Particle Shape Determination by Two-Dimensional Image Analysis in Geotechnical Engineering

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ABSTRACT

Particle shape of soil aggregates is known to influence several engineering properties; such as the internal friction angle, the permeability etc. Previously shape classification of aggregates has mainly been performed by ocular inspection and e.g. by sequential sieving. In geotechnical analysis has been a lack of an objective and rational methodology to classify shape properties by quantitative measures.

Recent development in image analysis processing has opened up for classification of particles by shape. In this study 2D-image analysis has been adapted to classify particle shape for coarse grained materials. This study covers a review of soil classification methods for particle shape and geometrical shape descriptors. The image analysis methodology is tested and it is investigated how the results are affected by resolution, magnification level and type of shape describing quantity. Evaluation is carried out on as well idealized geometries as on soil samples. The interpreted results show that image analysis is a promising methodology for particle shape classification. But since the results are affected by the image acquisition procedure, the image processing, and the choice of quantity, there is a need to establish a methodology to ensure the objectivity in the particle shape classification.

Keywords: Image Analysis, Laboratory test, Soil classification, Granular materials, Geomorphology.

1 INTRODUCTION

1.1 Background

Particle shape is known to influence technical properties of soil material and unbound aggregates (Santamarina and Cho, 2004; Mora and Kwan, 2000). Among documented properties affected by the particle shape are e.g. void ratio (porosity), internal friction angle, and hydraulic conductivity (permeability) (Rouse et al., 2008; Shinohara et al., 2000; Witt and Brauns, 1983). In geotechnical guidelines particle shape is incorporated in e.g. soil classification (Eurocode 7) and in national guidelines e.g. for evaluation of friction angle (Skredkommisionen, 1995). This classification is based on ocular inspection and quantitative judgement made by the individual practicing engineer. There is today no general accepted system to apply ocular classification but there are several systems suggested (Powers, 1953; Krumbein, 1941). These systems are not coherent in definitions. The lack of possibility to objectively describe the shape hinders the development of incorporating the effect of particle shape in geotechnical analysis.

In the ballast industry there are established standardised classification systems incorporating particle shapes (e.g. EN 933-4, 2008 and ASTM D 4791, 2005). These systems have been developed basically for quality control and for industry requirements; e.g. railway ballast and concrete manufacturing and are focusing on simple geometries. Besides these examples there are
a number of potential areas of application of shape classification of soil materials.

Recent progress has resulted in that image acquisition and image analysis has been proven to be useful tools for two-dimensional analysis of simple geometries (Persson, 1998). The geometry of soil particles is however complex and there is a need of development to validate appropriate geometrical definitions and algorithms as descriptors for useful particle shape classification in practise. In Johansson & Vall (2011) a pre-study was performed in order to identify and compile information concerning particle shape of coarse grained soils; the impact on geotechnical properties, existing quantities and definitions, and determination by usage of image analysis. This paper incorporates the results from the mentioned pre-study.

1.2 Scope of study

The scope of this study is to explore the possibilities and limitations concerning applying image analysis for soil particle shape classification.

The goals of the study are:
1) To describe a methodology for soil particle shape determination by image acquisition and analysis.
2) To enlighten results from comparisons of different geometrical definitions, including usability and sensitivity.

The study consists partly of a literature review of as well particle shape determination as of existing definitions. Moreover, the image analysis methodology is tested and discussed.

2 PARTICLE SHAPE

2.1 Terms and quantities

In this study the word shape is used to describe a grain’s overall geometry. Furthermore, in order to describe the particle shape in more detail, there are a number of terms, quantities and definitions used in the literature. Some authors (Mitchell & Soga, 2005; Arasan et al., 2010) are using three sub-quantities; one and each describing the shape but at different scales. The terms are morphology/form, roundness and surface texture. In fig. 2-1 is shown how the scale terms are defined.

![Figure 2-1](image)

Figure 2-1 Shape describing sub quantities (Mitchell & Soga, 2005)

At large scale a particle’s diameters in different directions are considered. At this scale, describing terms as spherical, platy, elongated etc., are used. An often seen quantity for shape description at large scale is sphericity (antonym: elongation).

Graphically the considered type of shape is marked with the dashed line in Figure 2-1. At intermediate scale is focused on description of the presence of irregularities. Depending on at what scale an analysis is done; corners and edges of different sizes are identified. By doing analysis inside circles defined along the particle’s boundary, deviations are found and valuated. The mentioned circles are shown in Figure 2-1. A generally accepted quantity for this scale is roundness (antonym: angularity).

Regarding the smallest scale, terms like rough or smooth are used. The descriptor is considering the same kind of analysis as the one described above, but is applied within smaller circles, i.e. at a smaller scale. Surface texture is often used to name the actual quantity.

2.2 Geometrical definitions

For description of the scale dependent quantities, there are found a large number of terms and definitions. As what is stated in Johansson & Vall (2011) expressions and terms are used arbitrary.

There are a number of different definitions within the large and intermediate scale.
groups. There are also some definitions not fitting in to only one of these, but are influenced by as well the general form as by the angularity.

Regarding mathematical definitions for description of the surface texture, the authors views differ; some say that surface texture is to be determined by analogy with the intermediate scale shape, but with the scale decreased (e.g. Mitchell & Soga, 2005). In Santamarina & Cho (2004) it is meant that the lack of a characteristic scale of which surface texture is to be analyzed makes it difficult to do direct measurements. These authors are suggesting an approach to study interparticle contact area to describe roughness.

In Table 2-1 some definitions of shape describing quantities are presented.

Table 2-1 Some shape describing quantities are listed. As well definitions and figures as references are included. The quantities are used by the authors listed as references.

<table>
<thead>
<tr>
<th>EQ.</th>
<th>QUANTITY</th>
<th>DEF.</th>
<th>FIGURES</th>
<th>REF.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sphericity (Φ)</td>
<td>$\frac{D_a}{D_c}$</td>
<td></td>
<td>Wadell, 1935</td>
</tr>
<tr>
<td>2</td>
<td>Degree of circularity</td>
<td>$\frac{P_a}{P_p}$</td>
<td></td>
<td>Wadell, 1935</td>
</tr>
<tr>
<td>3</td>
<td>Roundness</td>
<td>$\frac{A_p}{A_c}$</td>
<td></td>
<td>Tickell, 1938</td>
</tr>
<tr>
<td>4</td>
<td>Angularity</td>
<td>$\frac{A_p}{A_{c2}}$</td>
<td>1)</td>
<td>Pentland, 1927</td>
</tr>
<tr>
<td>5</td>
<td>Roundness/Circularity</td>
<td>$\frac{4\pi A_p}{P_p^2}$</td>
<td></td>
<td>Riley, 1941/ ImageJ</td>
</tr>
<tr>
<td>6</td>
<td>Inscribed circle sphericity</td>
<td>$\sqrt{\frac{D_{isc}}{D_c}}$</td>
<td></td>
<td>Riley, 1941</td>
</tr>
</tbody>
</table>
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7 Circularity
\[ \frac{p_p^2}{A_p} \]

Blott & Pye 2008

8 Roughness
\[ \frac{p_p}{P_{\text{conv.}}} \]

Janoo, 1998

9 Roughness
\[ \frac{P}{\pi * D_{AVG}} \]

Kuo, et. al. 1998

10 Roundness
\[ \frac{\sum r_i}{N} \]

Wadell, 1932; Krumbein & Sloss, 1963; Mitchell & Soga, 2005

11 Sphericity
\[ \frac{\sqrt{\frac{b c}{a^2}}}{r_{\text{insc.}}} \]

Krumbein, 1941, (def.) Stückrath et al., 2006 (picture)

12 Aspect Ratio (AR)
\[ \frac{\text{Major}}{\text{Minor}} \]

ImageJ and Image Analysis Pro

\[ A_p \] Area of the particle outline
\[ D_a \] Diameter of a circle with an area equal to that of the particle outline
\[ D_c \] Diameter of smallest circumscribed circle
\[ P_p \] Perimeter of particle outline
\[ P_{a} \] Perimeter of a circle of the same area as particle outline
\[ A_c \] Area of the smallest circumscribing circle
\[ A_{c2} \] Area of a circle with a diameter equal to the longest distance between two points on the particle outline
\[ D_{\text{insc.}} \] Diameter of the largest inscribed circle
\[ P_{\text{conv.}} \] Perimeter, convex
\[ D_{\text{avg}} \] Diameter, average

1) This definition is almost the same as no. 3. There will be a difference if the particle is very bent, e.g. L-shaped.
2) The average diameter may be calculated by usage of software.
3) The dimensions a, b and c (length, width and thickness) are perpendicular to each other
4) AR defined as in the some image analysis software.
5) Used software.
2.3 Methods for particle shape determination

There are several methods used to determine the particle shape. Techniques have been developed from handmade measuring by direct scaling, convexity gauge’s, or tools developed for the specific task (Szadeczky-Kardoss 1933). Here, the use of classification chart and sieve analysis is further reviewed.

Classification chart

By usage of comparison charts, measuring may be avoided. Some comparison charts are those used by Powers (1953), Krumbein (1941) or Krumbein and Sloss (1963). The latter one is represented in Figure 2-2.

![Classification chart example](image)

**Figure 2-2 Example of a comparison chart (Santamarina and Cho, 2004)**

In the chart above, roundness is defined as in eq. 10 in Table 2-1. The definition of sphericity is vaguer. According to Krumbein & Sloss (1963), the sphericity is “related to the proportion between length and breadth of the image”. In Santamarina & Cho (2004) is said that “sphericity is quantified as the diameter ratio between the largest inscribed and the smallest circumscribing sphere”. Eq. 6 in Table 2-1 is a two-dimensional version of the latter definition. In Cho et al., (2006) the classification of sphericity was done by comparison of images of the analysed soil particles, and images in the chart in Figure 2-2. This subjective procedure makes it irrelevant how the quantities are mathematically defined. Folk (1955) concludes that when charts are used for classification, the risk of getting errors is negligible for sphericity but large for roundness.

Sieve analysis

Bar sieving, e.g. according to EN 933-3:1997, can be used to determine simple large scale properties. By combining mesh geometries the obtained results can be used to quantify flakiness and elongation index. The method is not suitable for fine materials. This due to the difficulty to get the fine grains passed through the sieve, and the amount of particles in relation to the area of the sieve (Persson, 1998).

Image analysis

The development of image acquisition techniques and image processing facilitates a systematic approach to use mathematical descriptors for classification of particle shape (Santamarina & Cho 2004). By using algorithms subjectivity related to e.g. ocular classification by charts, is avoided (Persson, 1998).

2.4 Standards and guidelines

As already mentioned, there are present standards and guidelines related to particle shape classification, especially within in the ballast industry focusing on paving-concrete and railway applications. These standards are valid for coarse materials. The ASTM D 3398 (ASTM 2006) are regarding shape and texture characteristics that may affect the asphalt concrete mixtures performance.

Standards based on sieve analysis, e.g. ASTM D 4791 (ASTM 2005) and EN 933-3:1997 (CEN 1997), are both regarding width/length ratio; e.g. by flakiness index. EN 933-4:2000 (CEN 2000) is used to measure individual particles by slide calliper to determine the shape index.

3 EVALUATION OF SHAPE DESCRIBING QUANTITIES

To evaluate different shape describing quantities and definitions both usability and sensitivity are relevant.
3.1 Usability

Regarding usability the connection between definitions and geotechnical parameters would be the most relevant factor. This is not touched in the present study. A more simplified way of looking upon the usability of different definitions is to compare images of grains. The comparison, which is fully described in Johansson & Vall (2011), involves particles which seem to have different shapes; i.e. some grains looking elongated, some others that do not. Some particles looking angular and some that are looking smooth/rounded. Furthermore, the grains are analysed with the software ImageJ (further described in section 4.4). The analysed quantities are AR (defined as eq. 12 in Table 2-1), Circularity (defined as eq. 5 in Table 2-1), and Solidity (defined as eq. 8 in Table 2-1, but with areas instead of perimeters).

3.2 Sensitivity

In this study has been carried out a sensitivity analysis regarding image resolution and geometrical definitions. Five idealized well defined geometries have been used to study the effect of resolution. The known geometrical properties, i.e. area, perimeter, etc., are compared with the analysis software results. Further on, a test on soil particles has been performed.

The idealized geometries (square, triangle, circle, star and cross) are presented in Figure 3-1.

In order to evaluate the sensitivity different image resolutions are studied. Henceforth, the resolution is defined as the side, s (expressed in pixels) as indicated in Figure 3-1. The square, the triangle and the circle were all built using six different resolutions. The star was built by one central square and four triangles put on each of the four sides of the square. The cross is formed similarly as the star but with four squares surrounding the central one. In Table 3-1 the layout of investigated resolutions as well the areas of the analyzed geometries are shown. The resolutions are grouped in orders, 1-6 depending on the resolution, s.

![Figure 3-1 Idealized geometries.](image)

Table 3-1 Area, A and side, s of the geometries are listed for each of the resolutions (1st, 2nd, etc.).

<table>
<thead>
<tr>
<th>Figure</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>A [pixels²]</td>
<td>100</td>
<td>400</td>
<td>1600</td>
<td>6400</td>
<td>25600</td>
</tr>
<tr>
<td></td>
<td>S [pixels]</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td>Circle</td>
<td>A [pixels²]</td>
<td>78</td>
<td>314</td>
<td>1256</td>
<td>5026</td>
<td>20106</td>
</tr>
<tr>
<td></td>
<td>S [pixels]</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td>Rectangle</td>
<td>A [pixels²]</td>
<td>50</td>
<td>200</td>
<td>800</td>
<td>3200</td>
<td>12800</td>
</tr>
<tr>
<td></td>
<td>S [pixels]</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td>Star</td>
<td>A [pixels²]</td>
<td>80</td>
<td>405</td>
<td>1805</td>
<td>7605</td>
<td>31205</td>
</tr>
<tr>
<td></td>
<td>S [pixels]</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Cross</td>
<td>A [pixels²]</td>
<td>75</td>
<td>300</td>
<td>1200</td>
<td>4800</td>
<td>19200</td>
</tr>
<tr>
<td></td>
<td>S [pixels]</td>
<td>4</td>
<td>9</td>
<td>19</td>
<td>39</td>
<td>79</td>
</tr>
</tbody>
</table>
The *Image-Pro Plus* software from Media Cybernetics was used to carry out the measurements. Basically there were taken seven measures; diameter of inscribed circle, diameter of circumscribing circle, area, particle diameter, perimeter, and convex perimeter. All the measures can be seen in Table 2-1. Regarding the diameter, two different techniques were used. The first used was the “maximum feret box”. In this case the diameter is defined as a straight line (the longest that can possibly be drawn) measured between two parallel tangents of the particle’s boundary. The second used was the diameter through the centroid of the particle. By usage of the latter definition the average diameter can be determined. The convex perimeter can be defined as the length of a string stretched around the tips of all possible Feret diameters; i.e. a fictitious elastic band stretched around the particle, see eq. 8 in Table 2-1.

Based on the measures by the software seven shape quantities of large or intermediate scale and two quantities of roughness was evaluated. The definitions are presented in Table 2-1 and numbered 1-9.

For each of the definitions the analyzed measures are compared to the true values. The comparison is carried out by calculating a deviation, defined as:

\[
\text{Deviation} = \frac{\text{IGT} - \text{SGT}}{\text{IGT}}
\]  

(13)

where IGT is the Ideal Geometrical Term (pixels) and SGT is the Software Geometrical Term (pixels).

Besides the analysis on the idealized geometries, soil particles were used. As an extension on the sensitivity analysis presented in Johansson & Vall (2011), three microscope camera pictures of the same soil particle, taken using three different objectives with different magnification rates, were analyzed. The procedure regarding as well acquisition as analysis of the pictures is described in section 4.

4 STUDY OF IMAGE ANALYSIS APPLIED ON SOIL PARTICLES

The laboratory work, consisted of image acquisition has been carried out by usage of as well a microscope camera as a conventional digital SLR.

4.1 Equipment

The used microscope is named *Motic B1*; it is equipped with lightening sources from above and below. There are three lenses with magnification rates of 4x, 10x, and 40x. The camera mounted on top of the microscope is named *Infinity 2* and has a 2 megapixel resolution. The SLR is a *Nikon D80* equipped with a macro lens with a focal length of 55 mm. The equipment used for image acquisition was arranged as shown in Figure 4-1.

![Image of microscope and SLR](image)

*Figure 4-1  To the left is shown the microscope with the top mounted camera connected to the computer on which the soil particles are previewed. To the right is shown the SLR.*

4.2 Sample preparation

Samples of dried soil were used. Pictures were captured on mixed soil particles, as well as on sorted i.e. sieved material. The sieving work was carried out with a conventional stack of sieves placed on a vibrating plate, and ended up with soil samples of the fractions 0-0.063 mm, 0.063-0.125 mm, 0.125-0.25 mm, 0.25-0.5 mm, 0.5-1.0 mm and 1.0-2.0 mm.

4.3 Image acquisition

Before the shooting and the analysis work was initiated, some preparations were done. Different directions of lightening were tested, pictures of different particle size were taken, and the software *Infinity Capture 5.0.4*, for...
controlling the microscope camera, was tested. The variables contrast, brightness, white balance, gamma and gain were varied, whereupon pictures of different type, i.e. with different features, were taken. Moreover, different microscope lenses were used; tests with varying rates of magnification and different particle sizes were carried out. The acquisition of pictures taken with different settings was done in order to make further comparison and optimization possible.

4.4 Image analysis

In general, there are a number of different techniques for assimilating information from a taken picture (Mora et al., 2000). In Persson (1998) is described one procedure mainly made up by six steps: capturing, normalization of the grayscale, segmentation, filtering and filling, grain separation, and definitions of outlines.

5 RESULTS AND ANALYSIS

5.1 Geometrical quantities

Usability

Here is shown results from the simplified usability analysis. The selection of particles is done according to the scale based definitions explained in section 2.1. The used quantities are circularity, aspect ratio (AR), and solidity and the calculations are done using eq. 5, 12, and 8 (but with area instead of perimeter), found in Table 2-1.

In Figure 5-1 are seen three particles which are judged to be spherical and three more elongated, respectively.

To the left in Figure 5-2 are seen particles which are judged to be elongated and rounded. To the right are seen two particles judged to be more spherical but angular.

In Table 5-1 result values coming from the image analysis are presented.

<table>
<thead>
<tr>
<th>ID</th>
<th>Circularities</th>
<th>AR</th>
<th>Solidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.764</td>
<td>1.202</td>
<td>0.943</td>
</tr>
<tr>
<td>2</td>
<td>0.809</td>
<td>1.118</td>
<td>0.958</td>
</tr>
<tr>
<td>3</td>
<td>0.822</td>
<td>1.159</td>
<td>0.960</td>
</tr>
<tr>
<td>4</td>
<td>0.604</td>
<td>1.919</td>
<td>0.913</td>
</tr>
<tr>
<td>5</td>
<td>0.590</td>
<td>1.999</td>
<td>0.894</td>
</tr>
<tr>
<td>6</td>
<td>0.563</td>
<td>2.403</td>
<td>0.906</td>
</tr>
</tbody>
</table>

It is concluded that AR-values can be used apart from other values and still give information about the shape of the grain. On the contrary, values of circularity have to be combined with values of other parameters, in order to be used as an indicator on a particle’s angularity or large scale shape, respectively.

Sensitivity

In Figure 5-3 deviations calculated by usage of eq. 13 are presented. The deviations selected to be graphically presented origins from analysis of the triangle and rectangle-geometries. The patterns of the curves from other investigated geometries are similar to the presented.

In Table 5-2 result values coming from the image analysis are presented.

<table>
<thead>
<tr>
<th>ID</th>
<th>Circularities</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.593</td>
<td>2.640</td>
</tr>
<tr>
<td>8</td>
<td>0.578</td>
<td>2.562</td>
</tr>
<tr>
<td>9</td>
<td>0.660</td>
<td>1.079</td>
</tr>
<tr>
<td>10</td>
<td>0.589</td>
<td>1.419</td>
</tr>
</tbody>
</table>

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In Table 5-2 result values coming from the image analysis are presented.

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It is concluded that AR-values can be used apart from other values and still give information about the shape of the grain. On the contrary, values of circularity have to be combined with values of other parameters, in order to be used as an indicator on a particle’s angularity or large scale shape, respectively.
The overall trend is that a higher resolution results in a lower deviation. Moreover, there are other variables as well. For instance, at a resolution of \( s = 10 \), eq. 1 applied to the geometries circle, square and cross, results in deviations lower than 5%. The same definition applied on the star and the triangle results in higher deviation values. When the resolution is increased from the 1\textsuperscript{st} to the 2\textsuperscript{nd} order, usage of eq. 1, 2, and 6, results in deviations lower than 10% for all of the geometries. For the rest of the equations the resolution needs to be increased even more (to the 3\textsuperscript{rd} order) in order to get deviations lower than 10% obtained. This shows that eq. 1, 2, and 6 are less sensitive than the others.

In Figure 5-4 and Figure 5-5 is seen to what extent the quantities defined by eq. 8 and 9 in Table 2-1 (by the reference authors called roughness), are affected by the resolution. Regarding eq. 9 both the feret diameter and the centroid crossing one are used. The use of the centroid diameter is more unstable than the feret measurement.

Deviation is found to be influenced by as well resolution as the combination of definition and analysed geometry.

On soil material, one single soil particle, seen in Figure 5-6, was analysed in three different images. Since the images were taken at different magnification levels, the effect of the magnification on the geometrical quantities was valuated.

In Figure 5-7 the result from the sensitivity analysis are presented. On the x-axis are presented the three magnification rates. On the y-axis are seen the calculated values of the quantities.

The results show that there is an effect on the result for the different geometrical quantities depending on the zoom-level on the particle.
and that some quantities are more sensitive than others. The graphs based on eq. 2, 5 and 7 are showing values of the shape quantities, varying by changed resolution. All of these three quantities are dependent of the perimeter of the particle.

6 DISCUSSION

6.1 General

The use of image analysis on particle shape classification is promising but need further development. Besides the pros and cons regarding the actual performance of image analysis, the subject itself is fraught with uncertainties. The misusing of quantities and definitions, in detail discussed in Johansson & Vall (2011), is definitely faced even during performance of this present study. The scattered way on which terms are used needs to be homogenized. Further research should aim on standardization of as well analysis procedures as terminology in order to ensure an objective particle shape classification.

6.2 The methodology

It is found that images of particles with diameters of 0.125-1.0 mm, taken with the microscope camera, were successfully analyzed. Regarding usage of the SLR, a diameter of 2.0 mm, were found to be a lower limit. The gap identified between the fraction for which good quality results were retrieved by usage of the microscope camera, and by usage of the SLR should not be too problematic to eliminate. It can probably be done by usage of other microscope lenses.

Even though valuable advantages as reduced influence of subjectivity and possibility of rational efficiency in analysis are achieved, there are disadvantages not to neglect; e.g. problems related to aggregating particles, and not satisfying focus range in the image. This makes it important to get the soil dried before performance of the image analysis. Focus and angle of image acquisition is important for the analysis result. Focus affects the interpretation of the boundaries by analysis program and the photo angle affects the analyzed projection of the particle.

Regarding the analysis part it is stated that none of the tested applications for image analysis (neither ImageJ nor Image Analysis Pro) permits determination of the intermediate scale quantity roundness as defined in eq. 10 in Table 2-1. This means that values for application of existing soil parameter relations that include the roundness cannot be done without developing the tools.

In order to get representative results, the image acquisition should be carried out aiming at getting as many particles as possible imaged simultaneously. It can be stated that there is needed some balancing work to get the procedure fast and efficient, but still get results of sufficient quality.

6.3 Expressions and definitions

It is to be emphasized that the scale approach regarding quantities used for description of shape is not a general one, and that all names of quantities and all definitions are just suggestions from different authors. Still, the breakdown based on the scales is found to be quite practical and useful.

Usability

It is important to reflect on the meaning of specific values of different shape describing quantities. According to what is concluded in the usability part of section 5.1, it is stated that there are quantities that do not give unambiguous information if they are used by themselves. On the other hand, these quantities might be very useful if the determined values are combined with values of other definitions.

To investigate the usability of different quantities, the possibility of getting them determined is also to be considered. In the end, usability is a matter of as well the definition of the shape describing quantity, as the possibility of getting a reliable value. It is stated that quantities depending on particle area, particle perimeter, and different types of diameters, all can be determined and valuated. Still, these are not as usable in existing relations between particle shape and
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geotechnical properties, as e.g. roundness (defined as in eq. 10 in Table 2-1) is. The latter one is, on the contrary, more difficult to determine.

**Sensitivity analysis**
Resolution has an important role when image analysis is carried out; it is necessary to determine the minimum resolution acceptable (it may vary depending on the goal of the classification) in order to obtain low deviations. It is easy to get pictures of good quality when the analysed particles are big enough; it is more complicated when the particle size diminish. In such cases it might be necessary to use more sophisticated and expensive equipment. In this study five ideal geometrical figures were tested; this is of course a small spectrum of all possible particle shapes. To get a large, rich and varying base for all type of studying, it is of course important to perform analysis on real particles (soil or not). Still, the idealized geometries are very suitable for this type of theoretical key study.

The acceptable deviation limit in this study was chosen to be <10%. To keep the deviation below 10%, the eq. 1, 2 and 6 should be limited by a minimum area of 405 square pixels. For the rest the limit is found to be 1805 square pixels. These areas correspond to soil particles of the 2nd and the 3rd order of resolution, respectively. If the sensitivity results in this study are extrapolated, the authors recommend performance of a simple resolution test, to obtain reasonable deviations.

The use of the diameter crossing through the centroid of the analysed geometry gives for the triangle deviations up to 100%. This fact makes it reasonable to avoid usage of this measurement, and also confirms that existing quantities and definitions have to be used carefully.

Regarding the sensitivity analysis carried out on actual soil particles – results shown in Figure 5-7 – it can be concluded that definitions including the particle perimeter are the most sensitive ones. The plotted results are showing that eq. 2, 5 and 7, which all contain the perimeter, are not stable when resolution changes. Increased rate of magnification, leads to decreased focus along the boundary, which in turn results in increased length of the outline (higher number of pixels) and, furthermore, changed affected values.

6.4 **Evaluation of image analysis as a method applied on soil particles**
Image analysis is a promising method for shape classification on soil particles. It is objective and the procedure could in large extent be automated. Traditional methods such as subsequent sieving procedures by combining sieves of different mesh geometries and manually scaling are time consuming and are limited to describe simple geometric descriptors.

7 **CONCLUSIONS**
Although there are a lot of different ways of defining shape and describing quantities, the breakdown based on the scales is found to be quite practical and useful.

The fact that a soil’s tendency to aggregate is increasing with decreased particle size and increased water content, makes it important to get the soil dried before performance of the image analysis.

To permit performance of further studies on the connections between shape and geotechnical properties, used tools i.e. the image analysis applications, are to be developed and optimized.

To avoid deviations that may influence the results from image analysis processing, the minimum resolution has to be taken into consideration.

Perimeter is a key factor of changing results when the resolution changes.

8 **FURTHER WORK**
Further research should aim on standardization of analysis procedures and terminology usage.

The procedure from sample preparation to interpretation of the image acquisition needs to be further developed focusing to establish
a methodology that ensures objective and useful results.

The effect on chosen geometrical definitions in the particle shape classification needs to be compared to today empirical knowledge of influence of particle shape on soil properties as a first step to connect the image analysis methodology to be incorporated into geotechnical analysis.

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10 REFERENCES


