  can be determined as follows:

$$D = \sqrt{\frac{18\mu}{g(\rho_s - \rho_w)} \frac{L}{t}}. \quad (2)$$

$L$  at time  $t$  is measured on the basis of the hydrometer reading ( $\gamma$ ). When the hydrometer and measuring cylinder are tested as a pair,  $L$  and  $\gamma$  are in a linear relationship.

$$L = a\gamma + b. \quad (3)$$

Here,  $a$  and  $b$  are the slope and intercept, respectively. Assuming that at time  $t = 0$ , a particle of mass  $m_{s1}$  is uniformly suspended in a volume  $V$ , the mass of the particle contained is  $m_{s1}/V$  and the volume is  $m_{s1}/(V\rho_s)$  in a unit volume of suspension. Thus, the volume and mass of water in a unit volume of suspension are  $1 - m_{s1}/(V\rho_s)$ ,  $\rho_w(1 - m_{s1}/(V\rho_s))$ , respectively. Therefore, the density of the suspension ( $\rho$ ) is as follows:

$$\rho = \frac{m_{s1}}{V} + \left( \rho_w - \frac{m_{s1}\rho_w}{V\rho_s} \right) = \rho_w + \frac{m_{s1}}{V} \left( \frac{\rho_s - \rho_w}{\rho_s} \right) \quad (4)$$

At time  $t = t$ , only particles having diameters smaller than  $D$  are present at depths smaller than  $L$ . Therefore, if the ratio of the mass of the particles having diameters smaller than  $D$  to the total mass is denoted  $P(D)$ , the density of the suspension at  $L$  is

$$\rho = \rho_w + \frac{m_{s1}}{V} \left( \frac{\rho_s - \rho_w}{\rho_s} \right) \frac{P(D)}{100} \quad (5)$$

In this case,  $\rho$  has the following relationship to the hydrometer reading ( $\gamma$ ):

$$\frac{\rho_s - \rho_w}{\rho_w} = \gamma + C_m + F, \quad (6)$$

where  $C_m$  is meniscus correction and  $F$  is the temperature correction coefficient. Thus, using Equations (5) and (6),  $P(D)$  can be calculated as follows:

$$P(D) = \frac{V}{m_{s1}} \frac{\rho_s}{\rho_s - \rho_w} (\gamma + C_m + F) \rho_w \times 100. \quad (7)$$

### 3. Materials and Methods

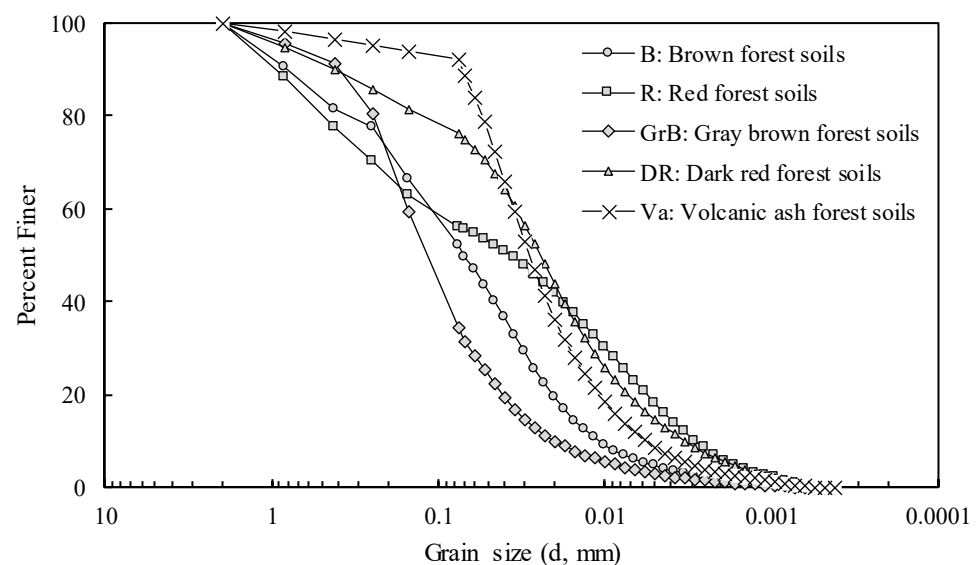
#### 3.1. Soil Properties

Table 1 summarizes an overview of the soil types used in the present study and their corresponding sampling locations. The investigation focused on five forest soils, namely, B, R, GrB, DR, and Va. These are representative soils in the Korean forest soil group.

**Table 1.** Description and sampling location of soil samples.

| Soil Group (Subgroup)                        | Symbol | Latitude  | Longitude |
|----------------------------------------------|--------|-----------|-----------|
| Brown forest soils                           | B      | 37.309404 | 127.30986 |
| Red & yellow forest soils (Red forest soils) | R      | 37.23417  | 126.80021 |
| Gray brown forest soils                      | GrB    | 35.98825  | 127.63727 |
| Dark red forest soils                        | DR     | 37.28844  | 126.84164 |
| Volcanic ash forest soils                    | Va     | 33.414417 | 126.48421 |

Particle size analysis and soil property tests were carried out on a set of five soil samples. The tests included a specific gravity test, as well as liquid and plastic limit tests (LL and PL), along with a loss of ignition (LOI) test. These experiments focused on particles measuring 2 mm or smaller. Furthermore, particle size analysis was performed on particles measuring 0.075 mm or larger using sieve analysis, while a particle size analyzer Malvern Mastersizer 2000 (Malvern Panalytical Ltd., Worcestershire, UK) was employed to analyze the smaller particles. The resulting particle size distribution curve for each soil sample, which combines the outcomes from the sieve analysis and particle size analyzer, is shown in Figure 1.



**Figure 1.** Particle size distribution curve of soil samples obtained using sieve analysis and a particle size analyzer.

Table 2 summarizes findings obtained from the particle size analysis and soil property tests. The specific gravity measurements for soil samples B, R, GrB, and DR were within the typical range for soils, while Va stood out with notably low specific gravity. Additionally, Va exhibited a significant LOI value of 32.6%, indicating a substantially higher organic matter content than the other soils examined. In terms of plasticity, B, GrB, and Va were classified as non-plastic, whereas R and DR showed low plasticity. Moving on to the particle size analysis results, GrB was identified as a coarse-grained soil, with 34.3% of particles passing through a 0.075 mm sieve, while the remaining were classified as fine-grained soils. Determining soil texture based on the sand, silt, and clay content proportions revealed that B, R, and GrB soils could be categorized as sandy loam, while DR and Va could be categorized as silt loam and silt, respectively.

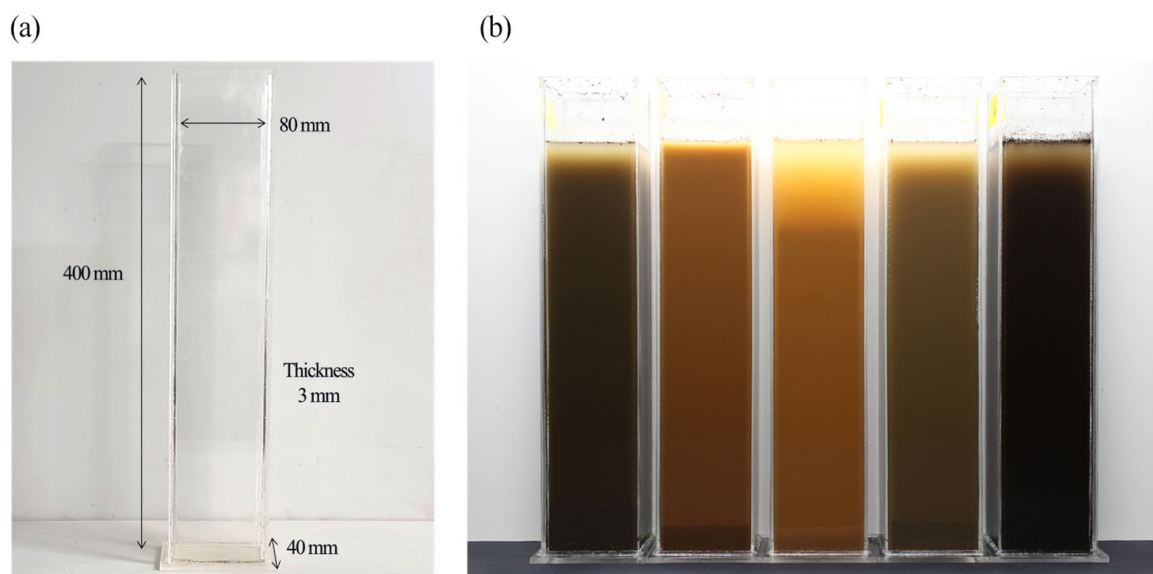
**Table 2.** Result of soil property tests and particle size analysis.

| Symbol | G <sub>s</sub> * | LL *   | PI *  | LOI * | <0.075 mm (%) | Sand (%) | Silt (%) | Clay (%) | USDA *     |
|--------|------------------|--------|-------|-------|---------------|----------|----------|----------|------------|
| B      | 2.53             | N.P. * | N.P.  | 12.9  | 52.1          | 52.2     | 46.1     | 1.7      | Sandy Loam |
| R      | 2.59             | 36.64  | 20.67 | 6.8   | 56.0          | 45.2     | 48.6     | 6.2      | Sandy Loam |
| GrB    | 2.61             | N.P.   | N.P.  | 6.9   | 34.3          | 70.6     | 28.2     | 1.2      | Sandy Loam |
| DR     | 2.57             | 28.78  | 11.79 | 9.0   | 76.3          | 26.4     | 67.8     | 5.8      | Silt Loam  |
| Va     | 2.07             | N.P.   | N.P.  | 32.6  | 92.0          | 14.5     | 82.2     | 3.3      | Silt       |

\* G<sub>s</sub>: Specific gravity, LL: Liquid limit (%), PI: Plastic index, N.P.: Non plastic. LOI: Loss of ignition (%), USDA: US Department of Agriculture.

### 3.2. Image Acquisition during Settlement of Soil Particles

In this study, we aimed to predict the particle size distribution of fine-grained soil with a diameter of 0.075 mm or less based on digital image analysis. For this purpose, it is necessary to acquire a series of digital images of the soil–water suspension during settlement. The particle size analysis of fine-grained soils was performed using the hydrometer test as aforescribed. The hydrometer test employs a measuring cylinder with an external scale for measuring the volume. In addition, measuring cylinders are typically made of glass, which can reflect light and result in low-quality images when used for capturing soil images. Hence, to overcome this issue, a settling tank was devised to replace the measuring cylinder, as illustrated in Figure 2.



**Figure 2.** Settling tank for soil particle size analysis: (a) dimensions of settling tank; (b) experimental setup.

The settling tank used in the study has the following dimensions: a height of 400 mm, a width of 80 mm, and a depth of 40 mm. It is constructed using acrylic material having

a thickness of 3 mm. Each soil–water suspension in the settling tank weighs 100 g, and the total volume of the suspension is 1000 mL. Before adding the soil to the tank, it was thoroughly dried, and only the portion that passed through the 2 mm sieve was used, consistent with the particle size analysis test.

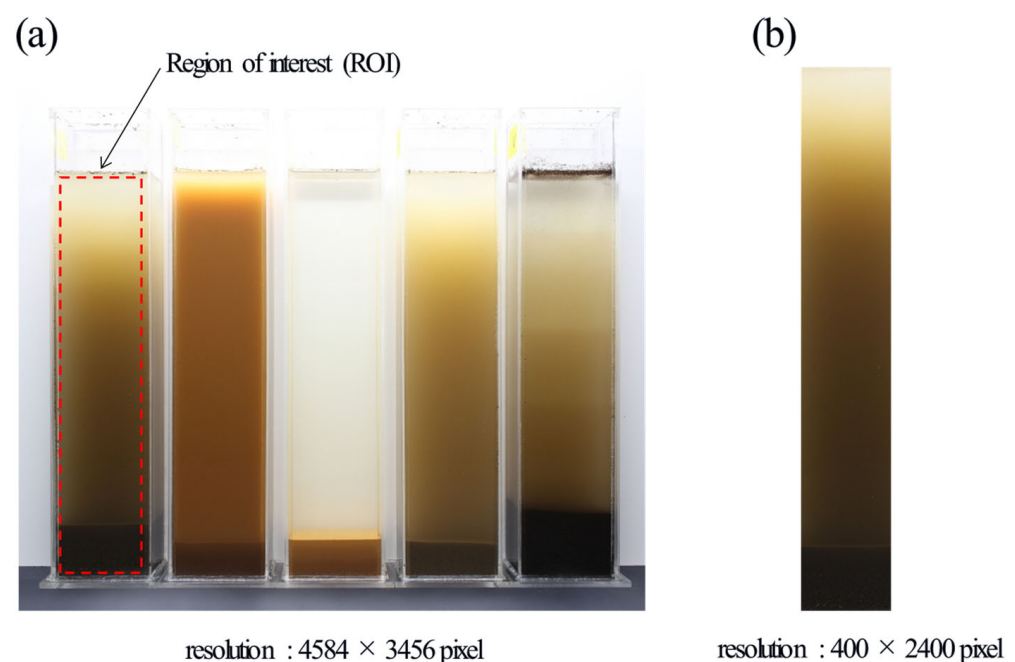
To capture digital images of the soil–water suspension during the settling process, a Canon EOS 100d camera (Canon Inc., Tokyo, Japan) was used. The photographs were acquired from the front of the settling tank, and a white matte plate was positioned at the back of the tank to eliminate color distortion caused by the background. The photography sessions were conducted in an indoor studio to maintain consistent lighting conditions. The camera settings were configured as follows: a shutter speed of 0.125 s, an aperture value of 5.6, and an ISO setting of 200.

For automated continuous shooting, the camera's shooting time was controlled by a computer. Canon's EOS Utility program was employed for this purpose. The elapsed time from the initiation of the settling process to the moment the  $n$ -th photograph was taken was defined as  $T_n$ .

In the hydrometer test, readings from the hydrometer are recorded at specific time intervals: around 1, 2, 4, 15, 30, 60, 240, and 1440 min, with the option for more readings to enhance accuracy. In this study, photographs were acquired every 10 s within the first 20 min, followed by intervals of one minute until 1520 min, and then at ten-minute intervals up to 2980 min. From this collection of images, those taken within the initial 120 s, as well as at 3, 4, 6, 8, 12, 15, 30, 60, 120, 240, 480, 960, and 1440 min, were chosen for in-depth analysis. As a result, a total of 25 images were utilized for the image analysis and particle size analysis.

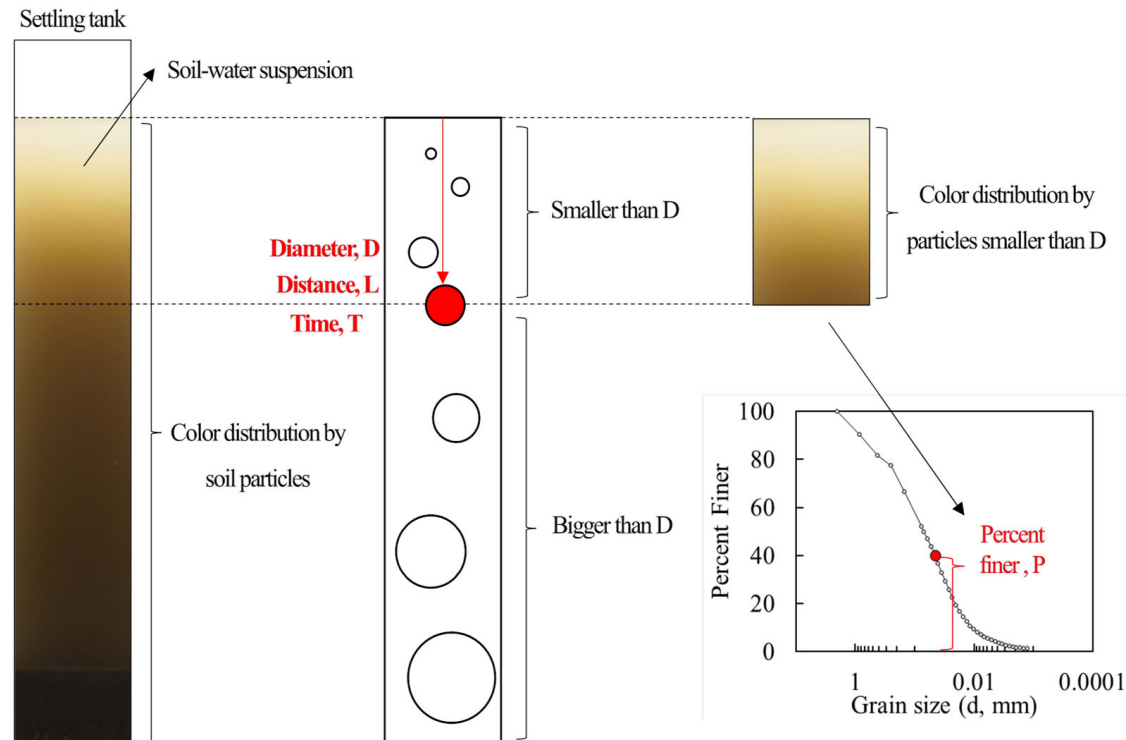
### 3.3. Image Analysis

In Figure 3, a specific region of interest (ROI) is highlighted within the digital image. The ROI corresponds to the area spanning the top to the bottom of the soil–water suspension in each settling tank. This area was designated as the ROI for analysis purposes. The dimensions of the ROI are 400 pixels in width and 2400 pixels in height.



**Figure 3.** Region of interest in settling tank: (a) position of the region of interest; (b) cropped image of the region of interest.

Figure 4 illustrates the proposed concept of machine vision-based soil particle size analysis (MVSPSA). In the settling tank, the soil particles within the soil–water suspension gradually settle over time. As the particles settle, the color distribution within the suspension changes.

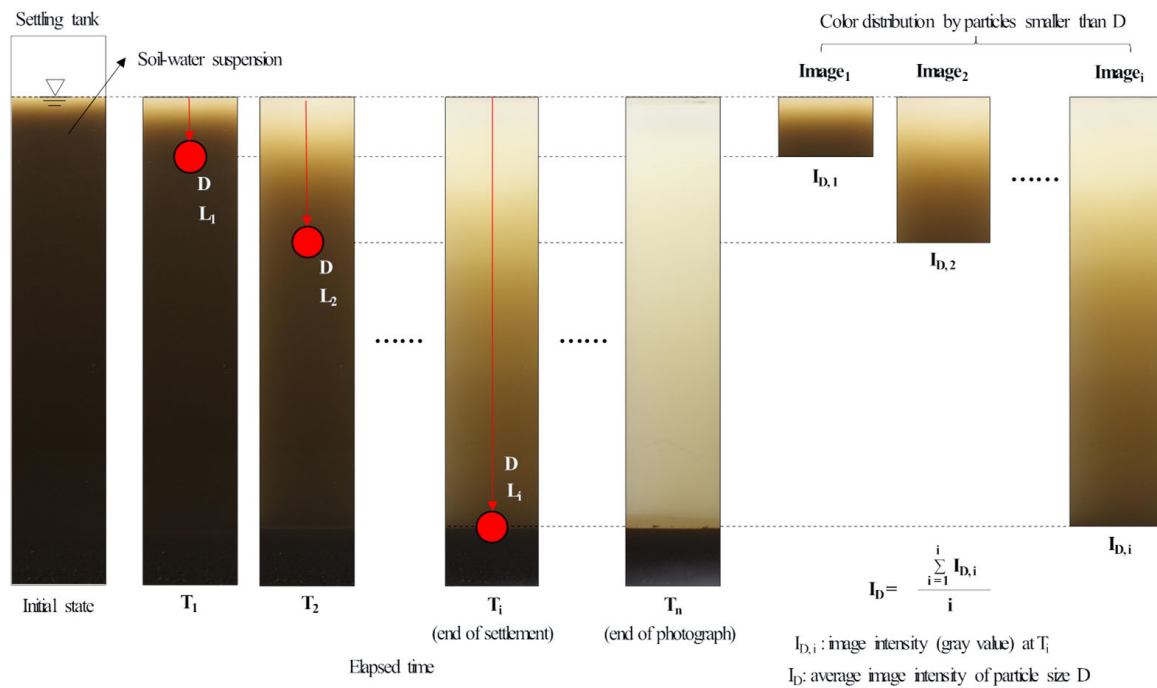


**Figure 4.** Conceptual diagram of machine vision-based soil particle size analysis.

The settling distance ( $L$ ), at time  $T$  for a particle having a diameter  $D$ , can be determined using Equation (2).  $L$  is directly proportional to the square of  $D$ . Consequently, particles that have settled below the distance  $L$  have sizes larger than  $D$ , whereas particles above the distance  $L$  have sizes smaller than  $D$ . Consequently, the color distribution in the image, specifically within the range of  $L$ , is primarily influenced by particles having diameters smaller than  $D$ .

In the hydrometer test, the hydrometer reading ( $\gamma$ ) at a particular value of  $L$  is measured using the hydrometer. This reading  $\gamma$  represents the density of the soil–water suspension, including particles having diameters smaller than  $D$  that have settled above  $L$ . According to Equation (7),  $\gamma$  is proportional to the percent finer ( $P$ ). Thus,  $\gamma$  serves as a measure of the weight of particles with sizes smaller than  $D$ . In this study, instead of using a hydrometer, we sought to represent the weights of the particles smaller than  $D$  by using image features.

Figure 5 depicts a schematic diagram of the movement of a particle of diameter  $D$  over time and its color change in a soil–water suspension. When the end of settlement of a particle with diameter  $D$  is  $T_i$ ,  $i$  images from  $T_1$  to  $T_i$  each contain images  $L_1$  to  $L_i$ . Each of these images represents the  $P$  values of particles smaller than  $D$ . Therefore,  $I_{D,i}$ , which is the average of the gray value of the  $i$ -th images ( $I_{D,i}$ ) taken from  $T_1$  to  $T_i$ , was calculated and used as a factor to predict the percent finer  $P$  of particles smaller than  $D$ .



**Figure 5.** Calculation process of machine vision-based soil particle size analysis.

Python was utilized for performing image processing tasks, including crop and color extraction. Various libraries such as NumPy, pandas, pillow, OpenCV, and matplotlib, among others, were employed for this purpose. The ROI was extracted by cropping it from the original image. Subsequently, the ROI was converted into a grayscale image. To analyze the grayscale image, the average gray value was calculated from the top of the image up to a specific value of  $L$ .

Root mean squared error (RMSE) is used as a metric to evaluate the accuracy of image-based particle size analysis. RMSE is calculated as follows:

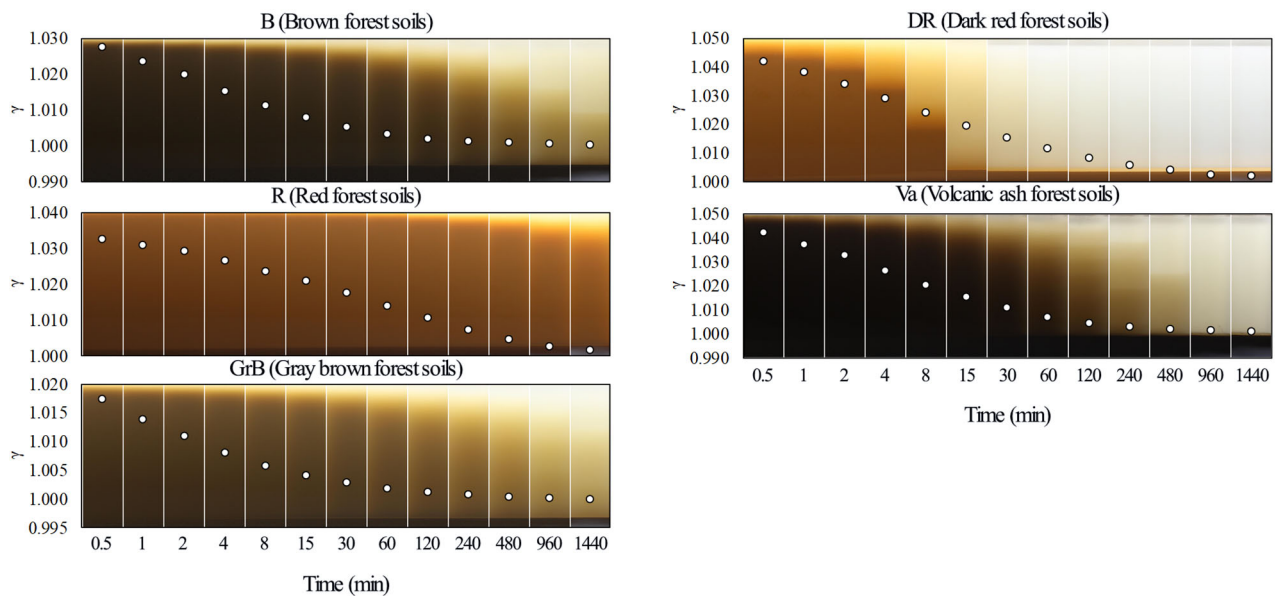
$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Predicted_i - Actual_i)^2} \quad (8)$$

where  $Predicted_i$  is the predicted  $i$ -th percent finer and  $Actual_i$  is the observed  $i$ -th percent finer.  $n$  is the number of data points.

## 4. Results

### 4.1. Image Analysis of Soil–Water Suspension during Settlement

Figure 6 shows the change in soil–water suspension and hydrometer reading during soil settlement over time. As time progresses, an observable trend emerges wherein the average color of the soil–water suspension gradually lightens. Specifically, in a soil–water suspension, the color tends to become lighter from the top downward. This phenomenon can be attributed to the gradual reduction in the concentration of suspended soil particles within the suspension. As settling occurs, the soil particles gradually settle down, leading to a decrease in their presence in the suspension. Consequently, the overall color of the suspension becomes lighter. Among the different soil types analyzed, Soil DR exhibited the most rapid color change, while Soil R exhibited the slowest. Within the initial 30-min period, most of the color change for Soil DR took place, with minimal additional color alteration thereafter.

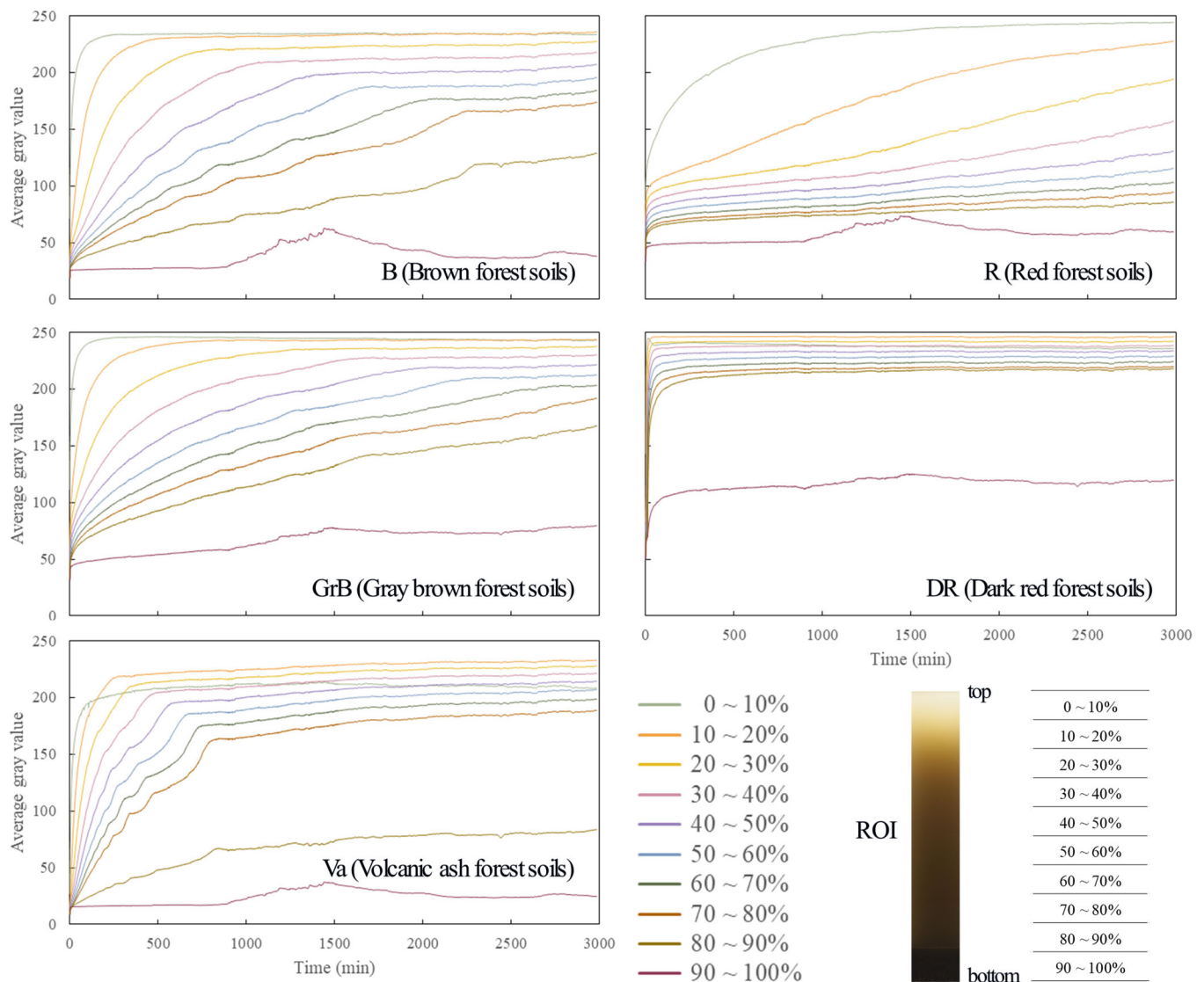


**Figure 6.** Changes in the hydrometer ( $\gamma$ ) reading and color in soil–water suspension according to time.

The presence of dark areas at the top of the region of interest (ROI) can be attributed to the settling of organic matter that was initially present on the water surface. During the settling process, these organic particles tend to migrate downward and accumulate in the upper portion of the ROI, resulting in the observed dark areas. On the other hand, at the bottom of the settling tank, particles that have completed the settling process are observed. It's important to note that the volume of settled particles after the settling process varies for each soil type. This discrepancy arises due to differences in particle size distribution, organic content, and other soil-specific characteristics. These variations result in differences in the volume of settled particles among different soil samples.

Additionally,  $\gamma$  gradually decreases over time in the settling process. The initial  $\gamma$  values differ among the soils due to variations in fine content (0.075 mm sieve passage). However, as the settling process progresses, the hydrometer readings ( $\gamma$ ) tend to converge towards a value close to 1. In hydrometer tests,  $\gamma$  is measured to calculate  $P$ , as expressed by Equation (7). Given this correlation between  $\gamma$  and particle sizes, it becomes feasible to explore whether certain image features of the soil change similarly to  $\gamma$ . By identifying image features that exhibit similar variations, the particle size distribution can be analyzed using image processing techniques.

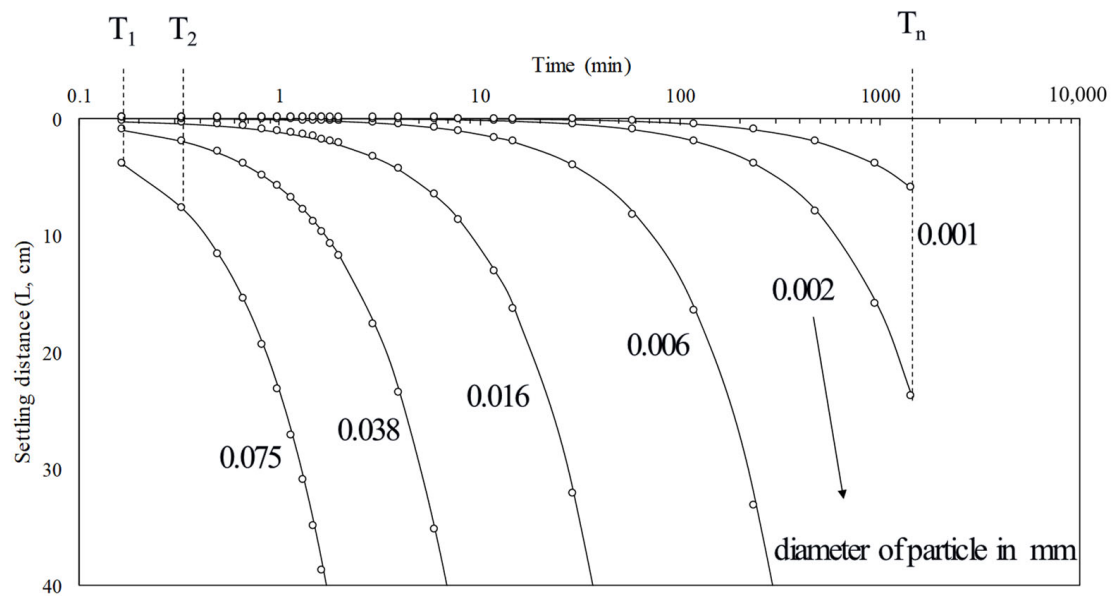
Figure 7 shows the changes in gray value observed in a soil–water suspension as the settling process occurs. Over time, the gray value gradually increases, indicating a lightening of the soil–water suspension as the soil particles settle. The color change within the soil–water suspension varies across different elevations within ROI. Notably, the upper section of the soil–water suspension (0–10% range) exhibits significant color change initially but eventually converges towards a constant value after the completion of the settling process. In contrast, the lower section of the soil–water suspension (90–100% range) is where the sedimentation of the soil occurs. Consequently, the color value trend in this area differs from the rest of the ROI. For soil Va, it is worth noting that a relatively large volume of soil deposition occurs compared to the other soils. In fact, deposited soil is observed even within the 80–90% range of the suspension. As a result, subsequent analyses were performed within the 0–80% range of the ROI, excluding potential soil deposition, to ensure accurate color measurements in soil–water suspension.



**Figure 7.** Changes of average gray value in soil–water suspension according to time.

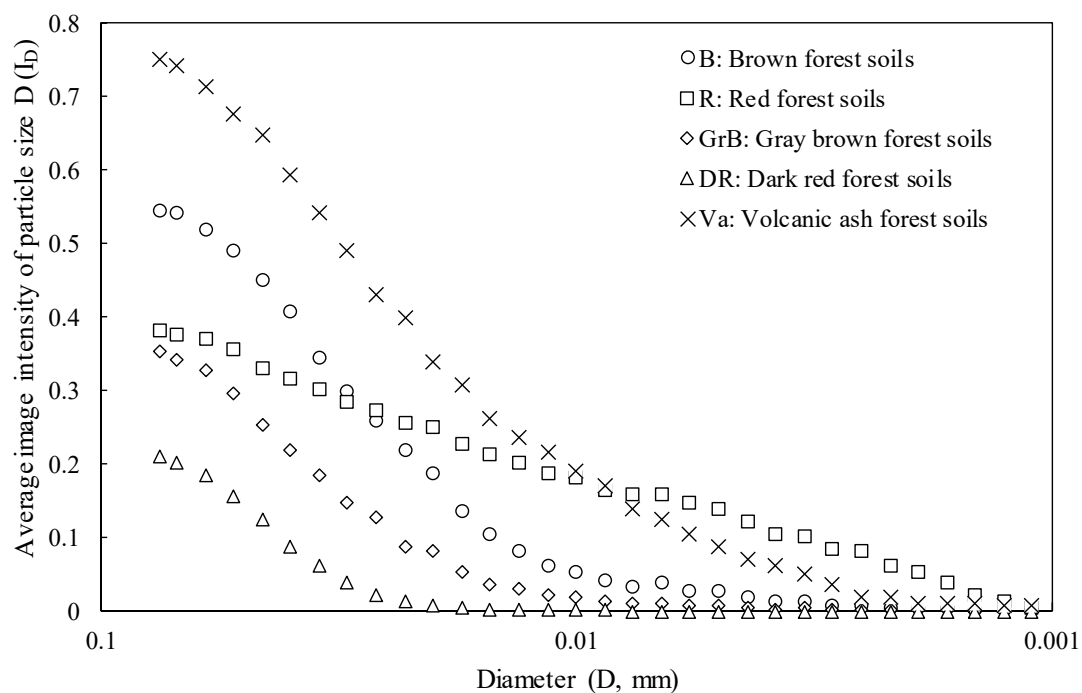
#### 4.2. Prediction of Particle Size Distribution by MVSPSA

Figure 8 shows the relationship between  $L$  and  $D$  for soil B. According to Equation (3),  $L$  is proportional to the square of  $D$ . Hence, larger diameter particles exhibit increasingly rapid settlement. Considering that the height of the soil–water suspension in the settling tank is 38.4 cm, it can be observed that a particle with a diameter of 0.075 mm takes approximately 1.6 min to completely settle. In contrast, a particle with a diameter of 0.038 mm takes approximately 6 min. Furthermore, a smaller particle with a diameter of 0.002 mm settles a distance of 23.9 cm after 1440 min, while a particle with a diameter of 0.001 mm settles a distance of 6.0 cm. Using this approach, the value of  $L$ , based on the  $D$ , can be calculated for each soil type.  $L$  is also influenced by the specific gravity ( $G_s$ ) of the soil particles. This is because heavier particles tend to settle relatively faster. Consequently, soil types such as R, GrB, and DR, which have  $G_s$  approximately 1.5–3% higher than that of soil B, would exhibit increased values of  $L$  compared to soil B. In contrast, soil Va, with  $G_s$  approximately 18% smaller than that of soil B, shows a slower settling velocity compared to other soils, resulting in a decrease in  $L$  over the same period.



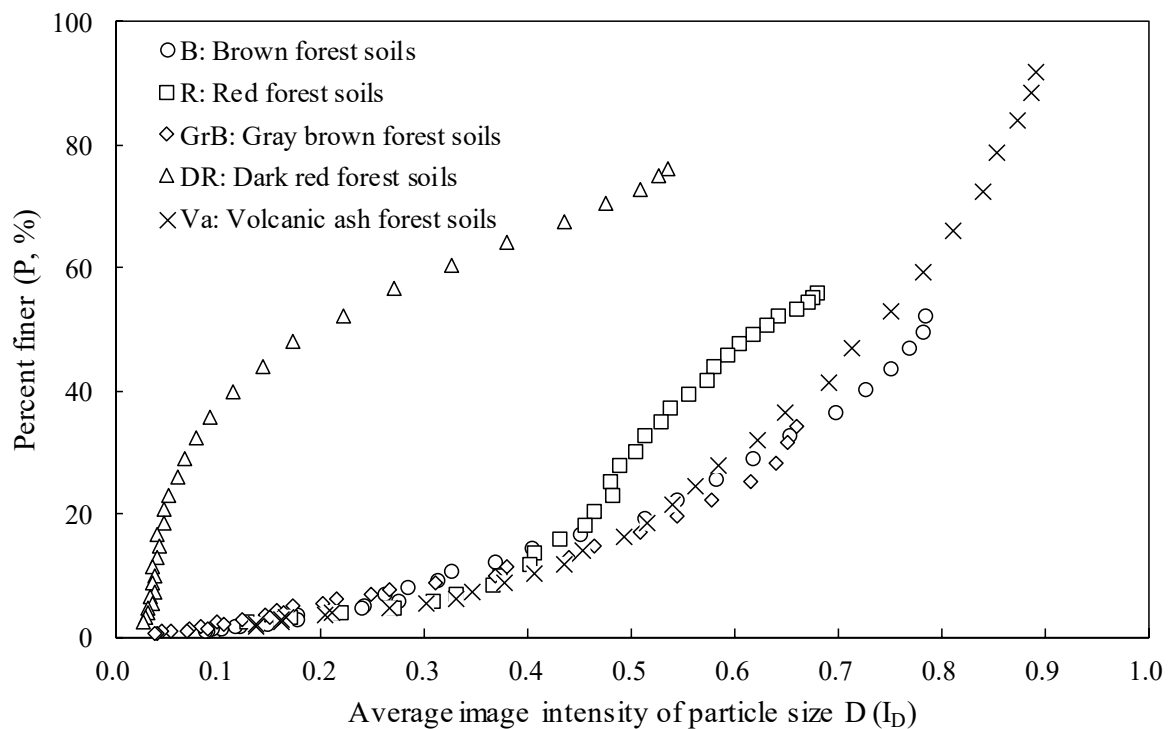
**Figure 8.** Relationship of settling distance ( $L$ ) and time ( $T$ ) for soil B.

Figure 9 illustrates the calculated values of  $I_D$  based on the particle diameter ( $D$ ). In an 8-bit grayscale image, the pixel intensity or gray value is represented by a value ranging from 0 (black) to 255 (white). Consequently, when the soil content within the soil–water suspension is high, the corresponding gray value of the image tends to be closer to 0. Conversely, if there is a minimal amount of soil present, the gray value tends to be closer to 255. For ease of interpretation, the scale of gray values has been adjusted to range from 0 (white) to 1 (black) rather than the original 0 (black) to 255 (white). Therefore, an  $I_D$  value closer to 1 signifies a darker image with a higher concentration of soil particles, whereas an  $I_D$  value closer to 0 represents a lighter image with a lower concentration of soil particles.  $I_D$  shows a decreasing trend as the diameter of the particle decreases, similarly to  $\gamma$ . This indicates the possibility of replacing  $\gamma$  with  $I_D$ .



**Figure 9.** Calculation result of  $I_D$  for various diameter of soil particles.

Figure 10 shows the relationship between  $I_D$  and  $P$ . This indicates that  $P$  has an exponential tendency to increase with  $I_D$ . Depending on the value of  $I_D$ ,  $P$  tended to increase exponentially. Consequently, it is inferred that by applying a suitable exponent to  $I_D$ , it is feasible to accurately predict  $P$ . However, it is important to note that Soil DR exhibited a distinct trend compared with the other four soil types. The relationship between  $I_D$  and  $P$  for Soil DR deviated from the expected exponential behavior observed in the remaining soils.



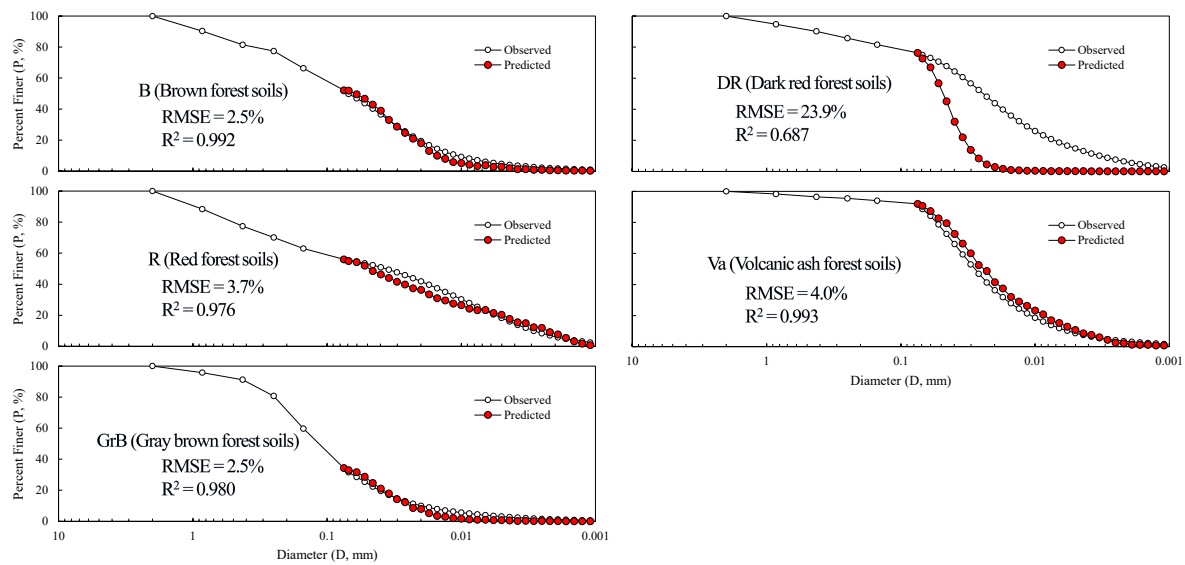
**Figure 10.** Relationship between average image intensity of particle size  $D$  and percent finer.

Considering the relationship between  $I_D$  and  $P$  shown in Figure 10, the prediction formula of  $P$  based on  $I_D$  is as follows:

$$P_D = I_D^m \times \frac{P_{0.075}}{I_{0.075}} \quad (9)$$

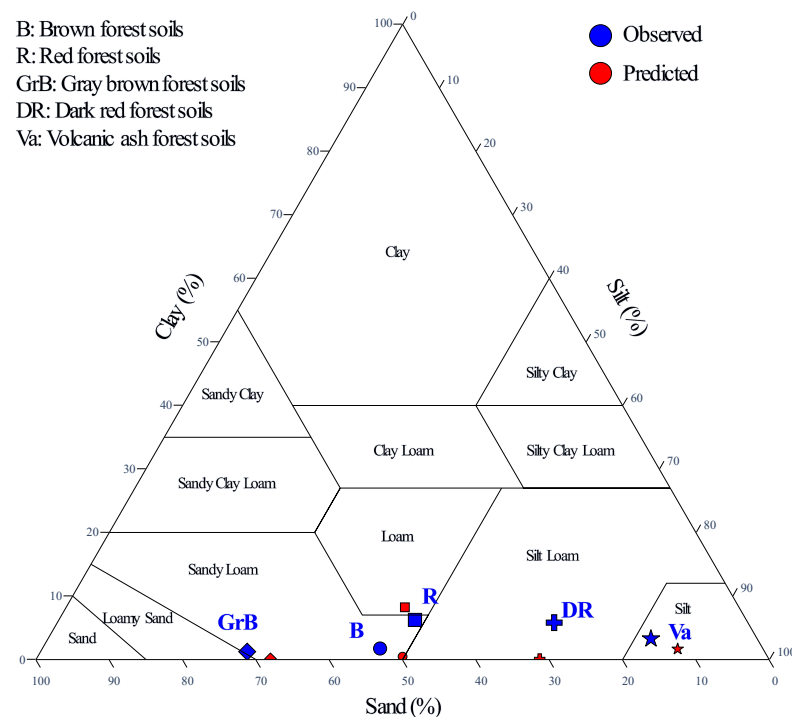
where  $m$  is exponent of  $I_D$ ,  $P_{0.075}$  is percent finer at  $D = 0.075$  mm,  $I_{0.075}$  is average image intensity of particle size = 0.075 mm.  $P_{0.075}$  and  $I_{0.075}$  were introduced to align the initial values of the image-based analysis results with the results of the sieve analysis. Depending on the value of  $m$ , the accuracy of the analysis results can vary. The optimal  $m$  for each soil was found to be different, but with the exception of DR, the other soils were found to be highly correlated when  $m$  ranged from 2 to 3. For Soil DR, the  $I_D$  did not exhibit an exponential relationship with  $P$ , resulting in a gradual decrease in correlation coefficient as  $m$  increased. On average, the highest correlation was found when  $m$  was 2.5. Therefore, it was decided to utilize  $m$  of 2.5 for predicting  $P$  using  $I_D$  across all soil types.

Figure 11 shows the results of the particle size analysis predicted using the proposed method. Except for Soil DR, the four remaining soil types yielded particle size distribution curves that closely matched the experimental results obtained from the laser particle size analyzer. Moreover, the root mean squared error (RMSE) of the prediction results, excluding Soil DR, demonstrated a high level of accuracy, ranging from 2.5 to 4.0%. This indicates that the proposed method provides reliable particle-size predictions for the analyzed soils, offering an effective alternative to hydrometer tests.



**Figure 11.** Particle size distribution curve predicted by machine vision-based soil particle analysis method for soil samples.

Figure 12 shows the USDA soil texture triangle depicting the sand, silt, and clay content calculated from the particle size analysis results. By utilizing the soil texture prediction derived from the image analysis, it becomes evident that the predicted soil texture closely corresponds to the soil texture determined from the actual particle size tests. This alignment between the predicted and calculated soil textures indicates the reliability and accuracy of the image analysis method for determining soil texture. The results confirm that the proposed approach successfully captures the essential characteristics of soil particles and enables the accurate prediction of soil texture based on particle size analysis.



**Figure 12.** Soil texture triangle predicted by machine vision-based soil particle analysis method for soil samples.

## 5. Discussion

### 5.1. Practical Considerations and Limitations

There are important considerations when implementing the machine vision-based soil particle analysis method proposed in this study.

Firstly, the analytical method relies on the average color of the image. However, it should be noted that color values in digital images can vary based on camera settings and lighting conditions. This means that the analysis results for the same sample can differ due to external factors affecting image color. To address this issue, establishing standardized lighting and shooting conditions or developing appropriate measures for correction when variations in shooting conditions occur is crucial. By ensuring consistency in image acquisition, the reliability and comparability of the analysis results can be enhanced.

Additionally, the analysis of the DR sample was not conducted appropriately, leading to different results compared with the other soil samples (B, R, GrB, and Va). This discrepancy is attributed to the rapid color change observed in the DR images within a very short period. While the other soils exhibited gradual color changes over a duration of 1440 min (1 day), the DR sample underwent significant color change within the initial 30 min, followed by a minimal color change afterward. However, it should be considered that the sedimentation of particles in the DR sample may still be occurring during periods when color changes are not observed. This discrepancy could be due to inadequate lighting or camera settings, which may have hindered proper observation of the settling process of small particles. To address these issues and ensure accurate and reliable results, optimizing the experimental setup, lighting conditions, and camera settings is recommended to capture the full range of particle settlement. Additionally, further investigations and adjustments specific to the DR sample may be necessary to improve the analysis methodology for this particular soil type.

### 5.2. Advantages of Proposed Method

This study introduces a machine vision-based soil particle analysis method utilizing a standard digital camera, presenting it as a viable alternative to the hydrometer test. The method offers several notable advantages.

Firstly, it enables experimentation on many samples. In this study, a single test successfully predicted the particle size of five samples. Although the resolution of commercial cameras imposes limitations on sample size, future improvements in camera technology and test setup optimizations can increase the number of simultaneous tests.

Additionally, the proposed method offers simplicity compared to hydrometer testing. Unlike the labor-intensive process of ongoing measurements required in hydrometer testing, the test described in this study can be automated after the initial setup, enhancing efficiency and reducing manual labor.

Furthermore, advancements in camera technology can further enhance the results. While a common commercial digital camera was utilized in this study, specialized cameras such as NIR or hyperspectral cameras allow for the observation of wavelengths beyond RGB. This opens possibilities for analyzing samples like DR that were challenging to study in this particular research. However, a notable strength of this study lies in its reliance on commonly available cameras, ensuring wider accessibility and distribution.

The proposed machine vision-based sedimentation test offers advantages such as the ability to experiment on larger sample sizes, simplicity compared to hydrometer testing, and potential enhancements with the progression of camera technology. Notably, this method utilizes widely accessible cameras, making it practical for various applications.

For the automation of hydrometer testing, Murad et al. [35] presented an automated hydrometer testing system for about \$70 using Time of Flight Distance (ToF). The system measures the distance between the hydrometer and the ToF sensor and converts it into a hydrometer reading. The study reported an  $R^2$  of percent finer of 0.857 to 0.896 when comparing the results of the automated system to the results of the pipette method. In this study,  $R^2$  at  $m = 2.5$  was 0.976 to 0.993 for the soils except DR. The clay content of

the soils in this study ranged from 1.2 to 6.2%, which is lower than the clay content of the soils used by Murad et al. [35], which ranged from 24.5 to 73.8%, which may explain the relatively high correlation. Compared to the above study, this study is considered to have the advantages of relatively simple system configuration and easy testing of a large number of samples. It is also significant that this study proposed a new method to analyze particle size by applying the principle of hydrometer test based on Stoke's law without using a hydrometer.

In particular, in this study, the percent finer was predicted based on the color change of the digital image, but in the further research, the hydrometer reading can be obtained directly by tracking the change of the position of the hydrometer in the digital image. In this regard, Souza et al. [36] applied machine vision technology to calibrate hydrometers that can be utilized in various industrial sites. Therefore, it is expected that machine vision-based hydrometer reading automation will be possible through further research.

## 6. Conclusions

This study focused on predicting the particle size distribution of fine-grained soil using digital image analysis. The study utilized a settling tank instead of a measuring cylinder to acquire digital images of soil–water suspensions during settlement. Image analysis techniques were applied to extract relevant features and predict the percent finer of particles smaller than a given diameter. The results showed a correlation between the average gray value of the images and the percent finer, indicating the potential of image-based analysis for particle size prediction.

The study investigated five forest soils, namely B, R, GrB, DR, and Va. The image analysis process involved cropping the region of interest (ROI) from the acquired images and calculating the average gray value up to a settling distance. The gray value decreased with decreasing particle diameter, similar to the hydrometer reading. The obtained gray values were then used to predict the percent finer of particles smaller than a given diameter.

The prediction results showed that the proposed method could closely align with the experimental results from a laser particle size analyzer for four out of five soil types. The RMSE of the prediction results ranged from 2.5% to 4.0%, indicating a high level of accuracy in particle size prediction.

Overall, this study demonstrates the potential of digital image analysis for predicting particle size distribution in fine-grained soils. The proposed method can provide a convenient and efficient alternative to traditional particle size analysis techniques, offering insights into soil properties and aiding in soil classification and characterization.

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