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Automated granulometric analysis and grain-shape estimation of beach sediments using object-based image analysis

J. Urbanski, A. Wochna and A. Herman
Institute of Oceanography,
University of Gdansk,
81-378 Gdynia, Poland
cgisju@ug.edu.pl, cgisaw@ug.edu.pl, oceagah@univ.gda.pl

ABSTRACT

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This work presents an automated, image-analysis based method for determining the grain characteristics of sandy, unconsolidated beach sediments. The main purpose of the study is to develop an efficient and reliable alternative to the traditional, very laborious sieving analysis. Moreover, the method should provide a wide range of features characterizing the sediment, including the grain-size distribution and the main geometric measures of the grains. The method proposed here is based on the Object-Based Image Analysis (OBIA) techniques available in Definiens Developer 7 (DD7). They are applied to high-resolution digital images of sand grains placed on a light box screen. The main stages of the algorithm include a multi-resolution segmentation of the image, separation of the background from the remaining objects and a method of distinguishing between separate grains and their agglomerates, based on the so-called elliptic-fit feature of DD7. In the final, calibrated algorithm, the probability of grain clusters being incorrectly classified as separate grains is less than 3%. The results obtained with OBIA are compared with those obtained by sieving for 22 sand samples. The statistical analysis of the grain-size distributions obtained with both methods showed that in most cases they give very similar results, especially for narrow size distributions with a clearly pronounced peak. For samples with a wider range of grain sizes, and/or with more irregular grain shapes, the differences are larger and depend on the details of the method in which the grain-size distribution is calculated from the data provided by OBIA.

ADDITIONAL INDEX WORDS: *sand, OBIA, beach sediments, granulometry, grain-size distribution*

INTRODUCTION

Typical beach and nearshore sediments consist of sand or gravel particles of various sizes, composition and density (Bird, 2008). Physical and morphometric sediment properties influence both speed and direction of the wave- and current-induced sediment transport in the coastal zone, thus influencing the cross-shore beach profile, the sandbar morphology and migration, as well as the erosion-accumulation patterns. In numerical modeling, grain-size distribution and grain density are the most important input variables in (mostly semi-empirical) sediment transport formulae. In the state-of-the-art morphodynamic models (e.g. Delft3D or XBeach), a number of sediment classes can be taken into account, thus allowing for simulation of sediment sorting during storm events. However, it is possible to take a full advantage of all these advanced techniques only if sufficient information concerning sediment properties in the study area is available. This is often not the case. Traditional sieving-based granulometric analysis is time consuming and laborious. Moreover, granulometric distribution curves obtained by sieving are created using arbitrary, discrete classes (determined by the mesh sizes of the sieves). Obviously, more efficient, reliable methods for estimating sediment properties are highly desirable. In recent years, several authors proposed different automatic or semiautomatic methods based on image analysis: Blot and Pye (2008), Brzezicki and Kasperkiewicz (1999) and Lira and Pina (2009), among others. However, some of these methods need a preprocessing sieving or they are not easy to implement because of custom software solutions. The main aim of this paper is to propose a method that is not hampered by the above-mentioned drawbacks. It uses high-resolution digital images of the analyzed sediments and is based on the object-based image analysis (OBIA). This method proved to be efficient for land surface and biological tissue classification, as both structures may be modeled as a collection of objects of different scales. The two basic concepts of OBIA are: segmentation, which groups pixels into objects using some measures of objects internal homogenity and external heterogeneity; and a subsequent classification of objects resulting from the segmentation, based on their features.

The objects may be described by a number of features based on their spectral characteristic, texture, geometry and relations to neighbours. These feature characteristics are used in object classification. As a sand grains on an image may be modeled as objects and appropriate features may describe their geometry parameters and indices, we decided to test the usefulness of this method for obtaining sand grain-size distribution data. These

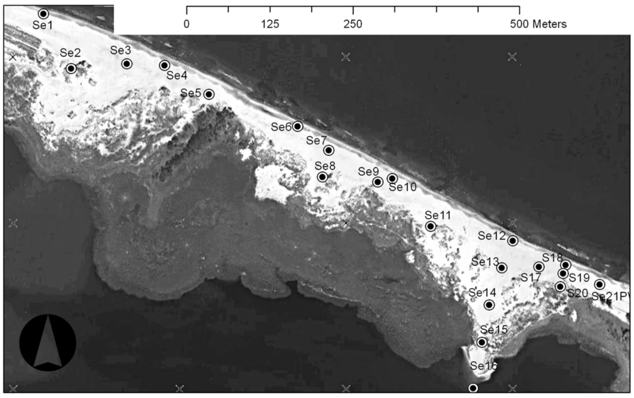

Figure 1. Location of the 22 stations sampled on 27 November 2010. Source: "Sobieszewo" 54°21'N and 18°48E, **Google Earth**, May 1, 2008, December 4, 2010.

data are necessary in our project connected with beach errosion modelling in which sand grain distribution on many stations and levels has to be determined. The use of the OBIA method may improve the efficiency of work and thus allow for densier sampling. In the paper, both methods, OBIA and traditional sand sieving, are compared in terms of their efficiency and the obtained results.

The paper is structured as follows: in the next section, a brief description of the study area is given, followed by a detailed description of the OBIA methods and the algorithms developed in this work, as well as of the sieving analysis performed for reference. In the second section, presenting the results of the analysis, the grain-size distributions obtained with both methods are compared. Finally, the last section contains the conclusions.

METHODS

Study area and sampling method

The location of the sampled stations is presented in Figure 1. The area of interest is a narrow sandspit located near Gdansk, Poland, separating a shallow coastal lake from the Gulf of Gdansk. The choice of the study area was dictated by the fact that the sandspit and its neighboring beach and surf zone, being subject to intensive morphodynamic processes and erosion, is the main study area of a project, in which those processes are modelled numerically. One of the purposes of this study was to develop and test an efficient procedure of preparing the input data for modeling in terms of the spatial distribution of sediment properties within the study area. The 22 sand samples were collected using a simple sand-sludge sediment probe, appropriate for sampling sand and other types of loose, unconsolidated sediments from the surface up to 50 cm depth.

After being colected, the samples were analyzed using both methods OBIA and sand sieving, as described in the following sections.

Object-based image processing

OBIA implemented in Definiens Developer 7 software (Definiens Developer 7, 2007) contains many features to describe objects. The most basic geometric features are length and width of an object. The length and width of sand grain is approximated using the calculation of the length-to-width ratio. Two methods are used for that purpose. In the first, this ratio is defined as the ratio of the eigenvalues of the covariance matrix of the pixel set belonging to an analyzed object. The second method uses a bounding box defined as the smallest rectangular area that encloses all pixels of a given object. Both calculations are compared and the smallest value is chosen. The length and width is calculated by division of the total numbers of pixels by length-to-width ratio. The area is defined as the number of pixels forming an image object. As the edge length of a pixel is readily available, the number of pixels can be converted into an area measurement. The perimeter is defined as a border length. It is calculated as the sum of edges of the image object shared with other image objects.

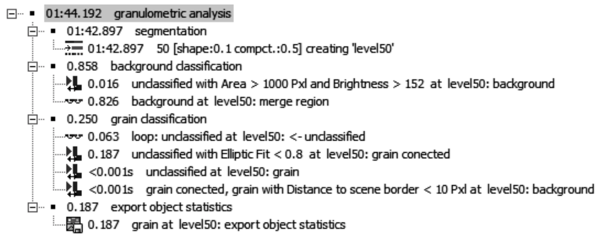

Figure 2. Cognition Network Language script for automated grain shape estimation, created in the Definiens Developer 7 software.

The shape parameters commonly used in morphometric characteristics of sand particles are: elongation, shape index, circularity index and roundness (Lira and Pina, 2009). The elongation index is computed as the ratio between the length and width of particle. The shape index is calculated as the ratio of the area and the square of perimeter times 4π. The circularity index, which uses in the calculation a convex hull area, may be calculated in GIS after exporting the sand grains image objects from Definiens to GIS. The roundness is traditionally evaluated by image comparison with the visual roundness chart developed by Powers (1953). The Definiens Developer offers a roundness feature which describes how similar an image object is to an ellipse. It is calculated from the size difference of the enclosing and the enclosed ellipse.

In Definiens (Definiens Developer 7, 2007), the image analysis process is described by a script in a high level language (the Cognition Network Language). In our project, we developed such a script for an automated grain shape estimation (Fig. 2).

The procedure is as follows: the sand particles are placed on a light box screen and the image is taken using a digital camera with macro lens in scale 1:1. The spatial resolution of such an image is 0.005 mm (see Figure 3A for an example). The main problem in the image analysis of geometrical characteristics of particles is to delineate sand grains in contact with each other. To decide if the object is a single sand grain we used the Elliptic Fit feature. The Elliptic Fit describes how well an object fits into an ellipse of a similar size and proportions. It has values between 0 and 1 and its calculation is based on a ratio of the area of an image object outside the ellipse and inside the ellipse. A test for 60 sand grain images shows that for the value higher than 0.8, no more than 3% of connected grains were incorrectly classified as separate. The complete script in the Cognition Network Language is presented in Figure 2. In the first step, a multi-resolution segmentation is carried out for a 50-pixel level (0.25 mm), which has been chosen in relation with the spatial scale of created objects. In the second step, the background objects are classified using they large area

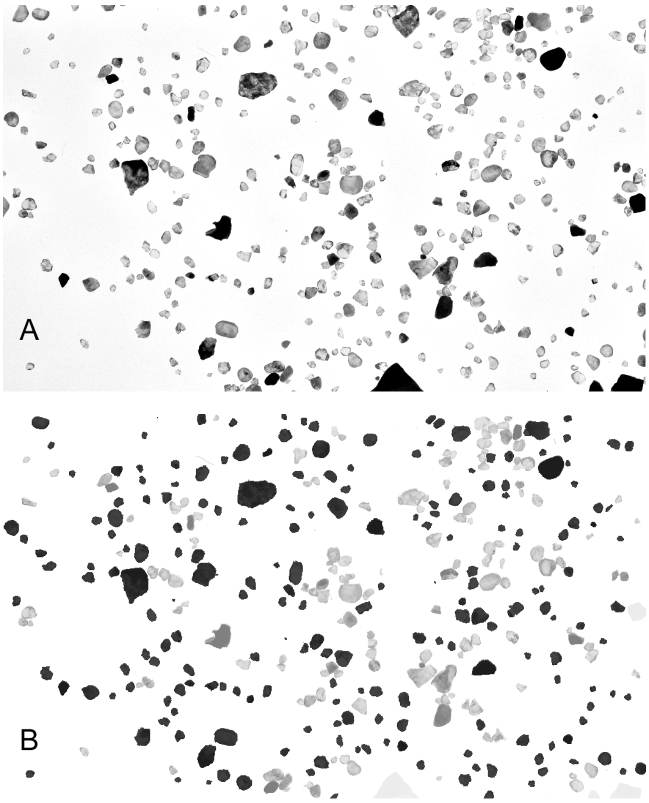

Figure 3. A – Image of a sand grains sample. B – Results of the OBIA classification of this sample. In B, the objects identified as separate grains are dark gray, and the light gray objects represent connected grains.

and brightness. Afterwards, they are merged together creating one large object of the background class. In the third step, the remaining unclassified objects are 'dissolved' in an iterative way forming separate objects for sand grains and their clusters. The clusters of sand grains are classified as connected using the Elliptic Fit. All remaining objects are classified as separate sand grains. In a final stage, all objects with the distance to the scene border less than 10 pixels are classified as background. The example results of the above described procedure are presented in Figure 3B. The dark objects are those that have been recognized as separate grains, and the light gray objects represent the agglomerates of connected grains. In the last step of the process, a text file is exported in which each row contains a set of features describing one sand grain. In our project, such the values of such features as length, width, area, perimeter, shape index and roundness were saved.

Sand sieve analysis

The sand sieve analysis was performed using a standard dry-sieving procedure. Dried sand samples of a known weight (about 100 g) were passed through a set of eleven sieves with known mesh sizes (2.0, 1.4, 1.0, 0.71, 0.5, 0.355, 0.250, 0.180, 0.125, 0.09, and 0.063 mm). The sieves were mechanically vibrated for 10 minutes. The weight of sediment retained on each sieve was measured and converted into a percentage of the total weight of the sediment sample.

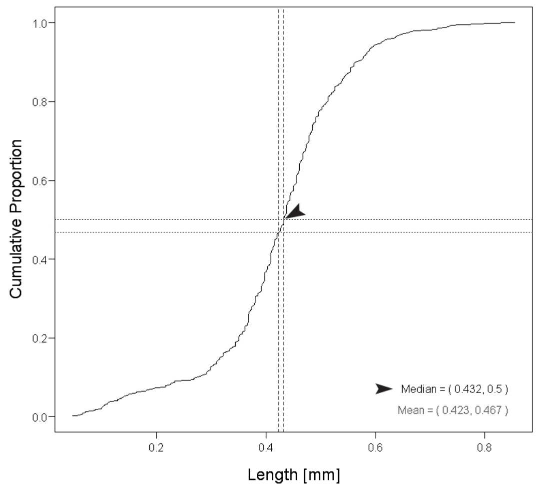

Figure 4. A cumulative proportion plot of sand grains lengths at station Se17, obtained automatically by means of the described procedure from a sample of 585 sand particles.

RESULTS AND DISCUSSION

Visualization and analysis of the results

There are several possibilities for the graphical presentation of the grain-size data. The most common ones are a histogram and a cumulative proportion plot (Figure 4). Such form of presenting data may be useful to overlay several cumulative distribution curves for the visual analysis of spatial patterns of beach-sand sorting. In a numerical form, such sediment grain characteristics may be used as input for numerical sediment transport models.

When comparing the results of the OBIA-based and the sieving method in terms of the resulting sediment grain-size distributions, one has to keep in mind the underlying differences inherent to these two approaches. In the case of the sand sieve analysis, as a result one obtains a percentage of the total sediment sample *weight* for each *mesh size* interval. In the case of the OBIA (as well as other image-analysis based methods), the grain-size distribution may be estimated in a number of ways. However, none of these will be fully analogous to the one obtained as a result of sieving. In particular, the size classes may be defined in terms of the width or length or some other measure describing the grain size. Similarly, in the case of OBIA, the most natural way of counting the grains belonging to each size class is in terms of their *number*, and not *weight*, which, obviously, cannot be calculated directly from a two-dimensional image.

In this work, we test two of the many possible approaches to calculating the grain-size distribution from the information obtained with OBIA. In both cases, in order to facilitate the further statistical comparison of the results, the number and width of the intervals (classes) is the same as in the sieving analysis (it is worth mentioning, however, that the sample sizes obtained from a typical image are high enough so that they would permit a much larger number of classes, i.e., a much higher resolution of the resulting distributions). In both cases, the width of grains is used as a measure of their size. In the first, more straightforward approach, a number of grains belonging to each class is counted. In the second approach, the weight of grains is estimated, with an

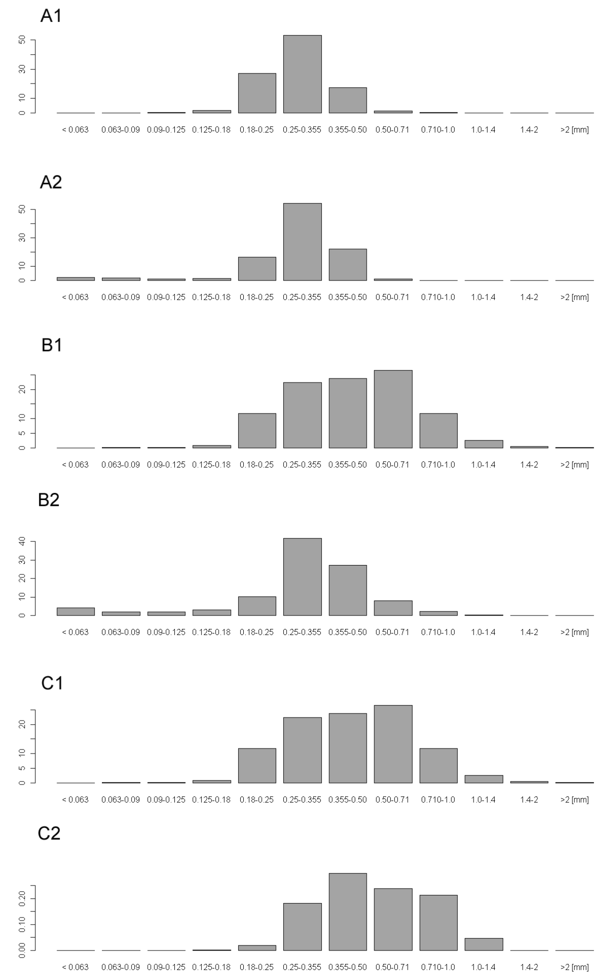

Figure 5. Histograms from two selected stations, Se1 (A) and Se2 (B,C), as obtained from the sand sieve analysis (A1, B1, C1) and from the OBIA method (A2, B2: calculated for the number of grains in each class; C2: calculated for the estimated weight of grains in each class). For the location of stations, see Fig.1.

assumption that, firstly, all grains are made from the same material (for example, quartz), and secondly, that each grain is an ellipsoid, with the major axis equal to its length and the two minor axes both equal to its width. The comparison of the results using the two methods described above is presented in Figure 5 and Table 1 for two selected stations, Se1 and Se2, representative for the whole analyzed dataset. In Figure 5, panels A1, B1, and C1 show the sieving analysis results; the remaining panels contain the corresponding results of the OBIA method, obtained with the approach based on the number (A2, B2) or weight (C2) of grains within each size class. For a quantitative analysis of the results, a pair-wise comparison of the grain-size distribution functions representing all 22 samples was performed by means of a standard nonparametric Kolmogorov–Smirnov (KS) test, suitable for small sample sizes.

Discussion

Generally, from the point of view of the results of the KS tests,

Table 1. Grain-size statistics at the stations Se1 and Se2.

Point	Se1		Se2		
	sieve	OBIA_size	sieve	OBIA_size	OBIA_mass
Mean	0.335	0.367	0.363	0.319	0.401
σ std	0.143	0.097	0.138	0.103	0.112
Skew.	5.3	0.7	1.7	0.2	0.6

the samples analyzed can be divided into two groups. The samples from the first group contain grains with relatively uniform sizes and thus the corresponding size-distributions are narrow, with a clearly defined peak (histograms A1 and A2 in Fig. 5 are good examples). The null hypothesis of the KS tests, stating that the distributions being compared are equal, could not be rejected (at a 95% confidence level) for any of the samples from this group, independently on the method used to calculate the size distribution from the OBIA results. In the second group of samples, the range of grain sizes and was much larger (histograms B and C in Fig.5), leading to histograms with broad, wide peaks. In that case, the similarity between the distributions obtained from sieving and from the OBIA were very sensitive to the method of their estimation (B2 and C2 in Fig.5). In the KS tests, for most samples from this group the null hypothesis was rejected if the number of grains was used to obtain the OBIA distributions. To the contrary, the distributions based on the simulated weight of grains agreed much better with those resulting from sieving. Clearly, in the case of samples with various-in-size, irregular grains, no simple relationship exists between different measures of their size distributions; an optimal choice depends on the subsequent application of that information (e.g., if the amount or mass of grains is important). Finally, when judging the results of the OBIA method, typical drawbacks of the sieving analysis must be remembered, especially in the case of particles deviating from a regular, round shape.

CONCLUSIONS

The OBIA-based sediment grain-size analysis is incomparably faster and efficient than the traditionally used, very laborious sieving method, especially if large numbers of samples have to be analyzed. The results it produces are consistent, comparable with other methods in a straightforward manner, and provide a much wider range of features characterizing the shape of grains (and it can be easily extended to further, additional features). Our study showed that OBIA-based algorithm enables to distinguish the agglomerates of grains from separate grains with an accuracy of a few percent.

Contrary to the sieving analysis, the OBIA-based method provides a number of ways to calculate the grain-size distribution. As demonstrated in the previous section, for samples composed of highly nonuniform grains, the number- and weight-based approach may produce very different results (with differences generally higher for larger grains). Thus, OBIA enables to better adjust the information it provides to the particular purpose and further application of that information – for example, in numerical morphodynamic modeling, in which the mass of the sediment must be known, the weight-based approach would definitely be more suitable.

Finally, it is worth mentioning that Definiens Developer 7 gives a possibility of exporting shapefiles with the objects (grains) represented as polygons. These shapefiles can be then imported into a GIS software, which provides a much wider spectrum of advanced shape parameters used in morphometric analyses.

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