Research Article

An Image-Based Gradation Calculation Method considering Crushed Stone Morphology

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1. Introduction

Crushed stone is small pieces of the broken rock due to natural reasons or man-made destruction, which has irregular size, shape, and texture. Materials with different particle size distributions are often used to form coarse aggregate [1, 2], backfill material [3–6], and rockfill [7–9] in high fill, subgrade [10–12], and mining engineering. There are various parameters describing soil materials, among which the particle size and gradation are commonly used. Gradation is known to be defined as the distribution of aggregate particles of different sizes, which can be determined by a sieving analysis test. However, the pore of the sieves is generally composed by a lattice square according to the method of the British Standards Institute [13], which sometimes makes particles of quite different characteristics have the same size [14]. This brings about difficulties to design the gradation for different kinds of materials in engineering.

Particle geometry is a result of the genesis of the parent rock, stages of transportation and depositional history, and chemical and biological effects [15]. For particulate materials including crushed stones, the characteristics of the particle shape govern their complex mechanical behavior at multiscales, about which the research interest has been growing in recent years [16, 17]. Since Wadell [18] first proposed the shape parameter: sphericity, the parameter evaluating the particle shape has been developed and the number of the parameter has been added. Traditional methods are to make use of charts such as the charts of Krumbein and Sloss [19] and Cho et al. [20]. The roundness and sphericity of a given particle are assessed by visual comparison with the reference shapes in these charts. Lee et al. [17] not only redefined sphericity but also selected elongation, slenderness, and convexity to describe the irregularity of sand grains. Berrezueta et al. [21] evaluated the representativity of four independent 2D particle parameters which included fractal dimension, Wadell’s roundness, a perimeter-area normalized ratio, and sphericity. Liu et al. [22] proposed an empirical small-strain shear modulus model including a Fourier-based particle shape factor modified by gradation through a series of shear wave velocity tests.
Recently, with the application of the computer image processing technology, the accuracy of the particle shape measurements has been improved. An image-based method is known to be a relatively convenient and accurate method, which can obtain particle shape data by using image processing software [22–34]. Basically, particles are usually pictured finely or roughly and the photos are processed in specific software such as ImageJ [22, 31, 33] and OnDemand3D [34] to obtain the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices. Some researchers used professional instruments to measure the particle shape of sand and review the particle shape indices.

The gradation of materials is usually described by nonuniformity coefficient \( C_u \) and curvature coefficient \( C_c \), which is determined by effective particle size \( (D_{10}) \), mean particle size \( (D_{50}) \), and controlling particle size \( (D_{60}) \). However, the method cannot fully express the characteristics of the gradation. A gradation curve equation method is proposed by researchers to overcome the shortcomings. Since Fuller and Thompson [35] and Talbot and Richart [36] proposed the equations of maximum density gradation curves and fractal gradation curves, respectively, the studies on gradation curve equations have been developed. Zhu et al. [37] and Guo et al. [38] proposed a gradation equation mainly focused on soil and coarse-grained soil. Then, Wu et al. [39] improved the method to reduce the required parameters. Zhu et al. [40] provided a gradation design method for rockfill materials based on fractal theory. Sun et al. [41] studied the particle generation procedure in DEM and proposed a gradation algorithm based on the particle number. The gradation curve equations are used to design the required gradation and have been gradually applied on the engineering.

To figure out the effect of particle shape when designing the gradation of aggregate, in this paper, eight kinds of crushed stones are prepared. The stones are divided into two groups which are the small particle group and the large particle group. The gradations for each group are processed to be the same by sieving. Meanwhile, the image processing software is used to obtain shape indices, including the minimum Feret diameter, aspect ratio, convexity, and sphericity. The minimum Feret diameter of particles is measured to form gradations which can reflect the particle shape effect. To quantitatively analyze this particle shape effect, a developed overall regularity is proposed, which is calculated by the weight of the aspect ratio, convexity, and sphericity. The developed overall regularity is applied on the gradation curve equations to provide an image-based gradation calculation method. The newly proposed gradation calculation method is validated to be well fitted, and the method is applied to two examples of gradation designation.

2. Test Materials and Particle Characteristics

Eight kinds of materials of different particle shapes are involved in the experiment as Figure 1. Table 1 shows the summary of the geological classification and characteristics and particle shape classification of the materials.

2.1. Particle Size and Gradation. Because the size of the crushed stone prepared in the experiment is around 20 mm, the circular sieve aperture diameter is 10 mm to 30 mm with 1 mm interval. To obtain representative and repeatable data for each material, about 5 kg for each kind of crushed stone with hundreds of particles is used to establish cumulative distribution curves. The particle size distribution curves of the eight crushed stones are controlled by sieving to be exactly the same, giving the mean particle diameter \( D_{50}^{\text{sieve}} = 15.5 \) mm and uniformity coefficient \( C_u^{\text{sieve}} = 1.34 \) for smaller particles as the black line in Figure 2(a); \( D_{50}^{\text{sieve}} = 20.5 \) mm and uniformity coefficient \( C_u^{\text{sieve}} = 1.15 \) for larger particles as the black line in Figure 2(b).

Besides the conventional sieving results, an imaging-based method is also used to obtain particle size and grading. Several indices measured by this method can describe the
Table 1: Summary of the geological classification and characteristics and particle shape classification.

| Stone       | Geological classification and characteristics                        | Particle shape |
|-------------|---------------------------------------------------------------------|----------------|
| White pebbles | Nearly pure silica stone with smoother surface                     | Subrounded    |
| Black stone  | Carbonate stone                                                     | Angular        |
| Basalt       | Porous stone about 40% void ratio, 45% silica, and 30% Fe₂O₃, CaO  | Angular        |
| Perlite      | Fragile vitreous stone composed of 70% silica and 12% alumina       | Subrounded    |
| Medical stone | Aluminosilicate stone with dense composition                       | Subangular    |
| Guangxi stone | Carbonate stone with quartz grain                                   | Angular        |
| Sepenggiante | Hard marble stone with the grain of a tree                          | Subrounded    |
| Limestone    | Carbonate stone with roughness surface, CaCO₃ over 90%              | Subangular    |

Figure 2: Particle size cumulative distribution for sieve analysis and $D_{F \text{min}}$ analysis.
size of the particle, along which the minimum Feret diameter \((D_{\text{F min}})\) is used in this paper, and \(D_{\text{F min}}\) means the smallest distance between two tangents on opposite sides of the particle, as shown in Figure 3(a). The gradation curve provided by \(D_{\text{F min}}\) as the size index has been found to be close to but different from that determined by sieve analysis [23], and the influence of the particle shape can be reflected with the \(D_{\text{F min}}\) analysis [29]. Figure 2 shows the similar results. Additionally, Table 2 shows more details about the size distribution curves.

2.2. Particle Shape Measurements. All particles in the experiment are pictured by a camera. Because the particle sizes are around 20 mm, a camera with a normal configuration (80 megapixels) is adequate to capture the particle shape characteristics [21]. Then, an image processing software Image-Pro Plus 7.0 [42] is used to convert the real image to a binary image to obtain shape indices. The experiment procedure is shown as Figure 4.

Three shape indices are used in this paper and have been widely used in recent years [23, 24, 29, 30], namely, the aspect ratio \((\text{AR})\), the convexity \((C)\), and the sphericity \((S)\), as shown in Figure 3: AR is defined as the ratio between \(D_{\text{F min}}\) and \(D_{\text{F max}}\); \(C\) is defined by the ratio between the area of the convex hull of the particle \((A+B)\); \(S\) is defined as the ratio between the perimeter of a circle with the same area as the projected area of the particle and its real perimeter.

![Figure 3: Definition of shape and size indices](image)

**Figure 3:** Definition of shape and size indices [29].

### Table 2: The shape data of the eight materials for the minimum Feret \((D_{\text{F min}})\) analysis.

| Material     | \(D_{\text{F 10}}\) (mm) | \(D_{\text{F 50}}\) (mm) | \(D_{\text{F 60}}\) (mm) | \(C_u\) |
|--------------|---------------------------|--------------------------|--------------------------|---------|
| White pebbles| 11.5                      | 14.9                     | 15.6                     | 1.35    |
| Black stone  | 12.2                      | 16.0                     | 16.8                     | 1.37    |
| Basalt       | 12.9                      | 16.8                     | 17.7                     | 1.37    |
| Perlite      | 11.4                      | 15.0                     | 15.6                     | 1.38    |
| Medical stone| 12.1                      | 15.8                     | 16.3                     | 1.35    |
| Guangxi stone| 18.1                      | 21.6                     | 22.4                     | 1.24    |
| Sepenggiante | 18.3                      | 21.4                     | 22.1                     | 1.21    |
| Limestone    | 18.7                      | 22.1                     | 22.8                     | 1.22    |

Note: \(D_{\text{10}}\) is the particle size of the 10% size distribution curve; \(D_{\text{50}}\) is the mean particle size; \(D_{\text{60}}\) is the particle size of the 60% size distribution curve; \(C_u\) is the uniformity coefficient defined by \(D_{\text{60}}/D_{\text{10}}\).

\[\text{OR} = \frac{((\text{AR}_{50} - \text{AR}_{\text{min}})/((\text{AR}_{\text{max}} - \text{AR}_{\text{min}})) + ((\text{C}_{50} - \text{C}_{\text{min}}))/((\text{C}_{\text{max}} - \text{C}_{\text{min}})) + ((\text{S}_{50} - \text{S}_{\text{min}}))/((\text{S}_{\text{max}} - \text{S}_{\text{min}})))}{3},\]
where the subscript "max" and "min" means the upper and lower bound of the 95% confidence interval, respectively, as shown in Figure 6. The figure shows the counting number distribution for the three shape indices. It is obvious that the contribution of each particle shape index is concentrated in a certain range. Equation (1) makes the weights of the three indices the same through the normalization method. Thus, OR with Equation (1) can describe the particle shape in a collective manner.

As shown in Figure 7, the difference is obvious for the rather different kinds of particles, comparing with the method of Yang and Luo [29]. The calculation results of Yang and Luo [29] for the used particles all concentrate at 0.8. By using the present method, the range of OR are from 0.3 to 0.8. For example, OR = 0.367 for basalt which is irregular and porous, and OR = 0.720 for perlite which is sub-rounded and smooth. This proves that for different kinds of particles, the proposed developed method can distinguish the morphology more obviously.

3. Gradation Equations

Traditional calculation of particle gradation needs to draw an initial gradation curve first and interpolate to get the value of effective particle size ($D_{10}$) and controlling particle size ($D_{60}$). Then, calculate the uniformity coefficient ($C_u$) and curvature coefficient ($C_c$) to check whether the result meets the engineering requirements and adjust the initial curve continuously until it finally meets. Comparing the complicated process shown above, the calculation process can be simplified by using the gradation equation method.

The continuous gradation equation proposed by Zhu et al. [37] and Guo et al. [43] is used in this paper:

\[ P = \frac{1}{1 - b}(D_{\text{max}}/D)^a + b \times 100\%, \]

where $D$ is any particle size within the gradation range; $P$ is the percentage of particles smaller than $D$; $D_{\text{max}}$ is the maximum particle size; $a$ and $b$ are dimensionless parameters that need to be determined. For minimum Feret diameter ($D_{\text{F min}}$) analysis, Equation (2) can be expressed as follows:

\[ P = \frac{1}{1 - b_{\text{F min}}}(D_{\text{F max}}/D_{\text{F min}})^{a_{\text{F min}}} + b_{\text{F min}} \times 100\%, \]

where the superscript "F min" means the parameter is obtained by minimum Feret diameter analysis, and the superscript "sieve" used in the following part means the parameter is obtained by sieve analysis.

Zhu et al. [37] indicated that the gradation curve shape was like “S” for a higher value of $b$. Because the shapes of the gradation curves in Figure 2 are all like “S,” $b = b_{\text{F min}} = 0.95$ is considered to be reasonable. Fitting $D_{\text{F min}}$ curves with Equation (3), the values of $a_{\text{F min}}$ for each kind of particles are as shown in Table 4. And fitting sieve curves with Equation (2), the values of $a_{\text{sieve}}$ for sieve analysis of small and large particles are calculated to be 10.37 and 15.28, respectively. The ratios between $a_{\text{F min}}$ and $a_{\text{sieve}}$ are also shown in Table 4.
Figure 5: Continued.
Figure 8 shows the relationship between overall regularity (OR) and parameter $a_{\text{F}}^\text{min}/a_{\text{sieve}}$. A linear equation is considered to be reasonable and is provided as follows:

$$a_{\text{F}}^\text{min}/a_{\text{sieve}} = 0.4\text{OR} + 0.5.$$  \hspace{1cm} (4)

It is obvious that a certain range of OR can be found for particles with different particle shapes in Figure 8. In engineering, particle shape indices are needed to calculate OR, sometimes making the work relatively complex and inconvenient. Thus, the paper provides an approach to obtain the value of OR as shown in Figure 8: nearly spherical particles are classified as “rounded” and OR = 0.8 ~ 0.9; elliptical or well-shaped particles are classified as “subrounded” and OR = 0.6 ~ 0.8; particles with some edges and corners are classified as “subangular” and OR = 0.4 ~ 0.6; crushed and irregular particles are classified as “angular” and OR = 0.3 ~ 0.4.

The value of $D_{\text{max}}^\text{F}$ is also related to OR, as shown in Figure 9. The figure shows that more angular particles have larger $D_{\text{max}}^\text{F}$ comparing to rounded particles. It is noted that the $D_{\text{max}}^\text{F}$ size of most rounded particles is exactly the same as the sieve pore size, referred to $D_{\text{sieve}}^\text{max} = D_{\text{max}}^\text{F}$. Then, an asymptotic relationship is more suitable between $D_{\text{max}}^\text{F}/D_{\text{sieve}}^\text{max}$ and OR. The equation can be expressed as follows:

$$D_{\text{max}}^\text{F}/D_{\text{sieve}}^\text{max} = e^{-3\text{OR}} + 1.$$  \hspace{1cm} (5)

| Material           | Aspect ratio (AR$_{50}$) | Convexity (C$_{50}$) | Sphericity (S$_{50}$) | OR of Yang and Luo | OR of the present study |
|--------------------|--------------------------|-----------------------|------------------------|--------------------|------------------------|
| White pebbles      | 0.708                    | 0.977                 | 0.842                  | 0.842              | 0.648                  |
| Black stone        | 0.683                    | 0.971                 | 0.792                  | 0.815              | 0.562                  |
| Basalt             | 0.686                    | 0.949                 | 0.681                  | 0.772              | 0.367                  |
| Perlite            | 0.701                    | 0.988                 | 0.869                  | 0.853              | 0.720                  |
| Medical stone      | 0.700                    | 0.958                 | 0.813                  | 0.824              | 0.523                  |
| Guangxi stone      | 0.659                    | 0.967                 | 0.740                  | 0.789              | 0.486                  |
| Sepenggiante       | 0.681                    | 0.968                 | 0.788                  | 0.812              | 0.543                  |
| Limestone          | 0.696                    | 0.976                 | 0.781                  | 0.818              | 0.588                  |
Figure 6: Continued.
Then combining Equation (3) with Equations (4) and (5), the following equation can be provided to calculate the gradation considering the effect of particle morphology:

\[
P = \frac{1}{1 - bF_{\min}} \left[ (e^{-3OR} + 1)D_{\max}^{\text{sieve}}D_{\min}^{F_{\min}} \right]^{0.4OR+0.5} bF_{\min}^{4} + bF_{\min} \times 100\%.
\]

In the engineering, some parameters are required to design or calculate the gradation: uniformity coefficient \( C_u \), curvature coefficient \( C_c \), effective particle size \( D_{10} \), mean particle size \( D_{50} \), controlling particle size \( D_{60} \), or the maximum particle size \( D_{\max} \). These parameters are enough to determine a certain gradation curve or a series of gradation curves. Then, with Equation (2), \( a_{\text{sieve}} \) and \( b_{\text{sieve}} \) can be obtained (the process can be referred to in
Table 4: The values of $a_F^{\min}$ and $D_F^{\min}$ for each kind of gradation curves.

| Gradation curves    | $a_F^{\min}$ | $a_F^{\min}/D_s^{\text{min}}$ | $D_F^{\min}$ (mm) | $D_F^{\max}/D_s^{\text{min}}$ |
|---------------------|--------------|-------------------------------|-------------------|-------------------------------|
| White pebbles       | 7.735        | 0.746                         | 22.282            | 1.114                         |
| Black stone         | 7.589        | 0.732                         | 24.015            | 1.201                         |
| Basalt              | 6.912        | 0.667                         | 26.169            | 1.308                         |
| Perlite             | 8.438        | 0.814                         | 21.330            | 1.066                         |
| Medical stone       | 7.268        | 0.701                         | 24.071            | 1.203                         |
| Guangxi stone       | 10.52        | 0.688                         | 29.970            | 1.199                         |
| Sepenggiante        | 10.94        | 0.716                         | 29.541            | 1.182                         |
| Limestone           | 11.24        | 0.736                         | 29.071            | 1.163                         |

Figure 8: Curve fitting for overall regularity (OR) versus $a_F^{\min}/D_s^{\text{min}}$.

Section 5). The overall regularity (OR) can be assumed or be calculated more precisely with Equation (1). Because $D_s^{\text{min}}$ is usually provided first, the gradation curve of $D_F^{\min}$ analysis can be drawn in $D_F^{\min} - P$ plane with Equation (6). The above steps can be accomplished in paper, then using methods to measure $D_F^{\min}$ for these particles to form the drawn $D_F^{\min}$ gradation curve. At that time, these particles are composed of the required gradation considering the effect of particle shape. This process is provided as in Figure 10.

The key part of the proposed method is to obtain $D_F^{\min}$ of the particles. However, different from the sieve analysis, measuring the minimum Feret diameter $D_F^{\min}$ is relatively more difficult. If there are few particles, calipers can be used to simply measure $D_F^{\min}$. At present, there is no convenient way to obtain $D_F^{\min}$ for a lot of particles. It is time-consuming to measure $D_F^{\min}$ one by one by using calipers. The image-based method is a relatively practicable approach. Some apparatus are used to measure particle shape parameters in laboratory tests [16, 23, 44, 45]. Moreover, after the particles are pictured by a clear enough camera, the image processing software and numerical calculation software can also be used to obtain the shape parameters. Further studies and more apparatus need to be discussed and developed in the future.

4. The Validation of the Method

The image-based apparatus, known as QICPIC, have been widely used in recent years to characterize soil particle shape [16, 23, 44, 45]. The detailed description of how the apparatus works can be found in Sympatec [45]. Three kinds of particles with different shapes are used to figure out the influence of the particle shape on gradation by Yang and Luo [29]: glass beads (well-rounded), Fujian sand (subangular), and crushed glass beads (angular). As shown in Figure 11, the particles are sieved as the same gradation with $C_t = 1.20$ and $D_{{\min}} = 512.5 \mu m$, together with gradations by $D_F^{\min}$ analysis with apparatus QICPIC. Using the method of Equation (2), for $b = 0.95$, the gradation curve of sieve analysis is fitted and the result proves to be $a_F^{\text{min}} = 9.450$. The ranges of the aspect ratio (AR), the convexity ($C$), and the sphericity ($S$) are $0.6 \sim 0.1$, $0.9 \sim 0.1$, and $0.6 \sim 0.1$, respectively. The 50% cumulative distribution of the shape indices provided by Yang and Luo [29] and the values of the calculated OR with Equations (2) and (3) are shown in Table 5. The maximum sieve diameter ($D_s^{\text{max}}$) is 700 $\mu m$; then, the $D_F^{\min}$ gradation curves can be drawn with Equation (6) in Figure 11, which are well fitted with the results provided by the test of Yang and Luo [29].

It is noted that Equations (2) and (3) focus on the continuous gradation with “S” shape when $b$ approaches 1. For a smaller value of $b$, the gradation curve shape proves to be hyperbolic, and Equations (2) and (3) are still applicable. However, further research is needed when the curve shape is not continuous, and some researchers have studied the related contents [46, 47].

5. Application of the Method

Usually, there are two cases to calculate the particle gradations according to the particle parameters: ① several particle parameters (e.g., $D_{{\min}}$, $C_t$, and $C_s$) have been determined and a specific gradation needs to be designed; ② a particle parameter is fixed and other parameters are changed in a certain interval, and a series of gradations...
Particles required to form a certain gradation

Delivered parameter
$C_w$, $C_c$, $D_{10}$, $D_{50}$, $D_{60}$ or $D_{max}$

Draw gradation of sieve analysis

Calculate $a_{sieve}$ and $b_{sieve}$ with Eq. (2)

Assume or obtain OR

Draw gradation of $D_{Fmin}$ analysis

Particles composed of the required gradation

Form particles to fit the gradation curve of $D_{Fmin}$ analysis

Select particles that meets the requirements

Measure $D_{Fmin}$ of particles

Work of measuring

Figure 9: Curve fitting for overall regularity (OR) versus $D_{Fmin}^{max}/D_{sieve}^{max}$.

Figure 10: Process of obtaining gradations considering the effect of the particle shape.
need to be designed. The nonuniformity coefficient \( C_u \) and the curvature coefficient \( C_c \) are defined by the following equation:

\[
C_u = \frac{D_{60}}{D_{10}}, \tag{7}
\]

\[
C_c = \frac{D_{30}^2}{(D_{10}D_{60})}, \tag{8}
\]

where \( D_{10} \), \( D_{30} \), and \( D_{60} \) are the particle sizes of 10%, 30%, and 60% by weight, respectively. The calculation method by using the new image-based gradation calculation method is shown in detail in the following subsections.

5.1. Calculation for a Specific Gradation Curve. An example of three different kinds of particle shapes of sands is used to design gradation curves by Ren et al. [48]. Calcareous sand, standard sand, and glass beads are used and can be classified as “angular,” “subangular,” and “rounded.” The parameters \( C_u = 8 \) and \( C_c = 1.5 \) are needed and \( D_{\text{sieve}} = 8 \text{ mm} \). Based on Equation (2), for \( C_u = 8 \) and \( C_c = 1.5 \), the following equations can be provided as

\[
C_u = \frac{D_{60}}{D_{10}} = \left[ \frac{6(1 - 0.1b)}{1 - 0.6b} \right]^{\frac{1}{a_{\text{sieve}}}} = 8,
\]

\[
C_c = \frac{D_{30}^2}{D_{10}D_{60}} = \left[ \frac{3(1 - 0.1b)(1 - 0.6b)}{2(1 - 0.3b)^2} \right]^{\frac{1}{a_{\text{sieve}}}} = 1.5. \tag{9}
\]

The result of Equation (9) is \( a_{\text{sieve}} = 0.241 \) and \( b = 0.925 \). Then, using the same method, \( a_{\text{sieve}} = 0.237 \) and \( b = 0.870 \) for the case of \( C_u = 10 \) and \( C_c = 1.5 \). Taking the median value of the gradation range of “angular,” “subangular,” and “rounded,” OR is assumed to be 0.35, 0.5, and 0.85, respectively. By the method of Equation (6), the calculation results are shown in Figure 12, then using methods to measure \( D_{\text{F min}} \) for these particles to form the drawn \( D_{\text{F min}} \) gradation curve. At that time, these particles are composed of the required gradation considering the effect of particle shape. This process is the same as Figure 10.
5.2. Calculation for a Series of Gradation Curves. An example of coarse-grained soil to study the permeability by Peng [49]. The $D_{\text{sieve}}^{\text{max}} = 20$ mm for the aggregate of the coarse-grained. The percentage of particles smaller than 10 mm needs to be 55% ~ 75%. Then, the nonuniformity coefficient $C_u = 2.2$ and a series of changing $C_e$ is required. Based on Equation (2), the following equations can be provided as

\[
55\% < \frac{1}{(1-b)(D_{\text{sieve}}^{\text{max}}/10)^{0.16}} + b \leq 75\%,
\]

\[
C_u = \frac{D_{\text{max}}}{D_{\text{min}}} = \frac{6(1-0.16)}{1-0.8b} = 2.2.
\]

The sieve analysis result of Equation (10) is plotted on the plane of $b - a^{\text{sieve}}$, as shown in Figure 13(a). Because the used particles can be classified as “subregular,” $OR = 0.5$ is assumed in this paper. Then calculating $D_{\text{min}}^{\text{F}}$ to be 24.46 mm with Equation (5) and replacing $a^{\text{sieve}}$ with $[a^{\text{F}}_{\text{min}}/(0.4OR + 0.5)]$, the $D_{\text{min}}^{\text{F}}$ analysis result of Equation (10) is plotted on the plane of $b - a^{\text{F}}_{\text{min}}$, as shown in Figure 13(b). Four points are chosen for each analysis of $b = 0.9, 0.92, 0.94,$ and 0.96 as the red circle in the figure; then, the required $C_e$ is calculated in Equation (6) to be 1.054, 1.049, 1.044, and 1.040 and 0.738, 0.734, 0.731, and 0.728 for sieve analysis and $D_{\text{min}}^{\text{F}}$ analysis, respectively.
Figure 13: Calculation of a case of a series of gradations.
6. Conclusion

This paper proposed an image-based gradation calculation method considering crushed stone morphology. The pictures of the eight kinds of crushed stone particles are processed to obtain the particle shape indices. The gradation determined by the minimum Feret diameter analysis proves to be different from what is determined by sieve analysis. The modified overall regularity is used to describe the particle shape, which is calculated by three shape indices: aspect ratio, convexity, and sphericity. The developed overall regularity is applied on the gradation curve equations to provide an image-based gradation calculation method. The proposed gradation calculation method can fit well with real cases. Additionally, some other conclusions are also obtained as follows:

(1) Comparing with the sieve gradation, the minimum Feret diameter gradation can reflect the effect of the particle morphology. The difference between the two gradation curves is relatively small for rounded particles. Conversely, it is large for angular particles.

(2) There is a relatively fixed range for each shape indices of aspect ratio, convexity, and sphericity, but not distributed in the range of 0~1. This means to reflect the real weight of these shape indices, the range needs to be processed.

For continuous gradation equation, the relationship between OR and parameter $a$ is linear, and $a$ increases with increasing OR; the relationship between OR and parameter $D_{\text{min}}$ is progressive, and $D_{\text{max}}$ approaches $1$ with increasing OR.

Some problems should also be further studied. The image-based method in this paper is focused on 2D, which is a relatively effective method. The 3D methods have been developed in these years [50, 51], which is a potential method in the future. Moreover, to apply the shape-effect gradation calculation method to the engineering, some related apparatus and equipment need to be manufactured.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This manuscript has been preprinted (DOI: 1234/ABCE.5678) [52].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] C. Y. Kuo, R. S. Rollings, and L. N. Lynch, “Morphological study of coarse aggregates using image analysis,” Journal of Materials in Civil Engineering, vol. 10, no. 3, pp. 135–142, 1998.

[2] C. G. Pereira, J. Castro-Gomes, and L. Oliveira, “Influence of natural coarse aggregate size, mineralogy and water content on the permeability of structural concrete,” Construction & Building Materials, vol. 23, no. 2, pp. 602–608, 2009.

[3] L. Boergesson, L. E. Johannesson, and D. Gunnarsson, “Influence of soil structure heterogeneities on the behaviour of backfill materials based on mixtures of bentonite and crushed rock,” Applied Clay Science, vol. 23, no. 1–4, pp. 121–131, 2003.

[4] J. Zheng, Y. Zhu, and Z. Zhao, “Utilization of limestone powder and water-reducing admixture in cemented paste backfill of coarse copper mine tailings,” Construction & Building Materials, vol. 124, no. OCT.15, pp. 31–36, 2016.

[5] M. Li, J. Zhang, Y. Huang, and N. Zhou, “Effects of particle size of crushed gangue backfill materials on surface subsidence and its application under buildings,” Environmental Earth Sciences, vol. 76, no. 17, p. 603, 2017.

[6] M. Li, A. Li, J. Zhang, Y. Huang, and J. Li, “Effects of particle sizes on compressive deformation and particle breakage of gangue used for coal mine goaf backfill,” Powder Technology, vol. 360, pp. 493–502, 2020.

[7] A. K. Gupta, “Effects of particle size and confining pressure on breakage factor of rockfill materials using medium triaxial test,” Journal of Rock Mechanics and Geotechnical Engineering, vol. 8, no. 3, pp. 378–388, 2016.

[8] Y. Wang, Z. Zhao, and E. Song, “Discrete element modeling of the effect of particle shape on creep behavior of rockfills,” International journal of geological and environmental engineering, vol. 11, no. 9, pp. 843–847, 2017.

[9] Y. Wang, E. Song, and Z. Zhao, “Particle mechanics modeling of the effect of aggregate shape on creep of durable rockfills,” Computers and Geotechnics, vol. 98, no. JUN., pp. 114–131, 2018.

[10] B. Yuan, Z. Li, W. Chen et al., “Influence of groundwater depth on pile–soil mechanical properties and fractal characteristics under cyclic loading,” Fractals and Fractional, vol. 6, no. 4, p. 198, 2022.

[11] B. Yuan, M. Chen, W. Chen, Q. Luo, and H. Li, “Effect of pile-soil relative stiffness on deformation characteristics of the laterally loaded pile4913887,” Advances in Materials Science and Engineering, vol. 2022, 2022.

[12] B. Yuan, W. Chen, J. Zhao, F. Yang, Q. Luo, and T. Chen, “The effect of organic and inorganic modifiers on the physical properties of granite residual soil,” Advances in Materials Science and Engineering, vol. 2022, Article ID 9542258, 2022.

[13] British Standards Institute, “Tests for geometrical properties of aggregates. Part 1: determination of particle size distribution—sieving method,” The British Standards Institute, London, 1997, BS EN 933-1: 1997.
[48] R. Yubin, W. Yin, and Y. Qing, “Effect of particle size distribution and shape on permeability of calcareous sand,” Rock and Soil Mechanics, vol. 39, no. 2, pp. 491–497, 2018.

[49] P. Jiayi, Study on the effect of particle shape on the permeability of coarse-grained soil, Changjiang River Scientific Research Institute, 2017.

[50] B. Zhao and J. Wang, “3D quantitative shape analysis on form, roundness, and compactness with μCT,” Powder Technology, vol. 291, pp. 262–275, 2016.

[51] Z. Nie, X. Wang, Z. Liang, and J. Gong, “Quantitative analysis of the three-dimensional roundness of granular particles,” Powder Technology, vol. 336, pp. 584–593, 2018.

[52] C. Jiang, X. Ding, L. Pang, L. Deng, and Z. Shi, An Image-based Gradation Calculation Method Considering Crushed Stone Morphology, 2022, June 2022, PREPRINT (Version 2) available at Research Square.