Effect and correction of segregation error in coal size distribution estimation by image analysis on a conveyor belt

Zelin Zhang¹, Qi Hu, Zhiwei Zhang and Li Wang

Hubei Key Laboratory for Efficient Utilization and Agglomeration of metallurgic Mineral Resources, School of Resource and Environmental Engineering, Wuhan University of Science and Technology, Wuhan, Hubei 430080, China

¹Email: zhangzelin@wust.edu.cn

Abstract. Online monitoring of rock size is of great significance for mining and mineral processing, and machine vision is regarded as the most suitable approach. Segregation error of coal piles is inherent in image-based size distribution estimation, leading to the difference between surface size distribution and overall size distribution. In this research, we analysed the segregation error and proposed a correction method for image-based size distribution estimation of coal piles on a conveyor belt. The paint spraying of rock particles makes the compare of actual surface size distribution and overall size distribution possible. Rosin-Rammller particle characteristic equation was used to build the correction model to reduce the segregation error in size distribution estimation. Test results indicated that the corrected overall size distribution is close to the actual overall size distribution, and the maximal absolute error reduces from 19.98% to 2.04%. This investigation is useful and valuable for the optimization and improvement of image-based size distribution estimation of coal piles on a conveyor.

1. Introduction

Rock size affects the productivity of mining and mineral processing from the initial phase of drilling and blasting to crushing and grinding et al [1-7]. Conveyor is the most common means of transportation. Therefore, online size distribution estimation of rock piles on a conveyor has a great importance for the control and optimization in minerals engineering.

Sieving, the traditional measurement method, is considered accurate but time-consuming and not suitable for real-time monitoring. Hamzeloo et al. state that "Machine vision is probably the most suitable approach for on-line particle size estimation because it is robust, cost-effective and non-intrusive" [8]. In the last two decades, image-based monitoring technologies for rock size distribution kept growing fast. Until now, the image-based rock size distribution estimation has been studied and used in the fields of drilling, blasting, dump leaching, crushing, milling, iron ore pellets, rock micrographic analysis et al [3-5, 9-17].

Thurley and Ng pointed out a number of error sources relevant to image analysis techniques of rock size: segregation error (generally known as brazil nut effect), capturing error, partial profile error and overlapped particle error [18]. Segregation error of rock piles is inherent in image-based size distribution estimation, as shown in Figure 1. Smaller particles tend to migrate under the larger particles or migrate in the gaps, particularly in vibration environment such as conveyor or trucks. Segregation error leads to the difference between surface size distribution and overall size distribution. The smaller particles on surface should be less than that of overall pile, and the larger particles are the opposite.
Figure 1. The relationship of surface size distribution and overall size distribution.

However, most studies have focused on the surface size measurements, and little effort has been spent on the study of segregation error correction in the rock size analysis. Yen et al. had an extensive discussion about particle overlap and segregation problems in on-line coarse particle size measurement, and proposed an approach to correct the particle overlap and segregation errors simultaneously [19]. A 3D surface data segmentation, which can distinguish entirely visible rocks and overlapped or partially visible rocks, was used to estimate the surface size distribution of laboratory rock piles and directly compare to the overall size distribution in order to reduce the segregation error [18, 20]. Zhang and Liu assessed particle size segregation in a copper dump-leaching mine by aerial image analysis. The size distributions of copper rocks in different depth were estimated and analysed to demonstrate the segregation effect [21].

The aim of the present paper is to propose a correction method only for segregation error in size distribution estimation of coal piles on conveyor. The paint spraying makes the compare of actual surface size distribution and overall size distribution possible. Rosin-Rammler particle characteristic equation was used to build the correction model to reduce the segregation error in size distribution estimation.

2. Correction method of segregation error

Rosin-Rammler equation, namely R-R equation, is one of the most accepted particle characteristic equations to describe the size distribution of solid particles. One of the equation forms shows in Equation (1).

\[ R/100 = 1 - e^{-(d/b)^n} \]  

where \( R \) means the cumulative yield less than \( d \) mm, %; \( d \) means the sieving size, mm; \( e \) is the Napierian base; \( b \) is the parameter related to the size distribution of ores, which is equal to the sieving size with the undersize cumulative yield 63.2%; \( n \) is the parameter related to the nature of ores.

The parameters \( b \) and \( n \) of overall size distribution are different from those of surface size distribution because of the segregation error. Therefore, the segregation error can be corrected by establishing a model between \( b \) and \( n \) of overall size distribution and those of surface size distribution. However, the actual surface size distribution is difficult to obtained because of the overlapped particle error. The paint spraying was adopted to color the rocks in different size fractions, and the actual surface size distribution can be measured accurately for the pure segregation error analysis.

2.1. Experiment preparation

Coal particles in four size fractions (50~25 mm, 25~13 mm, 13~6 mm and 6~3 mm) from Tai-xi coal preparation plants of China were sieved manually and used as the experimental ores in this investigation. In order to easily identify the actual size fractions of coal particles, the particles in 25~13 mm, 13~6 mm and 6~3 mm were colored blue, red and yellow, respectively. The 50~25 mm particles remained their own color (black).
Image-based size distribution estimation was always carried out on the conveyor. We designed a belt unit to simulate the conveyor in this experiment, as shown in Figure 2(a), with the length 519mm, the width 325mm and the height 188mm. Eight pairs of parameters \( b \) and \( n \) \((10,1), (15,1), (15,1.5), (20,1.5), (20,2), (25,2), (25,2.5), (30, 2.5)\) were selected to form eight different size distributions, as shown in Figure 2(b), which includes the majority of size distributions in industrial production. Eight samples were prepared according to the above size distributions with the total mass 2.5kg, and the approximate mass of each size fraction was shown in Table 1.

![Image](image_url)

**Figure 2.** (a) The belt unit for experiment; (b) the size distribution curves of eight samples; (c) one of the surface images of samples; (d) the surface size distribution curves of eight samples.

### 2.2. Modelling

To simulate the ores transloading on conveyor, each sample was intensive mixed by the way of pile-to-pile three times. Then they were poured into belt unit with constant speed one after another. The pile surfaces were smoothed by slight vibration manually, shown as Figure 2(c). The surface images were acquired by industrial area-array cameras and the particle numbers of all size fractions were counted in zoom mode. The mass of coal particle was approximately estimated by the average mass of each size fraction, as shown in Table 2. The amount of coal particles was sufficient to guarantee the accuracy of average mass.

Therefore, the actual surface size distributions of eight samples can be calculated through the particle numbers and average mass of each size fraction, as shown in Figure 2(d). Comparing Figure 2(b) and Figure 2(d), the smaller particles on surface are obviously less than those of overall samples, which indicates the segregation error of rock piles on conveyor is serious.
Table 1. The mass distributions corresponding to parameters b and n.

| Size fraction, mm | $n=1$ Mass, g | $n=1.5$ Mass, g | $n=2$ Mass, g | $n=2.5$ Mass, g |
|-------------------|---------------|----------------|---------------|----------------|
| b=10              |               |               |               |                |
| 3-6               | 1127.7        |               |               |                |
| 6-13              | 692.1         |               |               |                |
| 13-25             | 478.1         |               |               |                |
| 25-50             | 199.8         |               |               |                |
| b=15              |               |               |               |                |
| 3-6               | 824.1         | 558.6         |               |                |
| 6-13              | 625.8         | 826.7         |               |                |
| 13-25             | 580.2         | 827.4         |               |                |
| 25-50             | 463.7         | 283.1         |               |                |
| b=20              |               |               |               |                |
| 3-6               | 378.6         | 215.3         |               |                |
| 6-13              | 642.1         | 647.2         |               |                |
| 13-25             | 863.5         | 1115.8        |               |                |
| 25-50             | 612.7         | 520.6         |               |                |
| b=25              |               |               |               |                |
| 3-6               | 140.1         | 69.5          |               |                |
| 6-13              | 453.1         | 374.4         |               |                |
| 13-25             | 990.7         | 1140          |               |                |
| 25-50             | 916.9         | 916.9         |               |                |
| b=30              |               |               |               |                |
| 3-6               | 44.2          |               |               |                |
| 6-13              | 246.5         |               |               |                |
| 13-25             | 883.3         |               |               |                |
| 25-50             | 1323.7        |               |               |                |

Table 2. Average mass of coal particles in each size fraction.

| Size fraction, mm | Number | Average mass, g |
|-------------------|--------|----------------|
| 3-6               | 5000   | 0.071          |
| 6-13              | 3000   | 0.712          |
| 13-25             | 1000   | 4.574          |
| 25-50             | 500    | 15.745         |

Nonlinear Least Square Method was used to fit the surface size distribution curves through R-R equation (Equation (1)). The parameters of surface size distribution were expressed as b' and n', and the overall size distribution parameters were expressed as b and n. The fitting results were shown in Table 3 and Table 4. Root Mean Square Error (RMSE) and R-squared were used to represent the fitting effects. A smaller RMSE is desirable, and R-squared is better when it is closer to 1.

Table 3. Parameters b’ and n’ of eight surface size characteristic equations.

| n=1 | n=1.5 | n=2 | n=2.5 |
|------|-------|-----|-------|
| n’   | b’    | n’  | b’    | n’   | b’   | n’  | b’   |
| b=10 | 1.814 | 19.27 | / | / | / | / | / | / |
| b=15 | 1.765 | 24.23 | 2.151 | 21.14 | / | / | / | / |
| b=20 | / | / | 2.267 | 27.12 | 2.698 | 24.3 | / | / |
| b=25 | / | / | / | 3.29 | 29.45 | 3.672 | 27.79 | / | / |
| b=30 | / | / | / | / | / | 3.679 | 30.8 | / | / |
The values of RMSE are lower and the values of R-square are close to 1, which indicates that all parameters $b'$ and $n'$ were fitted well. It is observed that $b'$ and $n'$ were larger than $b$ and $n$ in eight samples, and the growing rate of $b'$ is more conspicuous when $b$ and $n$ are lower. $b'$ is close to $b$ when $b$ and $n$ is 30 and 2.5 respectively. Parameter $b$ expresses the sieving size with the undersize cumulative yield 63.2%. The above results indicated that the segregation error is more serious when smaller particles play a dominant role.

### Table 4. Fitting effect of eight surface size characteristic equations.

| n  | RMSE  | R-square | RMSE  | R-square | RMSE  | R-square | RMSE  | R-square |
|----|-------|----------|-------|----------|-------|----------|-------|----------|
|    | 0.023 | 0.997    | /     | /        | /     | /        | /     | /        |
| b=10 | 0.035 | 0.993    | 0.019 | 0.998    | 0.010 | 0.999    | /     | /        |
| b=15 | 0.019 | 0.998    | 0.003 | 1        | 0.001 | 1        | /     | /        |
| b=20 | /     | /        | 0.020 | 0.998    | /     | /        | /     | /        |
| b=25 | /     | /        | /     | /        | /     | /        | /     | /        |
| b=30 | /     | /        | /     | /        | /     | /        | /     | /        |

The values of RMSE are lower and the values of R-square are close to 1, which indicates that all parameters $b'$ and $n'$ were fitted well. It is observed that $b'$ and $n'$ were larger than $b$ and $n$ in eight samples, and the growing rate of $b'$ is more conspicuous when $b$ and $n$ are lower. $b'$ is close to $b$ when $b$ and $n$ is 30 and 2.5 respectively. Parameter $b$ expresses the sieving size with the undersize cumulative yield 63.2%. The above results indicated that the segregation error is more serious when smaller particles play a dominant role.

### Table 5. (a) Multiple linear regression analysis results between $b$ and ($n'$, $b'$).

| DOF | F-Value | p-Value |
|-----|---------|---------|
| Regression | 7 | 111.6175 | 0.0001 |
| RMSE | 1.1465 |
| R-Square | 0.9781 |

(b) Analysis results of model parameters estimation

| Variable | Coefficient | Standard deviation | t-Value | p-Value |
|----------|-------------|--------------------|---------|---------|
| Constant term | -13.9794 | 3.1095 | -4.4957 | 0.0064 |
| $n'$ | 3.8928 | 0.9486 | 4.1038 | 0.0093 |
| $b'$ | 0.9249 | 0.1875 | 4.9341 | 0.0043 |

### Table 6. (a) Multiple linear regression analysis results between $n$ and ($n'$, $b'$).

| DOF | F-Value | p-Value |
|-----|---------|---------|
| Regression | 7 | 103.9959 | 0.0001 |
| RMSE | 0.1508 |
| R-Square | 0.9455 |

(b) Analysis results of model parameters estimation

| Variable | Coefficient | Standard deviation | t-Value | p-Value |
|----------|-------------|--------------------|---------|---------|
| Constant term | -0.2068 | 0.1991 | -1.0384 | 0.3391 |
| $n'$ | 0.7337 | 0.0719 | 10.1978 | 0.0001 |

Then, the transformation model of ($b$, $n$) and ($b'$, $n'$) can be developed. Multiple Linear Regression Method was adopted to establish the mathematical models of $b$ and ($n'$, $b'$), $n$ and ($n'$, $b'$). Through the comparison of linear polynomial regression and quadratic polynomial regression, Equation (2) and Equation (3) were the final models with the simple forms and high fitting effects. The regression analysis results were shown in Table 5 and Table 6. $\alpha$ is determined as 0.05, and DOF is 7. The p-Values of two models were less than 0.0001, indicating that the overall linear dependence is significant. The values of RMSE and R-Square all were satisfied. In the modeling of $n$ and ($n'$, $b'$), the p-value of $b'$ is larger than 0.05, indicating that the linear dependence of $b'$ and $n$ are non-significant. Hence the term of $b'$ needs to be deleted. Equation (2) and Equation (3) were the final transformation models.

$$b = 3.8928n' + 0.9249b' − 13.9794$$  \hspace{1cm} (2)

$$n = 0.7337n' − 0.2068$$  \hspace{1cm} (3)
As seen in the Equation (2) and Equation (3), parameters b and n of overall size distribution can be calculated by b' and n'. While parameters b' and n' can be fitted by Nonlinear Least Square Method when the surface size distribution of rock piles was estimated. Therefore, the segregation error in image-based size distribution estimation is able to be reduced by Equation (2) and Equation (3).

3. Tests and discussions
To test and verify the method for correcting particle segregation error, another 2.5kg coal pile with different size distribution (shown in Figure 3(a)) was used to compare the overall size distribution and the corrected size distribution. The overall size distribution is shown in Table 7.

The surface size distribution, as shown in Table 7, is obtained by counting the different color particles in Figure 3(a) and the average mass in Table 2. Then b' and n' can be fitted by Nonlinear Least Square Method based on R-R equation. The fitting curve and fitting model are shown in Figure 3(b) and the values of b' and n' are 21.78 and 2.232 respectively. Then b and n can be calculated by Equation (2) and Equation (3), and the results of b and n are 14.854 and 1.4308. The corrected overall size distribution can be calculated though the R-R equation finally, as shown in Table 7.

Figure 3. (a) The test coal pile; (b) The fitting curve of surface size distribution.

Table 7. The comparison of the actual overall size distribution and corrected overall size distribution.

| Size fraction, mm | 3-6, mm | 6-13, mm | 13-25, mm | 25-50, mm |
|------------------|---------|---------|-----------|-----------|
| Surface size distribution, % | 2.99    | 25.36   | 45.53     | 26.12     |
| Estimated size distribution, % | 23.92   | 32.32   | 31.60     | 12.17     |
| Actual size distribution, % | 22.97   | 34.21   | 32.70     | 10.13     |
| Absolute error between Estimated and Actual results, % | 0.95 | -1.89 | -1.1 | 2.04 |

The results indicated that the surface size distribution has a large difference with the actual overall size distribution because of segregation error. The maximal absolute error is up to 19.98%. Through the proposed correction method, the corrected overall size distribution is close to the actual overall size distribution, and the maximal absolute error reduces to 2.04%.

4. Conclusions
(1) Segregation error analysis of rock piles on conveyor was carried out in this investigation, and an effective correction method has been proposed for the image-based size distribution estimation.

(2) The paint spraying of rocks was adopted to eliminate the overlapped particle error, and obtain the actual surface size distribution of rock piles, which is the research basis of pure analysis of segregation error.
(3) Through the compare of surface size distribution and overall size distribution of eight samples, the smaller particles on surface are obviously less than those of overall samples, and the segregation error is more serious when smaller particles play a dominant role.

(4) R-R equation, Nonlinear Least Square Method and Multiple Linear Regression Method were used to establish the correction model of segregation error, and the modeling process was analyzed in detail.

(5) Test results indicated that the proposed method is effective to correct the segregation error. The corrected overall size distribution is close to the actual overall size distribution, and the maximal absolute error reduces from 19.98% to 2.04%.

Acknowledgments

The authors would like to thank the supported by National Natural Science Foundation of China (No.51604196), the Fund of State Key Laboratory of Mineral Processing (BGRIMM-KJSKL-2016-06), the China Postdoctoral Science Foundation (2017M612522).

References

[1] Aldrich C, Uahengo F D L and Kistner M 2015 Estimation of particle size in hydrocyclone underflow streams by use of Multivariate Image Analysis Minerals Engineering 70 14-19
[2] Campbell A D and Thurley M J 2017 Application of laser scanning to measure fragmentation in underground mines Transactions of the Institution of Mining & Metallurgy 1-8
[3] Igathinathane C and Ulusoy U 2016 Machine vision methods based particle size distribution of ball- and gyro-milled lignite and hard coal Powder Technology 297 71-80
[4] Little L, Becker M, Wiese J and Mainza A N 2015 Auto-SEM particle shape characterisation Investigating fine grinding of UG2 ore Minerals Engineering 82 92-100
[5] Ulusoy U and Igathinathane C 2014 Dynamic image based shape analysis of hard and lignite coal particles ground by laboratory ball and gyro mills Fuel Processing Technology 126(Supplement C) 350-358
[6] Ulusoy U and Igathinathane C 2016 Particle size distribution modeling of milled coals by dynamic image analysis and mechanical sieving Fuel Processing Technology 143 100-109
[7] Zheng J and Hryciw R D 2017 Soil Particle Size and Shape Distributions by Stereophotography and Image Analysis Geotechnical Testing Journal 42(2) 1-14
[8] Hamzeloo E, Massinaei M and Mehrshad N 2014 Estimation of particle size distribution on an industrial conveyor belt using image analysis and neural networks Powder Technology 261 185-190
[9] Agimelen O S et al. 2016 Chemical Engineering Science 144 87-100
[10] Aldrich C, Jemwa G T, Dyk J C V, Keyser M J and Heerden J H P V 2010 International Journal of Coal Preparation and Utilization 30(6) 331-348
[11] Andersson T and Thurley M J 2011 Powder Technology 206(3) 218-226
[12] Andersson T, Thurley M J and Carlson J E 2012 Minerals Engineering 25(1) 38-46
[13] Atteya M A, Salem M A M, Hegazy D and Rou M I 2016 Asian Journal of Applied Sciences 9(4) 170-177
[14] Igathinathane C, Ulusoy U and Pordesimo L O 2012 Powder Technology 215 137-146
[15] Jain A, Metzger M J and Glasser B J 2013 Powder Technology 237 543-553
[16] Nellros F, Thurley M J, Andersson C and Forsmo S P E 2015 Pattern Recognition 48(11) 3451-3465
[17] Thurley M J 2011 Journal of Process Control 21(2) 254-262
[18] Thurley M J and Ng K C 2008 Computer Vision and Image Understanding 111(2) 170-178
[19] Yen Y K, Lin C L and Miller J D 1998 Powder Technology 98(1) 1-12
[20] Thurley M J and Ng K C 2005 Computer Vision and Image Understanding 98(2) 239-270
[21] Zhang S and Liu W 2017 Hydrometallurgy 171 99-105