

DOLOČANJE KRIVULJE ZRNAVOSTI NEVEZLJI- VIH ZEMLJIN Z UPORABO SLIKOVNE ANALIZE

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Ključne besede

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Izvleček

Tehnologija obdelave slik vključuje shranjevanje slik predmetov na računalnik in njihovo obdelavo z računalnikom za določen namen. Slikovna analiza je številčni izraz slikovne podobe predmetov s posnemanjem delovanja človeškega očesa in ustvarjanje številčnih podatkov za izračune, ki bodo izvedeni kasneje. Digitalna slikovna analiza zagotavlja možnost za hitro merjenje, za številne parametre inženirskih materialov lahko takšno merjenje zagotovimo v skoraj realnem času. Slikovna analiza se v geotehnični inženirski praksi uporablja šele kratek čas. Krivulja zrna in oblika zrn sta temeljni lastnosti, ki se uporabljata za razlago izvora in obnašanja zemljin. Mehansko sejanje ima nekatere omejitve, npr.: ne meri se osna dimenzija delca, ni upoštevana oblika delcev, in zlasti za podolgovate in ploščate delce s sejalno analizo ne dobimo zanesljivih razmerij zrna. V tej študiji je bila porazdelitev velikosti zrn peska določena z uporabo tehnike slikovne analize, uporabljeni so bili preprost aparat, neprofesionalne kamere in odprto-kodna programska oprema. Analiza se izvede tako, da se vzorec postavi na pregledno ploščo, ki je z ozadja osvetljena z belo osvetlitvijo. Digitalne slike se dobijo s pomočjo CCD DSLR kamere. Segmentacija delcev se dobi z nastavljanjem pragov slike, binarno kodo in označevanjem delcev, geometrijske meritve posameznega delca pa z uporabo avtomatizirane tehnike štetja slikovnih pik. Lokalni stiki ali omejeno prekrivanje so bili premagani s pomočjo transformacijske tehnike ločevanja. Isti vzorec je bil testiran s tradicionalno sejalno analizo. Primerjave rezultatov kažejo, da se krivulji zrna dobljeni s slikovno in sejalno analizo dobro ujemata.

DETERMINING THE GRAIN SIZE DISTRIBUTION OF GRANULAR SOILS USING IMAGE ANALYSIS

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Keywords

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Abstract

Image-processing technology includes storing the images of objects in a computer and processing them with the computer for a specified purpose. Image analysis is the numerical expression of the images of objects by means of mimicking the functioning of the human visual system and the generation of numerical data for calculations that will be made later. Digital image analysis provides the capability for rapid measurement, which can be made in near-real time, for numerous engineering parameters of materials. Recently, image analysis has been used in geotechnical engineering practices. Grain size distribution and grain shape are the most fundamental properties used to interpret the origin and behaviour of soils. Mechanical sieving has some limitations, e.g., it does not measure the axial dimension of a particle, particle shape is not taken into consideration, and especially for elongated and flat particles a sieve analysis will not yield a reliable measure. In this study the grain size distribution of sands has been determined following image-analysis techniques, using simple apparatus, non-professional cameras and open-code software. The sample is put on a transparent plate that is illuminated with a white backlight. The digital images were acquired with a CCD DSLR camera. The segmentation of the particles is achieved by image thresholding, binary coding and particle labeling. The geometrical measurements of each particle are obtained using an automated pixel-counting technique. Local contacts or limited overlaps were overcome using a watershed split. The same sample was tested by traditional sieve analysis. An image-analysis-based grain size distribution has been compared with a sieve-analysis distribution. The results show that the grain size distribution of the image-based analysis and the sieve analysis are in good agreement.

1 INTRODUCTION

Researchers in the geotechnical community understand that heterogeneity is a basic characteristic of geomaterials and employ considerable efforts for these heterogeneity problems. The grain size distribution (GSD) is one of the basic and most important properties of granular soils that exhibit heterogeneity. It is used in soil classification systems (such as USCS, AASHTO) and empirical estimation equations to estimate the permeability, shear strength, deformability and compactability. GSD is very important for geotechnical engineering. In site investigations of large engineering structures, in earthquakes and liquefaction research and before filter material selection, it is necessary to make a number of GSD analyses. The gradation of the in-situ soil often controls the groundwater drainage of the site. A poorly

graded soil will have better drainage than a well graded soil. When a fill material is being selected for a highway embankment or an earthen dam, the soil gradation is considered. A well-graded soil can be compacted more than a poorly graded soil. These types of projects may also have gradation requirements that must be met before the soil to be used is accepted. When options for ground-remediation techniques are being selected, the soil gradation is a controlling factor. In addition to geotechnical applications in geological and agricultural studies, GSD is widely used.

There are two common test methods to determine the GSD: mechanical sieving for the coarse-grained soils and sedimentation tests (pipette and hydrometer methods) for the fine-grained soils. In sieve analysis, the particle size is determined by a dimension that represents the sieve aperture through which the particle passes. Although the size distribution can be obtained roughly, the shape of a grain cannot be taken into consideration in these traditional methods. Moreover, sample drying before the test and the sieving procedure make this method time and effort consuming; hence, it is an expensive method. Digital image analysis would be a practical alternative to make GSD measurements easier.

Digital image analysis extracts information from objects that are captured by an imaging system. The digital image processing and analysis techniques can be summarized in four basic steps: taking photographs with a digital camera, storing the image file as a digital file, image processing to edit the digital images for specific analysis, and analysis of the modified image to quantify the properties of an object. Digital image processing and analysis are used for detailed works of many disciplines, including medicine, genetics, biology, textiles, food science, geology, physics, chemistry, agriculture, forestry, mining, computer engineering, civil engineering and environmental sciences. In the past decade image-analysis techniques have been used with increasing intensity in areas of geotechnical engineering such as deformation measurements [1, 2], failure analysis [3], porosity analysis [4, 5], grain size and shape analysis [6, 7, 8, 9, 10] and the determination of geotextile properties [11].

In this study the grain size distributions of sands are determined using a mechanical method with traditional sieves and image-analysis techniques using simple apparatus and consumer-grade cameras. A new approach to determine the mass-based distribution from 2D images is introduced. The results of these two techniques are compared. The advantages and limitations of the image-analysis-based grain size distribution determination are evaluated.

2 IMAGE PROCESSING AND ANALYSIS

Digital image processing (DIP) is the use of computer algorithms to create, process, communicate, and display digital images for specified purposes. After the processing of the digital images, digital image analysis (DIA) techniques are used for measurement, classification, database and statistical purposes. Some properties of the numbers of objects in an image (shape, dimension, area, location, boundary properties etc.) can be determined easily by means of DIA. Most DIP and DIA studies are based on binary modeling. A binary model consists of pixels that are quantized using only two values, 0 and 1, representing the full black and the full white colors, respectively. Editing of the binary images is often required to enhance the delineation of the individual object.

There are many types of software used for filtering, color and contrast adjustment, measurement, and classification. ImageJ [12] is commonly used image-processing and analysis software that was developed as a Java-based program by the National Institutes of Health (NIH). ImageJ and similar programs (e.g., Scion Image, ImageTool, Digimizer, Clemex, Image Pro Plus) are being used to solve numerous tasks in scientific disciplines, including the analysis of geo-materials (e.g., Szramek et al, [13], Polacci et al., [14]). These softwares are designed to process input images that can include rectangular raster files (e.g., *.tiff, *.jpg, *.gif, etc.) encoded in 8-bit grey-scale formats.

Developments in digital-imaging technology and image-processing/analysis software have provided the means for the development of new methods for particle size analysis based on image analysis [15, 16, 17, 18, 19]. In addition to a grain size distribution, using the digital image-analysis techniques other soil grain characteristics, such as sphericity, particle elongation, roundness, etc. can be readily quantified [20].

3 GRAIN SIZE OF GRANULAR SOILS

The grain size and shape are the most fundamental properties used to interpret the origin and behaviour of soils. Grain size distribution (GSD), also known as gradation, refers to the proportions by dry mass of a soil distributed over specified particle size ranges. Although there are several methods for measuring the GSD of fine-grained soils (such as pipette, hydrometer, laser diffraction, X-ray sedimentation), for the GSD of granular soil there is no current method more practical than sieve analysis. Laser diffraction can be used for

fine sands, but it cannot work over 3 mm in size and the amount of sample tested is very small. Therefore, the sieve analysis is an indispensable and widely used method in geotechnical applications.

Mechanical sieving is a simple method that is commonly used in the civil engineering disciplines. Although the size distribution can be obtained roughly, the shape of a particle is not easy to describe in simplified terms. The size of a spherical object or a cube can be described with one dimension; however, the particles in a soil mass are irregular and nonuniform in shape in general. In a sieve analysis, the size of a particle is related to the size of the square aperture in which the particle passes. The size distribution is calculated based on the mass of all the particles retained on a sieve. The method has some limitations; it does not measure the axial dimension of a particle [19]. Particle shape is not taken into consideration, especially for elongated and flat particles a sieve analysis will not yield a reliable measure [21, 22, 23, 24].

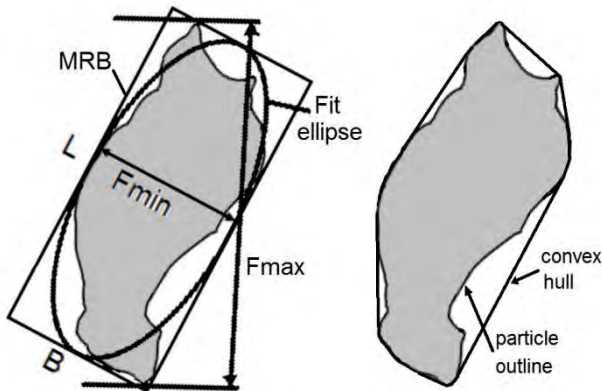


Figure 1. Dimension terms; F_{min} : Minimum Ferret's diameter, F_{max} : Maximum Ferret's diameter, MBR: Minimum bounding rectangle, B: Width, L: Length. Fit ellipse: Ellipse which fit in a MBR.

In reality, irregular particles need to be measured with more than one dimension. The maximum Ferret's diameter, F_{max} (also known as the maximum caliper) is the longest distance between any two points along the particle boundary. Similarly, the minimum caliper diameter of the particle is the minimum Ferret's diameter (F_{min}). The minimum bounding rectangle (MBR), also known as the bounding box, is an expression of the maximum extents of a 2-dimensional object that fits in a rectangle. The dimensions of the MBR can be used to obtain the dimensions of the fit ellipse (the ellipse that fits into the MBR) (Figure 1). Rectangularity and ellipticity are two index parameters that define the shape similarity of a particle to a rectangle or ellipse, respectively. A simple approach to measuring rectangularity is to use the ratio of the area of the region to the area of its minimum bounding rectangle (MBR). Similarly, ellipticity is the ratio of the area of the region to the area of an ellipse that fits in the minimum bounding rectangle (MBR).

4 METHODOLOGY

4.1 Imaging and Processing

The experimental arrangement used in the present work is simple and inexpensive. Figure 2 shows a schematic diagram of the imaging system. Sand samples to be analyzed were washed on a 0.075 mm sieve using tap water and dried in an oven. In practice an air-dried sample is adequate. The sand sample is put on a transparent glass plate that is illuminated with a white backlight. A high contrast between the soil grains and the background is supplied by backlight illumination. An upright mounted light and diffuser white plate under the glass plate provide uniform illumination and maintain a sufficient contrast. To increase the total image size

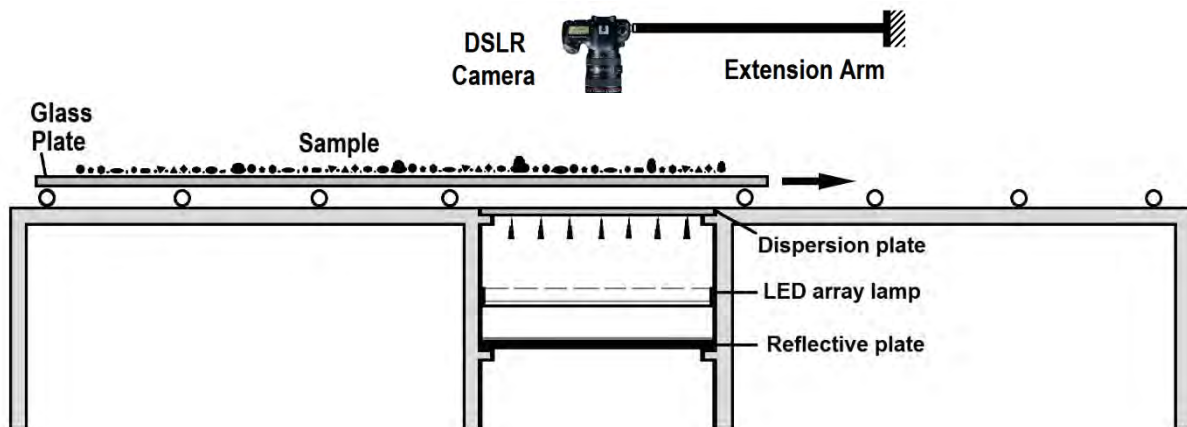


Figure 2. Experimental Set-Up.

without reducing the resolution, stitching consecutively taken pictures into a long strip picture provides a practical solution. In this technique, a camera that is mounted on a stage takes pictures continuously, while the glass plate moves laterally (Figure 2). The images of adjacent fields should be captured with at least a 30 % overlap.

Digital images have been acquired with a charged-coupled device (CCD) camera having a 15-megapixels resolution. To maintain high quality, a vibration-reduction (VR) lens and a remote-control device were used. Due to electronic noise in the camera system or nonuniformity in the background, random noise (dirt) occurs on an RGB (color) image. This problem can be effectively eliminated by filtering these noises, using noise-reduction filters. The segmentation of the particles is achieved by image thresholding, binary coding and particle labeling. The initial color image is converted into a binary image in which the particles are set to black (0), while the background is set to white (1).

Having a clear binary image after image processing, the geometrical measurements of each particle can be made by pixel counting. The true dimensions are determined by scaling. The soil sample should be placed sparsely, such that all individual grains should not overlap with each other. An overlap of the grains in the sample results in agglomeration. Local contacts or limited overlaps can be overcome using “watershed analysis”, which has been proposed to determine the boundaries of objects in digital images [25, 26]. In the case of the crowded placement of particles, watershed analysis may not be sufficient or lead to reduced individual particle sizes.

4.2 Calculations

The chain code (Freeman chain code) and mid-crack code are popular coding techniques for determining the outline of binary images. These codes encode the boundary of the object as a sequence of steps, from pixel to pixel, all around the object. The chain code moves along the center of the border pixels, while the crack code moves along a sequence of "cracks" between two adjacent border pixels. In both ways the outline is a connected sequence of straight-line segments with specified lengths and directions (Figure 3).

The chain code is disadvantageous when the area and perimeter of a particle is to be calculated. The inside chain code underestimates the area and perimeter, while the outside chain code overestimates them. The mid-crack code in area and perimeter computation results in a lower error value compared to the chain code and therefore the mid-crack code may be desirable in outline tracing [27]. However, if the backlight is used, such as in our case,

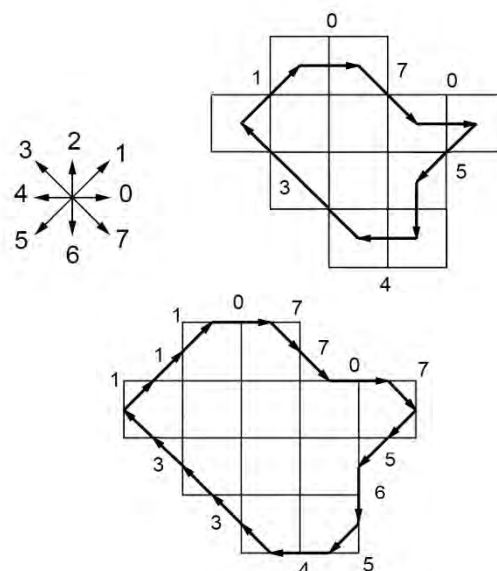


Figure 3. (a) 8 code words represent 8 directions (8-neighborhood), (b) The Freeman chain code of the object, (c) The mid-crack code of the object.

the situation is reversed. The measured area of a particle based on pixel counting will be larger than the true particle area. When a backlight is used the background pixels have a gray-scale value equal to just 255. If a particle boundary intersects a background pixel, the projected light is diminished and its gray-scale value will be less than 255. Thus, Raschke and Hryciw [15] calculated the true particle area as equal to the pixel counted area minus one half the areas of the boundary pixels. Actually, this can be achieved by using the Freeman chain code approach instead of the mid-crack code. In this study the particle outlines were drawn using the chain code and the areas of this outline were calculated accordingly.

Using image-analysis techniques the projection areas of individual particles are calculated automatically. An area-based particle size distribution can be obtained easily; however, a mass-based distribution would be more realistic. The problem here is the pictures are in two dimensions and a measurement of the particle thickness is impossible. A uniform particle shape in soils such as a cube or a sphere is rare. However, soil particles are nonuniform, most of the particles have resemblance to standard geometries such as cube, prism, sphere and ellipsoid. In fact a cube is a rectangular prism with three equal dimensions. Similarly, a sphere is a special case of an ellipsoid. Therefore, the volume of particles similar to an ellipse and a rectangle projection area can be calculated automatically.

If soil particles are dropped onto a horizontal plane, they will always drop on their smallest dimension perpendicular

ular to that plane. Therefore, particle thickness should be the minimum dimension of a particle. The thickness and volume of particles cannot be obtained directly from the 2D images. Based on the assumption that particles from the same source should have more or less the same shape characteristics [16], the mean thickness of a particle from the breadth of the particle can be estimated as:

$$\text{Mean thickness} = \text{breadth} \cdot \left[\frac{M}{\rho \cdot \sum_{i=1}^n (\text{breadth} \cdot \text{area})} \right] \quad (1)$$

where M is the total mass of the aggregate sample.

In Mora and Kwan's approach [16] the particle shape is supposed to be a polygonal prism. In reality the particle shape is irregular in 3D. However, some particles look like an ellipsoid (a sphere is a special form of an ellipse) and some a rectangular prism (a cube is a special form of a rectangle) (Figure 4). This assumption is more realistic and results in a smaller error.

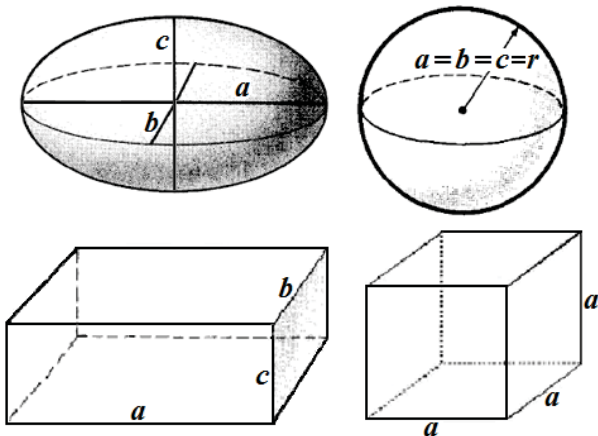


Figure 4. Ellipsoid (a sphere is a special form of ellipsoid) and rectangular prism (a cube is a special form of rectangular prism) assumption for soil particles.

In 2D image analysis the rectangularity and ellipticity of the particles can be calculated. Therefore, in this study the volume of the particles have been calculated for ellipsoidal shape if the ellipticity is higher than the rectangularity, otherwise the volume is calculated for a rectangular prismatic shape. Initially, the thickness of particles is assumed to be equal to the medial dimension (b). The density of dry sand ranges between 2.64 and 2.67 g/cm³, and a calculation of the mass, taking the dry density equal to 2.65, is reasonable. Dividing the weighted mass of the whole soil sample to a cumulative mass calculated according to the way explained above, a correction factor will be obtained (bracket in equation 1). Multiplying this by a medial dimension (b) of every individual particle, the thickness can be estimated (Equation 2).

$$\text{Thickness} = \left[\frac{M}{\rho \cdot \sum_{i=1}^n (\text{volume})} \right] \cdot b \quad (2)$$

The grain size distribution curve is drawn as a semi-logarithmic graph of percent passing - particle diameter. In a sieve analysis the particle diameter is assumed to be equal to the sieve opening. In reality, the medial dimension or minimum Ferret's dimension of a particle in 2D passes through the diagonal of a square sieve aperture (Figure 5a). Therefore, the equivalent particle diameter (D_e) for 2D analysis should be calculated as;

$$D_e = F_{\min} / \sqrt{2} \quad (3)$$

(Figure 5a). In this study the images of particles are assumed to be ellipsoid or a rectangular prism according

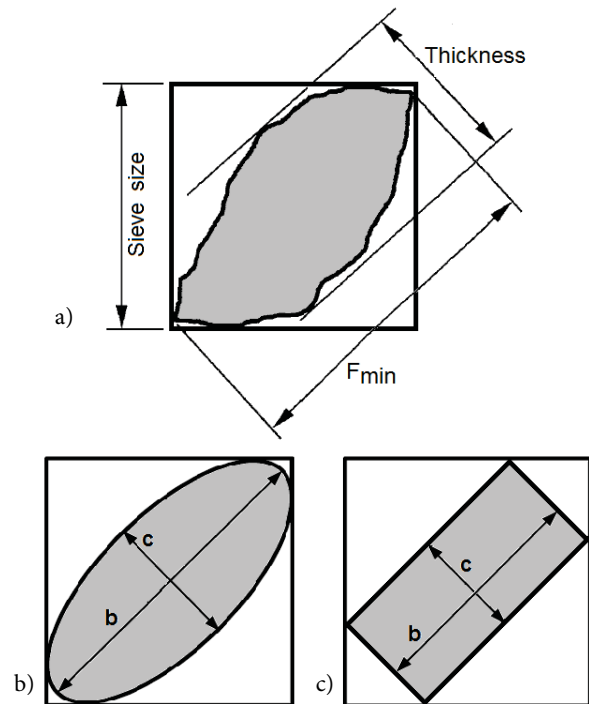


Figure 5. a) Minimum Ferret's dimension of a particle may pass through the diagonal of square sieve aperture, b) Ellipsoid assumption, c) Rectangular prism assumption.

to the shape similarity of a particle to an ellipse or a rectangle, respectively. Therefore, the equivalent particle diameter (D_e) should be:

$$D_e = \sqrt{0.5 \cdot (b^2 + c^2)} \quad (4)$$

for an ellipsoid (Figure 5b) and

$$D_e = (b + c) / \sqrt{2} \quad (5)$$

for a rectangular prism (Figure 5c).

4.3 Mechanical (sieve) analysis

A grain-size distribution by sieve analysis was performed in accordance with the procedure suggested by ASTM D422-63 [28]. Traditional grain-size distribution curves based on a sieve analysis are shown in figures 6-11.

5 RESULTS AND DISCUSSION

Six different samples were analyzed (Table 1). A 24 MP CCD DSLR camera, 300 mm / macro lens and remote control were used for the photography. In the binary images the grains were numbered and geometrical

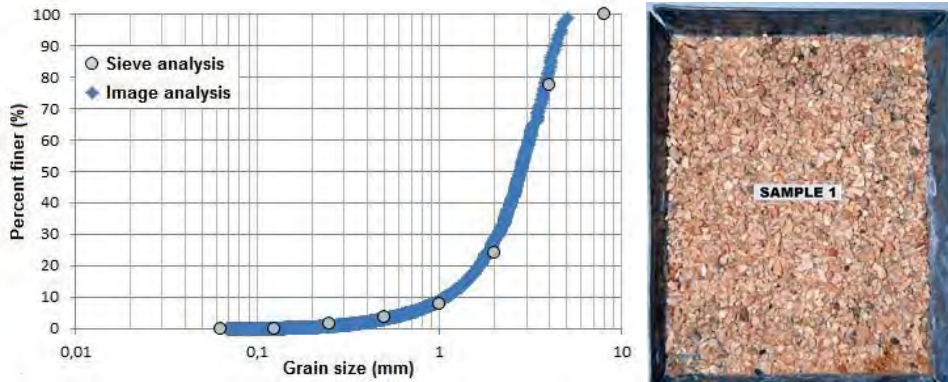


Figure 6. Comparison of sieve analysis and image analysis results for sample 1.

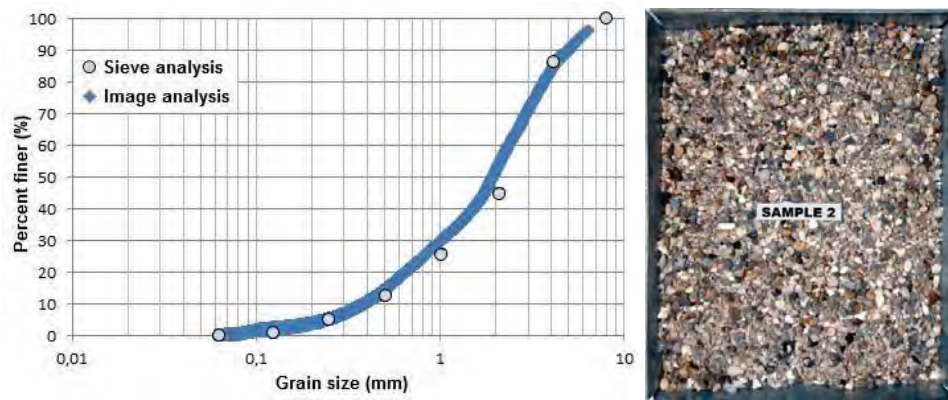


Figure 7. Comparison of sieve-analysis and image-analysis results for sample 2.

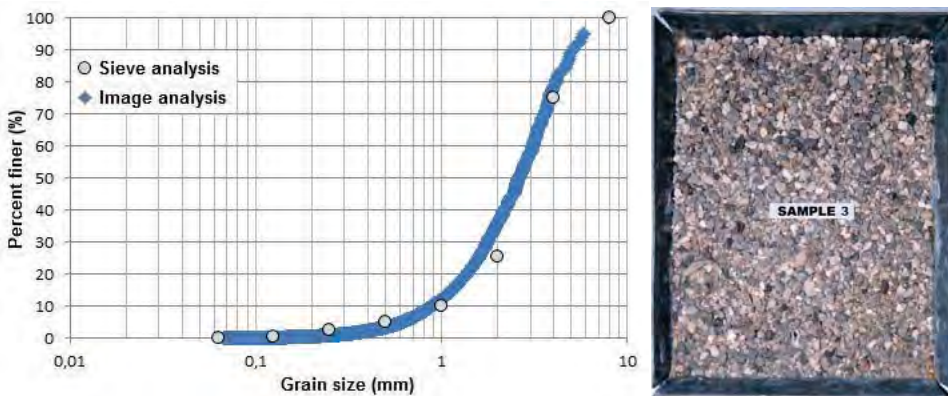


Figure 8. Comparison of sieve-analysis and image-analysis results for sample 3.

measurements of the grains were made automatically. F_{max} , F_{min} , the minimum boundary rectangle (MBR) and area measurements were made. The volume calculations were carried out with the assumption of a rectangular prism and ellipsoid. For every grain the equivalent grain size and percent finer values were calculated and

plotted on semi-logarithmic graphs (Figure 6-11). The soil samples were also tested using a conventional sieve analysis technique for comparison purposes. Most parts of the grain size distributions determined using the sieve analysis and the image analysis are in good agreement.

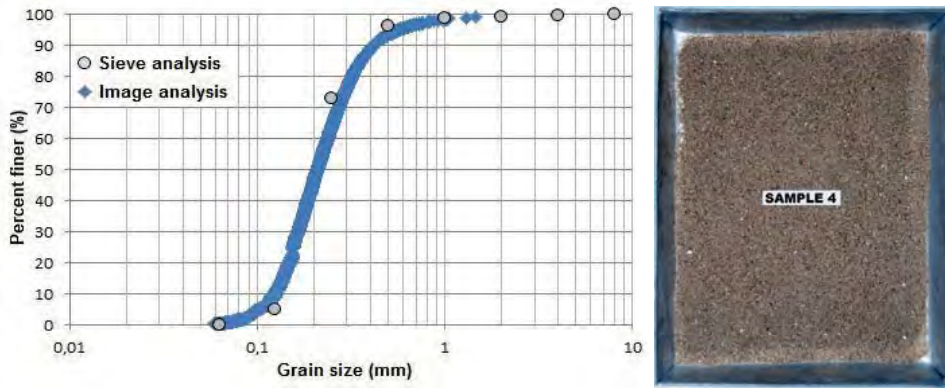


Figure 9. Comparison of sieve analysis and image analysis results for sample 4.

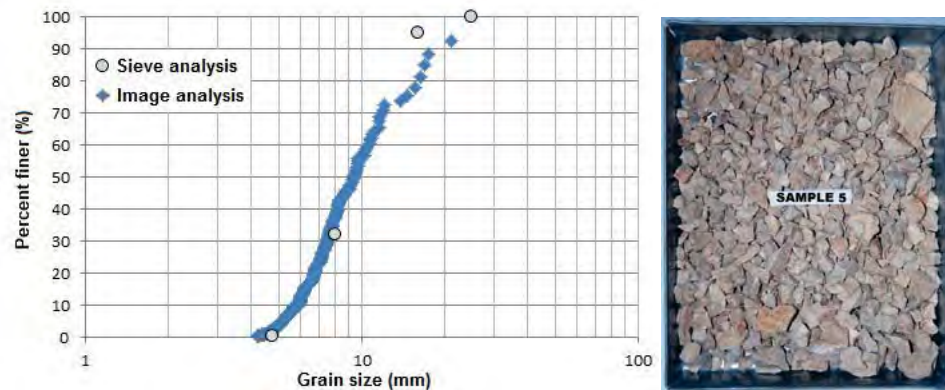


Figure 10. Comparison of sieve-analysis and image-analysis results for sample 5.

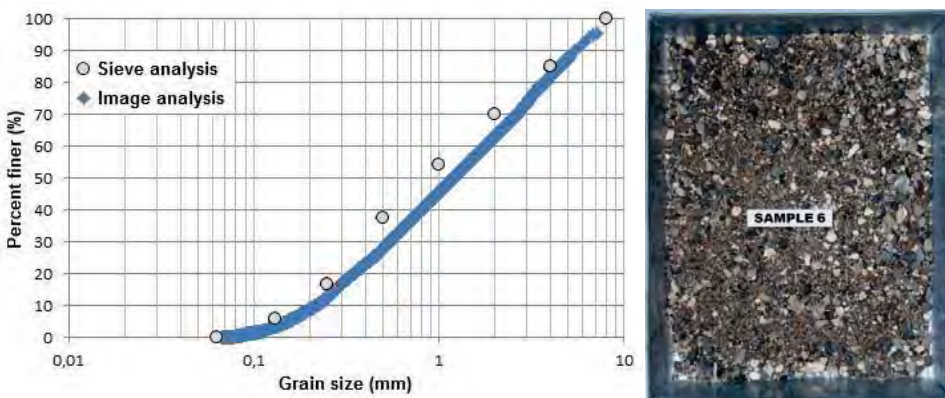


Figure 11. Comparison of sieve-analysis and image-analysis results for sample 6.

Table 1. Summary of measurements made by image-analysis method.

#	D ₁₀ (mm)	D ₃₀ (mm)	D ₆₀ (mm)	C _u	C _c	Soil class (USCS)	Number of grains	L _{max} (mm) *	L _{mean} (mm) *	L _{min} (mm) *	Mass (g)
1	1.10	2.05	3.00	2.72	1.27	SP	25163	12.74	0.48	0.08	18.31
2	0.37	1.05	2.30	6.21	1.29	SW	71245	10.62	0.40	0.08	14.69
3	1.00	2.10	3.00	3.00	1.47	SP	31318	17.77	0.48	0.08	17.23
4	0.14	0.17	0.22	1.57	0.94	SP	100981	2.77	0.25	0.08	2.06
5	6.00	7.80	10.0	1.67	1.01	GP	246	38.08	13.21	6.07	225.2
6	0.20	0.40	1.20	6.05	1.03	SW	65245	11.32	0.42	0.08	14.26

* L_{max}, L_{mean}, L_{min}: Maximum, mean and minimum values of maximum grain dimension (L)

In contrast to a sieve analysis, in the image analysis method a fully dried sample is not required. In the air dry condition to allow grains to scatter is enough. This means both energy and time saving. Volume and mass determinations are necessary to obtain grain size curves analogous to the sieve analysis. Area based distributions are not realistic. The image analysis software used should enable measurements of geometrical features other than the perimeter and the area (such as Ferret's dimensions, MBR etc). If the target is to obtain a GSD curve analogous to sieve analysis, by using the methodology given in this study, the width of the grain (B or F_{min}) is utilized as an equivalent dimension. Otherwise, we can plot GSD curves freely by taking any dimension of the grains, such as F_{max}, L or the mean dimension.

A uniformly distributed backlight intensity is crucial. At the start of the study incandescent light bulbs, fluorescent bulbs and fluorescent bars were tried. Even using a thick dispersion plate, a uniform light intensity was not possible. A nonuniform light intensity causes a nonuniform background, and during binary coding, dark-gray portions of the background may be coded as a grain. Bulb lamps located at the centre caused a shadow under large grains located at the sides. Finally, a cool white LED array lamp having dimmer power adjustment gave the best results. In this way an uniform light intensity is possible and the grain shadows are eliminated.

6 CONCLUSIONS

- 1) This study shows that the grain size distributions of sands can be determined via image-analysis techniques and using a simple setup and a consumer-grade camera. The results of the image analysis were compared with conventional sieve analysis results. The distribution determined by the sieve analysis was concluded to be compatible with the conventional sieve analysis.
- 2) The image analysis used for the grain size distribution practice has advantages over conventional sieve analysis. While in sieve analysis the percentages

for a certain range of grain size are determined, in the image-analysis method determining all the size properties of the each grain is possible.

- 3) The equivalent size in the sieve analysis can only be related to the median size of the grain. This is a limitation of the sieve method. However, in the image analysis the grain size distribution can be made for any of the grain dimensions.
- 4) Despite these advantages, the main limitation of the image-analysis method is the insufficiency of tests to represent the whole soil mass due to the use of a small amount of samples. This issue can be overcome by doing successive tests or increasing the length of the sliding table. In this case we need to spend more time and effort compared to previous, but this can be solved by improving the apparatus and writing special computer programs. This work hopes to be a first step towards the development of GSD application for image analysis and future work will include an improvement of the technique.

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