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Development of a mass model in estimating weight-wise particle size distribution using digital image processing

Maiti Abhik *, Chakravarty Debashish, Biswas Kousik, Halder Arpan

Department of Mining Engineering, Indian Institute of Technology, Kharagpur 721302, India

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A B S T R A C T

Particle size distribution of coarse aggregates through mechanical sieving gives results in terms of cumulative mass percent. But digital image processing generated size distribution of particles, while being fast and accurate, is often expressed in terms of area function or number of particles. In this paper, a mass model is developed which converts the image obtained size distribution to mass-wise distribution, making it readily comparable to mechanical sieving data. The concept of *weight/particle* ratio is introduced for mass reconstruction from 2D images of particle aggregates. Using this mass model, the effects of several particle shape parameters (such as major axis, minor axis, and equivalent diameter) on sieve-size of the particles is studied. It is shown that the sieve-size of a particle strongly depend upon the shape parameters, 91% of its variation being explained by major axis, minor axis, bounding box length and equivalent diameter. Furthermore, minor axis gives an overall accurate estimate of particle sieve-size, error in mean size (D-50) being just 0.4%. However, sieve-size of smaller particles (<20 mm) strongly depends upon the length of the smaller arm of the bounding box enclosing them and sieve-sizes of larger particles (>20 mm) are highly correlated to their equivalent diameters. Multiple linear regression analysis has been used to generate overall mass-wise particle size distribution, considering the influences of all these shape parameters on particle sieve-size. Multiple linear regression generated overall mass-wise particle size distribution shows a strong correlation with sieve generated data. The adjusted R-square value of the regression analysis is found to be 99 percent (w.r.t cumulative frequency). The method proposed in this paper provides a time-efficient way of producing accurate (up to 99%) mass-wise PSD using digital image processing and it can be used effectively to replace the mechanical sieving.

1. Introduction

Particle size distribution (PSD) and particle shape characterization are two important parameters in several industrial sectors. The variation in size and shape of the particles is large in the fields of geology, civil, mining, metallurgy, agriculture, etc. Therefore, the size and shape determination of aggregate particles is quite complex and time consuming.

One of the simple and popular methods of particle size estimation is mechanical sieving. However, there are certain limitations of this conventional sieving method. Sieve analysis is time consuming and it does not give any idea about particle shape. Two particles with completely different shape characteristics may have the same sieve size. Mechanical sieving is also inappropriate in case of sticky materials, or materials that may chemically react with the sieve. Therefore, the requirement for alternative ways of particle size analysis is one of the key motivations for the introduction of image-based particle sizing systems [1].

There are several advantages of using digital images for particle size estimation. While conventional sieving takes 30–45 min, digital image processing (DIP) can generate the same result in very quick time (∼5 min). As digital cameras and computers are very common these days, DIP based method is more convenient for general use and is relatively cheap. Conventional sieving method only gives us the weight distribution of the particles. In image processing, we can also measure a number of other parameters, such as area, major axis diameter, minor axis diameter, center of gravity, and equivalent diameter.

Several researchers have used different shape parameters (e.g. Ferret diameter, equivalent circle diameter, size of equivalent ellipses etc.) for characterizing the particle size [2–6]. Andersson et al. have discussed the best fit rectangle algorithm for particle size distribution from digital images, which gives a reasonably good estimate of particle size [7]. Thyabat et al. have proposed a technique to identify the equivalent diameter (dA) and mean

* Corresponding author.
E-mail address: abhikatoldtrafford@gmail.com (A. Maiti).

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Feret's diameter (dF) of each particle [8]. The distribution density of the data extracted from those particle profiles is then used to develop a model to estimate the particle sieve-size distribution, Tutumluer et al. [9].

Tafesse et al. has approached the problem in a different way. Here 'Glow-In-the-Dark' beads were used to create luminous background while capturing digital images. Then the particle size information from the GID method is compared to the result from mechanical sieving. The advantages of the GID method over the conventional mechanical sieving are also discussed in the article [2].

Fernlund et al. measured three axes of each particle by manually changing their orientations. Digital images of those particles were captured in two orientations, thus giving an accurate estimation of the particle size. The gradation curves determined by image analysis were compared to those obtained by Danish Box Method. This method, while being time-consuming, showed that particles oriented in their most stable positions obtained better results [3].

It is seen in the literatures that gradation curves obtained by image analysis differ from the data obtained by mechanical sieving. This may be due to the shadow effects generated from light sources, irregular shapes of the particles being sieved, etc. These issues were investigated in great details in the paper published by Kumara et al. [10]. Here, gradation curves of gravel were generated using the area of the particles obtained from image analysis.

One of the drawbacks of the digital image processing (DIP) techniques is that, the image of the particles captured only shows the two-dimensional projection of the particles. The particle thickness is not captured, and thus cannot be analyzed directly by DIP techniques. So, the results generated from DIP have to be expressed in terms of area function, or number of particles as opposed to mass function, in which traditional sieving results are obtained. So, DIP generated results are not readily comparable with conventional sieving, unless certain assumptions are made. Taylor, Tutumluer et al. and many other authors claim that it is extremely important to accurately determine the volume of the particles using image analysis, in order to express the particle size distribution curves with respect to mass [4,9].

There are numerous ways of calculating volume and mass of particles from their two-dimensional projections. Furnlund et al. proposed different methods to reconstruct volume and mass of the individual particles in an aggregate. He also proposed a universal method for conversion of image analysis generated particle size to mechanical sieve-size. However, the generated particle sizes and mechanical sieve-size were poorly correlated [11].

Zhang et al. developed an improved mass model from digital images using particle shape parameters like density, projected area, perimeter, best-fit rectangle, etc. The generated mass model, while being five times more computationally complex, gave accuracy up to 94%. However, the model discussed here is not very convenient for application in mineral industries, mainly due to large amount of computation time [12,13]. Several authors have discussed particle size distribution estimation from digital images in their papers. However, the methodologies discussed in these articles are not efficient and accurate enough to be used in large scale mineral processing plants [14–17].

In this paper, we propose a new method, using which an effective and accurate transformation of coarse aggregates from size based distribution to cumulative mass percent can be obtained. A mass model is developed, which allows image-based mass reconstruction of particles of different size ranges, making it readily comparable with mechanical sieving analysis generated data. The mass model takes account of the influence of different particle shape parameters on sieve-size of the particles. The correlations between different particle shape parameters and sieve-size of particles are also determined. Finally, an overall mass-wise particle size distribution is obtained using these particle shape parameters, which shows an accuracy up to 99%, w.r.t the sieve generated data.

2. Methodology

The proposed particle size estimation technique using digital image processing is discussed in the following steps as shown in Fig. 1.

2.1. Sample preparation and mechanical sieving

In order to develop an automated model for estimation of particle size analysis using digital images, coarse particles were collected from different construction sites across the campus of IIT Kharagpur. The samples included standard construction materials like stone chips, along with other pebbles, stone particles, etc. The samples were kept under bright sunlight on top of a clean cloth, so that the coarse particles were dried up completely, and the dirt (small fine grains, sand, etc.) which was sticking to those particles were separated from the samples. Then, the samples were collected in dry and clean buckets to perform sieving and image analysis.

In this study, a series of sieves of square apertures of sizes 9.5, 11.2, 13.2, 16.0, 19.0, 22.4, 26.5, 31.5, 37.5 and 63.0 mm were used. The samples were sieved and aggregates retained from each sieve were separated. As the objective of this study was to estimate PSD of coarse particles, the aggregates remaining in the pan of the sieve, i.e. those particles with equivalent sieve-size <9.5 mm were rejected. The weight of aggregates from each sieve is noted down, as well as the (*weight/particle*) ratio, which plays a big part in developing the mass model discussed here (Eqs. (1) and (2)). The mechanical sieving obtained data is shown in Table 1.

The sieving operation is only done to compare and validate the results with image processing generated results and is not necessary for the generation of PSD. Another purpose of the mechanical sieving operation is to obtain *the weight/particle* ratio for particles of each sieve size, which plays a huge part in reconstructing the mass of the particles from image analysis generated data.

2.2. Weight/particle ratio calculation from sieve data

The (weight/particle) ratio is obtained by counting the number of particles in each sieve, and dividing the total weight by the number of particles (Eq. (1)). In case of a large amount of particles, we randomly select few sets of particles from each sieve and measure the weight and the number of particles. Finally, we take the mean value of weight/particle for that particular sieve (Eq. (2)).

$$\left(\frac{Weight}{Particle}\right) = \frac{W}{P} = \left(\frac{Weight\ of\ all\ the\ particles\ in\ a\ sieve}{Number\ of\ particles\ in\ that\ sieve}\right) \tag{1}$$

When huge numbers of aggregates are present in a sieve,

$$\frac{W}{P} = \frac{\sum_0^n \frac{Weight\ of\ a\ set\ of\ particles\ taken\ from\ the\ sieve\ randomly}{Number\ of\ particles\ present\ in\ that\ set}}{Number\ of\ random\ sets\ selected\ from\ the\ sieve\ (n)} \tag{2}$$

This **W/P** ratio plays an important part in reconstructing the particle mass from digital images, hence generating mass-wise PSD and gradation curves of the samples. This conversion enables us to represent the image-analysed PSD result in the conventional way i.e. in terms of cumulative mass distribution. The results obtained from this mass model is validated by comparing them with mechanical sieve generated data. Also, as discussed and shown later in this article, this technique gives us more accurate PSD as opposed to mechanical sieving, which has some severe limitations and is also time-consuming.