Estimation of shape factor for irregular particles using three-axial measurement approach

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Abstract. Particle shape is an imperative term in civil engineering applications that play a significant role in the overall behavior of the particles; however, the shape factor becomes complex when it is related to the irregular-sized particle. The manuscript focuses on quantitative estimation of the shape factor of highly irregular metal particles of diameters ranging from 2.00 mm to 5.00 mm using a three-axial microscopic measurement. The measured data is used to compute the nominal diameter of a particle representing a circle of equivalent diameter and shape factor is computed. The result has been compared with the previously established studies and found to be corroborative.

Keywords: Shape factor, nominal diameter, irregularity.

1. Introduction
In geology, interest in particle shape emerged earlier than in geotechnical engineering. The particle shape is attained by its transportation from the original position to the deposits or during the machining process required in the metal industries.

There are also considerations for the process of particle genesis itself (rock structure, mineralogy, hardness, etc.). Many factors have been considered to define particle shape to classify and compare grains (axis lengths, perimeter, surface area, volume, etc.) to specify a particle shape and put forth empirical equations to substantiate the same. On that line [1] are endorsing form, roundness, and surface texture to describe the shape of a particle. Over the years, several attempts have been made to develop a methodology for measuring particle shape. Besides, other techniques of characterising a particle shape, a manual method including chart comparison [2] [3], also sieving [4], and, more recently, three-axial measurements using microscope were adopted in an industry with good results of characterizing a particle shape. Furthermore, using the computer-aided approach to measure particle shape saves a significant amount of effort [4].

1.1 The Objective
The shape of a particle can be described qualitatively or quantitatively. The qualitative description of the particle (e.g., elongated, spherical, flaky, etc.) is expressed in words, whereas the quantitative description relates to the measured dimensions; the quantitative description is more important in the engineering field due to reproducibility.

Particle quantitative geometrical measurements can be used to support qualitative classification. To describe the particle form, a few qualitative measures and several quantitative measures can be used.
Despite the abundance of qualitative descriptions, none were widely accepted. To analyse particle dimensions and shape factors, microscopic measurements are required. In myriad applications, particle shape is crucial to its behaviour. This property is finding its place in the various fields of engineering such as hydraulics, cross-drainage works, transportation, mining, etc. due to its importance of changing behaviour in different applications.

The global form, major surface feature scale, and surface roughness scale are used to determine particle shape. Each scale reflects aspects of the particle's formation history and contributes to the overall behaviour of the particle, from particle movement to mechanical response.

2. Background
A particle's shape is captured using three independent relative scales [5]: form, which describes differences in particle proportions

Roundness refers to the variations at the particle's corners that are superimposed on it. The characteristics that are superimposed on both corners and surfaces are referred to as roughness. Because these descriptors are distinct, one can differ significantly without affecting the others. The Fourier method, as well as fractal analysis if the shape is self-similar, can be used to characterise it.

2.1 Form, Roundness and Roughness

Form
The shape of a particle can be described using terms such as cubical, spherical, elliptical, elongated, flat, tubular, platy, lathlike, and needle. The form can be quantified using the length ratios of the three orthogonal axes. Barrett (1980) provides a list of at least 15 parameters that can be defined using these ratios. The aspect ratio is the ratio of the long axis \( L \) to the intermediate axis \( B \). It is also known as the elongation. The ratio of the intermediate, \( B \), and short axes is another term for flatness.

Two more mathematical descriptors of the form are sphericity and eccentricity. Sphericity is defined by [6] as the ratio of particle volume to circumscribing sphere volume. This definition is flawed because it includes a measure of roundness. The ratio of the particle's surface area to the surface area of an equal volume sphere is an improved definition of sphericity [7]. Eccentricity is defined as the \( 8p/Rp \) ratio of an elliptical particle, whose two-dimensional outline has been expressed as \( Rp = 8p \cos (20) \).

Roundness
The radius of curvature of each corner is averaged and compared to the radius of the particle Wadell's maximum inscribed circle to determine roundness [6]. The procedure is two-dimensional, but it can be made three-dimensional by replacing circles with spheres. Due to the difficulty in determining what constitutes a corner, subjectivity enters the test.

Roughness
Scale considerations are critical in the characterization of particle roughness. Because all surfaces are rough at some scale, roughness must be characterized at the scale deemed relevant to the problem at hand [7].

Krumbein's chart is used in this study to determine sphericity and roundness (1963). The procedure is as follows: A pinch of sand is placed on a Petri dish and examined under a Leica MZ6 stereomicroscope. Particles are indirectly illuminated by light reflected from a reflective shield. Approximately 30 grains are studied at various magnifications. The chart is then used to calculate representative grain sphericity and roundness finds a 10% variation in the roundness of particles from the same vial of sand when multiple students use the Powers chart.

The roughness of the particles subjected to shear wave velocity testing is also determined. The roughest sample particles are arbitrarily assigned a roughness value of 3, the smoothest sample particles a value of 1, and all others are assigned an intermediate value based on their relative roughness [6][3][2][5].

Sphericity \( S \) is preferred over ellipticity or flatness, roundness \( R \) over angularity, and smoothness over roughness. The sphericity is computed based on a diametric ratio of the largest inscribing sphere and smallest circumscribing sphere. On the other hand, roundness is computed by comparing a
curvature radius with a radius of the biggest sphere inscribing a particle under consideration. Surface features that are much smaller than particle diameter are referred to as roughness.

Sphericity and roundness can be estimated visually using charts like the one shown suggested by Folk 1955, and Barrett 1980. However, advanced techniques such as digital image analysis can also be applied to characterize the particle of irregular shape and size [8].

Because rough surfaces are fractal, they lack a characteristic scale, making the direct measurement of roughness difficult. As a result, the relevant roughness observation length is transformed into the inter-particle contact area: this is a particle's connection to its neighbor.

The shape parameters can also be derived from the soil mass's macro-scale behavior. The fall of particles or flow of particles in various applications is affected due to its shape, which results in complex drag force phenomena.

3. Methodology, Data Measurement and Estimation of Shape Factor

In hand measurement technique, sliding rod caliper, instruments were used to obtain the accurate data of particle geometry [3]. A particle under consideration needs to adjust on the sliding rod caliper to get the length accurately using a graduated scale attached to the instrument. Similarly, a convexity gauge is used to measure the curvature of the particle. To arrive at the shape of rock particles, an instrument was used and concluded that the tool gives good attribution [9]. The results so obtained was further reviewed and analyzed by many researchers.

3.1 Microscopic Measurements

Irregular mineral particles can be conveniently measured under a microscope. The accuracy further can be improved by attaching a video camera linked to a computer. The most obvious method is to compute the arithmetic or geometric mean of the number of measurements taken as well as the average distance between two cross-hairs. The third dimension (Z-axis) is obtained using a screw gauge. The extremities of the measured distance are standardized and used to calculate the mean cord length of the particle defined by Martine's or Ferret's diameter. Martine's diameter is the length of the line that divides the practical image in half. The dividing line is drawn in a parallel fixed direction regardless of the practical orientation. The mean distance between two tangents on opposite sides of the apparent outline of the particle is defined as Ferret's diameter. And the arithmetic or geometric mean value of length computed using both the methods is equal to the diameter of the reference circle; where arithmetic mean diameter is given as:

\[
\left( \frac{D_{\text{max}} + D_{\text{min}}}{2} \right) = D_{\text{am}}
\]

where,

\(D_{\text{max}}\) and \(D_{\text{min}}\) are the mean diameters of several Martine or Ferret measurements, and \(D_{\text{am}}\) is the arithmetic mean diameter.

3.2 Computation of Shape Factor

The coefficient of Drag and Reynolds Number can be very well related for particles of regular shape. However, it becomes difficult for irregularly shaped particles as the drag becomes complex. The empirical relationships have been developed for regularly shaped particles by many researchers to calculate the drag on it when it falls in a liquid media but to develop a correlation between \(C_d\) and \(Re\) for irregularly shaped particles, more precisely minerals between particles, shape factor is an essential parameter the can truly define an irregular particle in an equivalent sphere. S.F. is a shape factor that appears to be as satisfactory as any other.

\[
S.F. = \frac{(D_3)}{\sqrt{(D_1 * D_2)}}
\]
where $D_1$ is the longest axis, $D_2$ is the intermediate axis, and $D_3$ is the shortest axis of the three mutually perpendicular axes.

The shape factor considers three of its axial dimension of irregular particles and estimates the particle shape. Particles with the same shape factor can have rounded angular, rough, or smooth shape factors. This study is related to the particle of natural grain and some of the minerals having irregular shape and size. Shape factors based on particle roundness, sphericity, or other physical properties could be used, but they would not be adequate for hydraulic studies.

The set of irregular particles have been taken and three-axial measurements are noted using a microscope (major and intermediate axes) and screw gauge (thickness, as minor axis). Using equation 2, the shape factor is estimated as shown in Table 1. The plot of average diameter against the shape factor is shown in Figure 1.

Table 1. Microscopic measurement and shape factor

| SN | Major axis(X) $(D_1)$ | Minor axis(Y) $(D_2)$ | Perpendicular axis(Z) $(D_3)$ | Shape factor |
|----|-----------------|-----------------|-----------------|--------------|
| 1  | 4.039           | 1.941           | 1.512           | 0.540        |
| 2  | 3.014           | 3.821           | 1.999           | 0.589        |
| 3  | 3.387           | 2.953           | 2.063           | 0.652        |
| 4  | 4.050           | 1.995           | 1.302           | 0.458        |
| 5  | 3.958           | 2.653           | 1.401           | 0.432        |
| 6  | 2.899           | 1.941           | 1.512           | 0.432        |
| 7  | 2.885           | 3.821           | 1.999           | 0.720        |
| 8  | 2.667           | 2.953           | 2.066           | 0.435        |
| 9  | 3.041           | 1.995           | 1.353           | 0.341        |
| 10 | 1.933           | 2.653           | 1.398           | 0.521        |
| 11 | 2.913           | 0.863           | 1.533           | 0.966        |
| 12 | 2.978           | 1.922           | 1.403           | 0.586        |
| 13 | 2.948           | 2.968           | 1.050           | 0.354        |
| 14 | 2.933           | 1.907           | 0.386           | 0.163        |
| 15 | 2.957           | 1.907           | 1.013           | 0.426        |
| 16 | 2.968           | 2.040           | 1.050           | 0.426        |
| 17 | 3.972           | 1.927           | 0.090           | 0.020        |
| 18 | 3.910           | 2.000           | 0.090           | 0.032        |
| 19 | 3.095           | 1.957           | 1.060           | 0.430        |
| 20 | 3.040           | 2.923           | 1.030           | 0.345        |
| 21 | 1.316           | 1.497           | 1.030           | 0.733        |
| 22 | 2.649           | 1.018           | 0.866           | 0.527        |
| 23 | 1.360           | 1.525           | 1.020           | 0.708        |
| 24 | 2.637           | 1.057           | 0.866           | 0.518        |
| 25 | 2.948           | 0.998           | 0.733           | 0.427        |
| 26 | 2.004           | 2.000           | 1.026           | 0.512        |
| 27 | 2.974           | 1.800           | 0.866           | 0.357        |
| 28 | 2.005           | 1.961           | 1.033           | 0.520        |
| 29 | 2.036           | 2.010           | 1.026           | 0.506        |
| 30 | 2.009           | 1.970           | 1.013           | 0.512        |
| 31 | 2.003           | 2.000           | 1.026           | 0.512        |
## 4. Discussion and Conclusions

Based on the above microscopic measurements, experimental analysis, and graphical presentations, it is concluded that the shape factor's value varies with change in the perpendicular direction of the particle (Z-axis).

The graph depicts how the shape factor changes in the shorter direction. As the shape factor is directly proportional to the shortest axis.

The graph shows that the shape factor decreases as the minor axis value increases.

Microscopic analysis is objective, repeatable, produces quick results, and works with more data, but it still requires improvement to avoid the edition process being poorly-contrast particles.

Although there are numerous methods for defining shape factors and describing quantities, the measurement-based breakdown is quite practical and useful.

When performing microscopic analysis, the resolution must be considered because the effects can be significant. The resolution must be based on the requirements. The R-value reflects the effect of resolution on diameters as a perimeter.

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**Figure 1.** Average diameter Vs. shape factor

|    |    |    |    |    |
|----|----|----|----|----|
| 32 | 2.001 | 1.977 | 0.866 | 0.372 |
| 33 | 2.331 | 1.962 | 1.033 | 0.436 |
| 34 | 1.092 | 2.014 | 1.026 | 0.966 |
| 35 | 1.919 | 1.943 | 1.013 | 0.511 |

\[ y = -0.0379x + 2.6061 \]

\[ R^2 = 0.7262 \]
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