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Digital grain-size analysis based on autocorrelation algorithm

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ABSTRACT

Grain size is one of the most important parameters in geology and coastal engineering. However, all traditional methods are time consuming, laborious, and expensive. In this study, the autocorrelation technique, which was first expounded by Rubin (2004), was extended to estimate the size of well-sorted sediments and the grain-size distribution of mixed-size sediments. Long and intermediate axes of well-sorted sediments ranging from 1 to 20 mm obtained from applying the autocorrelation method are compared with the corresponding results measured using a vernier caliper. Using the autocorrelation technique, the sediment mean size was calculated and was found to compare better with point counts than sieving. Regarding the mixed-size sediment, a nonlinear programming method, which is different from the conventional 'least-squares with non-negativity' method, the kernel density method, and the maximum entropy method, was used to obtain the representative grain sizes and associated sediment inherent parameters, such as mean diameter, median diameter, sorting, skewness, and kurtosis. Image pre-processing was used in the present analysis to enhance the contrast of the recorded image, and a conversion method applied to take into account the difference between the two-dimensional digital image method and the three-dimensional sieving method. Using the modified fitting points and the improved Gaussian function fitting method, the cumulative grain-size distribution curve and the probability density curve of the mixed-size sediments were obtained. The enhanced autocorrelation technique that was developed from the traditional 'look-up-catalogue' approach provided a more accurate estimation of the grain-size distribution, as well as the relevant physical parameters of the mixed-size sediment.

1. Introduction

The movement of sediment particles, such as erosion, transport, and deposition, is governed fundamentally by grain size. Sieve analysis is the most conventional and convenient method for analyzing particle size distribution. Manual sieving and mechanical sieving are both laborious and time consuming, and other traditional methods, such as settling and laser diffraction, have their limitations as well. It is difficult to apply the settling method on coarse-grained systems, and the laser diffraction method has a limitation on the size range as well as requiring expensive equipment.

The digital grain-size analysis has been developed to overcome these problems. To quantify the grain size, a high-resolution digital camera has been used to take photographs by an increasing number of researchers. Ibbeken and Schleyer (1986) were the first to propose digital grain-size analysis. They used the 'photo-sieving method' first to quantify the grain size of coarse-grained, unconsolidated bedding surfaces. There are two main types of modern digital analysis methods. The first is the edge detection method (e.g., Butler et al., 2001; Sime and Ferguson, 2003; Graham et al., 2005a, b, 2010; Baptista et al., 2012; Chang and Chung, 2012; Karunatillake et al., 2014), which is a geometrical approach to determine grain-size properties. This approach is a combination of two basic image-processing steps: gray-scale thresholding to create a binary image and watershed segmentation to grow edges on the binary image to identify individual grains. Graham et al. (2005a, b) presented its application for measuring exposed fluvial gravels and other coarse-grained sediments. An improved automated image-processing algorithm was proposed by Baptista et al. (2012) and its accuracy and robustness were validated in both the laboratory and sandy shores. However, the edge detection method has limitations such as particle overlapping and indistinguishable grains in the image (Graham et al., 2010). Another limitation is the lower limit of clast detection at approximately 23 pixels, producing less accurate results (Graham et al., 2005a). On the other hand, to quantify the grain size, Rubin (2004) proposed the second method using an autocorrelation algorithm. This technique is a statistical approach that uses the photograph texture in an image. To derive the mean grain size of a mixed-size sand sample, Rubin et al. (2007) had validated its utility. Barnard et al. (2007) demonstrated that the autocorrelation technique works well on high-energy dissipative beaches. The autocorrelation method was further developed by Buscombe (2008) and Buscombe and Masselink (2008), and the grain-size distribution was successfully estimated. This method showed its validity in both coarse sand (0.7 mm) and gravel (up to ~20 mm). Warrick et al. (2009) presented an application of the autocorrelation method on a mixed sand and

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gravel beach. Pina and Lira (2009) demonstrated that the autocorrelation method is more similar to the sieve analysis than laser diffraction. In the case of large-scale airborne imagery of landforms, the derivative technique, using local semivariance, proved to be effective (e.g., Carbonneau et al., 2004, 2005). To characterize the mean grain size, Buscombe et al. (2010) recently used the spectral decomposition of sediment images. For its utility in field settings, especially in remote or inaccessible areas or long-term deployments, the new non-calibration method facilitates the development of a fully transferable method. In addition, the “autocorrelation” approach including subsequent wavelet method has been successful in obtaining grain-size distribution and associated parameters (Buscombe and Rubin, 2012; Buscombe, 2013; Buscombe et al., 2014).

Although Buscombe and Rubin (2012) explored a framework for the simulation of natural well-sorted granular material based on the principle of Voronoi tessellation, most former researchers generally focused on the mixed-size sediment on site, and for the well-sorted sediment detailed validation of autocorrelation method was scarce. However, well-sorted granular material is very common in nature, and the first step would be an appropriate estimation of its size characteristics before applying this technique to the mixed-size sediment case. For the mixed-size natural grains, most researchers failed to provide realistic grain-size distributions (Rubin et al., 2007; Barnard et al., 2007; Warrick et al., 2009). Buscombe (2008) pointed out that both the least squares method and the least-squares with non-negativity method produce unrealistic grain-size distribution. For more accurate grain-size distribution, Buscombe applied the nonparametric kernel density estimation method. To estimate grain-size distribution, Gallagher et al. (2011) adopted the maximum entropy method based on autocorrelation analysis. Both of the aforementioned methods ensure that each grain-size fraction is positive and the proportion summation is unity, and these two constraints improve the grain-size distribution estimation. However, Buscombe (2008) found that the kernel method as yet is ineffective for skewness estimation. Gallagher et al. (2011) stated that the maximum entropy method was more suitable for bi-modal grain-size distribution. Nevertheless, many researchers realized the systematic bias that digital image analysis was a two-dimensional approach but no effort was made to rectify it (Buscombe, 2008; Pentney and Dickson, 2012). In addition, Rubin's method requires the sample image containing many grains, which decreases the image resolution, producing less accurate results.

Based on Rubin's autocorrelation algorithm, an improved digital grain-size analysis method was proposed in this study to estimate the grain size of well-sorted sediments and the grain-size distribution of mixed-size sediments. This method offers accurate estimations of the grain size (e.g., the long axis, the intermediate axis, and the mean size) of the well-sorted surface sediment ranging from 1 to 20 mm. Regarding the mixed-size sediment, a newly developed method using a nonlinear programming technique, which is different from the ‘least-squares with non-negativity’ method, the kernel density estimation method, and the maximum entropy method, provides accurate grain-size distributions and associated sediment inherent parameters.

This paper is organized as follows. Section 2 describes the image recording technique and the preparation of sediment samples. Section 3 presents the detailed description of methodology and validation of the well-sorted sediments. Section 4 discusses digital grain-size analyses of several representative mixed-size sediment parameters, such as mean diameter, median diameter, sorting, skewness, and kurtosis; in addition, an improved Gaussian function fitting method was introduced to obtain the cumulative grain-size distribution curve and the probability density curve of the mix-sized sediments. Finally, Section 5 summarizes and concludes this paper.

2. Image recording and sediment samples

In this study, photographs were recorded using a Cannon EOS 60D digital camera, which was set on a tripod, to ensure that the camera is at approximately 0.48 m above the sample plate with a shooting angle being orthogonal to the sample plate. The recorded image had a resolution of 5184 × 3456 pixels. Using a plate, the grain surface was flattened before recording the image. Each photograph samples a 15 × 10 cm area, and the image spatial resolution is approximately 0.03 mm per pixel. For each grain sample, three photographs were recorded for grain-size analysis. Sediments in a grain sample were redistributed by shaking the sample plate before taking each photograph. All photographs were taken under the same lighting condition.

Natural sediments were sieved into 11 well-sorted groups after 12 sieves (i.e., 1, 1.25, 1.43, 1.6, 2.0, 2.5, 4.0, 5.0, 6.0, 8.0, 10.0, and 12.0 mm). These samples are regarded as well-sorted grains. The size of well-sorted sediments ranges from 1 to 20 mm, covering coarse sands, gravels, and pebbles. However, mixed-size grain samples were obtained by a mixture of the well-sorted sediment components in terms of a designed mass mixing proportion. In total, 11 mixed-size samples were considered. The designed mixing proportions of these samples are listed in Table 1, and six representative digital images (images of three well-sorted grains as well as three mixed-size grains) are shown in Fig. 1. As shown in Table 1, mixed-size sediments consist of coarse sands and gravels. MS. 1 is mixed with two grain sizes leading to a bimodal size distribution; MS. 2–7 consists of five continuous well-sorted sediment components; and MS. 8–11 consists of eight components.

3. Digital grain-size analysis of well-sorted sediments

3.1. Methodology

In this paper, we used the autocorrelation technique to quantify the size of well-sorted sediments. This approach is based on the spatial autocorrelation function that is sensitive to the dimensions of the grains in the images of sediments (Rubin, 2004). The spatial autocorrelation r between two regions in an image is given by,

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \quad (1)$$

where x_i and y_i are the intensities of corresponding pixels in the two regions, and $\bar{x}$ and $\bar{y}$ are the mean intensities of pixels in their own regions. The region of x moves with a certain amount of pixel shift (i.e., offset) and obtained the region of y. Grain sample of a certain size has its own autocorrelation curve, and the curve of fine grains

Table 1
Designed mixed-size grain samples and the corresponding mass mixing proportions of each component.

Mixed-sized samples (MS)	Well-sorted sediment components in a mixed-size sample (mm)							
	1–1.25	1.25–1.43	1.43–1.6	1.6–2	2–2.5	2.5–4	4–5	5–6
MS. 1	–	–	1	–	–	–	1	–
MS. 2	–	–	1	1	1	1	1	–
MS. 3	–	–	2	1	1	1	1	–
MS. 4	–	–	1	1	2	1	1	–
MS. 5	–	–	1	1	1	1	2	–
MS. 6	–	–	5	4	3	2	1	–
MS. 7	–	–	1	2	3	4	5	–
MS. 8	8	8	4	4	2	2	1	1
MS. 9	1	1	2	2	4	4	8	8
MS. 10	8	7	6	5	4	3	2	1
MS. 11	1	2	3	4	5	6	7	8