An inexpensive foldscopic approach for quantitative evaluation of the shape of sand particles

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Shape is a fundamental key property of any object and an important physical attribute that remains ignored, although its importance has been accepted for quite some time and is not accounted for in standard soil classification guidelines. One of the reasons for this could be the lack of inexpensive microscopic instruments or image scanners in most laboratories. This study quantifies particle shape characteristics using a cost-effective foldscope approach. Four different types of sand were used in this study and results were compared against scanning electron microscopy (SEM) measurements. In addition, the effect of the number of particles and resolution on the analysis is discussed. It was found that the foldscope-based approach yielded consistent results with SEM in measuring the aspect ratio and roundness parameter (except circularity). The variation between the two approaches was found to be less than 5% for both aspect ratio and roundness; however, a significant difference was observed in the case of circularity (more than 50%) due to the influence of resolution.

Keywords: Foldscope, image analysis, particle shape, resolution, sand.

SHAPE is a fundamental key property of any object and an important physical attribute that may provide the formation history of sedimentary particles or hydrodynamic behaviour in a transporting medium. It has been recognized that particle morphology such as size[1] and shape significantly influences the dynamic behaviour of coarse-grained soil[2–4]. The mechanical response or behavioural characteristics of an ensemble of granular materials such as shear strength, internal friction, permeability and the difference between two extreme void ratios ($e_{max} - e_{min}$, where e_{max} and e_{min} correspond to the maximum and minimum void ratio) or packing density, compressibility, etc. depend on grain shape[5–7]. Over the past few decades, several authors have developed, reviewed and modified different methods and techniques to study the morphology of the soil particles, including hand measurements, sieve analysis, chart comparison, fractal analysis and image analysis[8,9]. Cho *et al.*[2] specifically emphasized the inclusion of particle shapes in the soil classification guidelines. Nevertheless, this phase of studies has received less attention. Comparatively, there has been limited documentation about the characterization of these properties in the geotechnical engineering or civil engineering literature. This is primarily due to the limited access to high-quality particle measurement facilities like scanning electron microscopy (SEM), optical microscope, stereomicroscope, binocular microscope and other sophisticated image-capturing instruments.

The commonly used particle shape descriptors are sphericity (circularity in 2D), roundness and roughness. Most of the earlier studies characterized particle shape according to microscope-based or SEM-based quantification, which is too expensive to use. This shortcoming can be eliminated using the extremely inexpensive, origami-based paper microscope named foldscope, originally developed by Cybulski *et al.*[10]. The foldscope is a monocular microscope that provides ~140× magnification with a capacity of 2 μm resolution. It is portable, cost-effective, ultra-affordable and can replace expensive conventional microscopes or laser scanning techniques. However, its potential is yet to be explored by the civil engineering community and geologists.

Hence, this study was carried out to examine the usefulness of the foldscope in quantifying the shape of sand particles. The study includes the appropriate number of particles required to yield a representative result of an ensemble soil mass and the influence of resolution on particle shape parameters. To the best of our knowledge, there have been no earlier studies to exploring the capabilities of the foldscope and its usage as a scientific tool in civil engineering research.

Materials, methodology and test procedure

Materials

Four different types of natural sand obtained from various parts of India were chosen for the study. Two of the sand samples were collected from the bed of the Manu and Brahmaputra rivers. The third sample was obtained from the surface liquefied site, spewed out due to the 3 January 2017 Ambassa earthquake in Tripura, India[11] and the fourth sample was the naturally deposited Kalpakkam soil extracted

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at 1 m depth from the ground surface. All test samples fall under the category of poorly graded sand according to the unified soil classification system (USCS). The average diameter of sand grains is 0.32–0.35 mm for the Brahmaputra river sand; 0.194–0.204 mm for the Tripura surface liquefied sand; 0.255–0.265 mm for the Manu river sand; 0.45–0.47 mm for Kalpakkam sand.

Methodology

The sand particle images were captured using two instruments, viz. the foldscope and JEOL SEM. All the images were then transferred to ImageJ, and digital image processing was carried out to characterize the morphology of soil particles. Figure 1 shows photographs of JEOL SEM and foldscope. The sample preparation, image detection and image analysis are described briefly in the following.

Sample preparation and image detection using the foldscope

The foldscope is an origami-based assembly of a flat sheet of paper and lens which has been used for detecting images of individual sand grains in this study. The construction steps of the instrument consist of the lens stage, sample stage, panning guide and focus ramp. For the present study, a combined deluxe individual kit and basic classroom kit were procured, which contain 21 foldscopes, 22 numbers of 140× lens, 24 magnetic couplers (for attaching cellphone and LED to the foldscope), two LED magnifiers and other necessary components. More details can be found in the foldscope instruction manual[12]. To capture particle images under the foldscope, 10–20 g of oven-dried sand samples were taken. Next, some sand grains (about 1–3 g) were gently placed on the sticker and pasted on the sample slide (standard slide) of the foldscope. The sample slide was shielded with a transparent coverslip sticker on the other side of the instrument (Figure 2). Thus, the sand samples became sandwiched between two coverslip stickers, preventing the movement of particles. This helps to get an easier snapshot. The arrangement of the particles was done in such a way that they remained separated from each other (to avoid overlapping of particles). This would allow smooth capturing of each particle image, thereby processing the image analysis.

Figure 3 *a* shows a scale slide A1 with 1 mm grid lines and another scale slide A2 with 0.5 mm grid lines. Scale slides are made of thin polyvinylchloride (PVC) of 0.085 mm thickness. Based on the size of the soil particles, these scale slides were selected. The scale slide was placed at the bottom of the sample slide, whereas the sample slide was positioned towards the foldscope lens. While viewing soil particles through the slide to capture the images, the operator must ensure that the particles lie inside the grid-line boundary. This can be achieved by gently adjusting the position of the scale slide back and forth. Figure 3 *b* and *c* shows the sample slides (containing soil particles) placed at the top of the 0.5 and 1 mm grid lines.

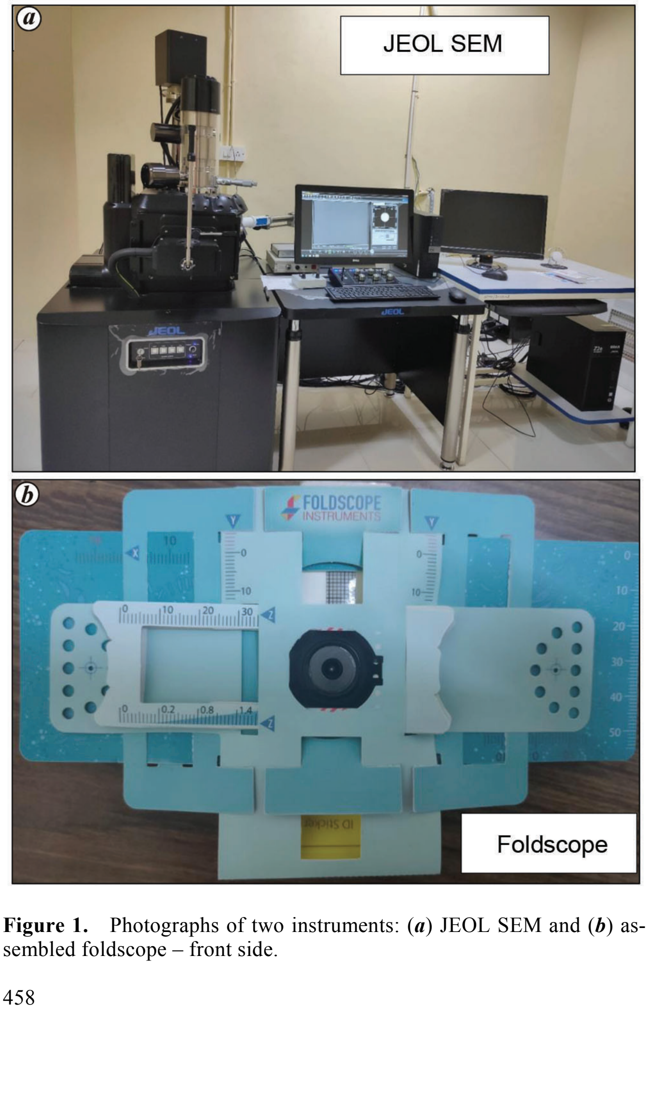

Figure 1. Photographs of two instruments: (***a***) JEOL SEM and (***b***) assembled foldscope – front side.

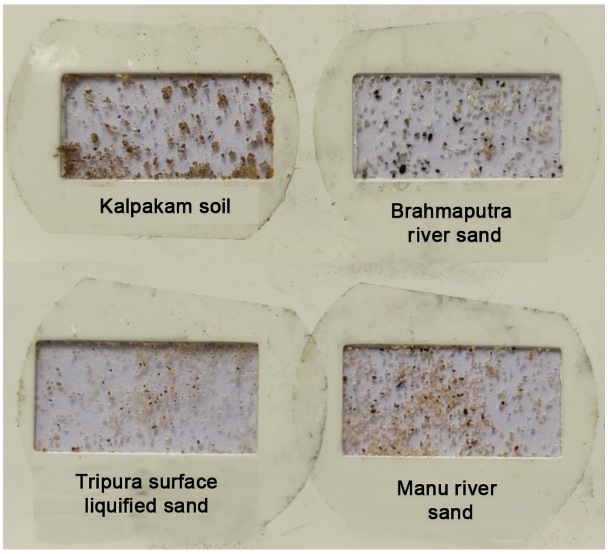

Figure 2. Sample preparation using the foldscope: placing of test samples on the standard paper slide (or sample slide) with a shielded transparent sticker on it for image detection.

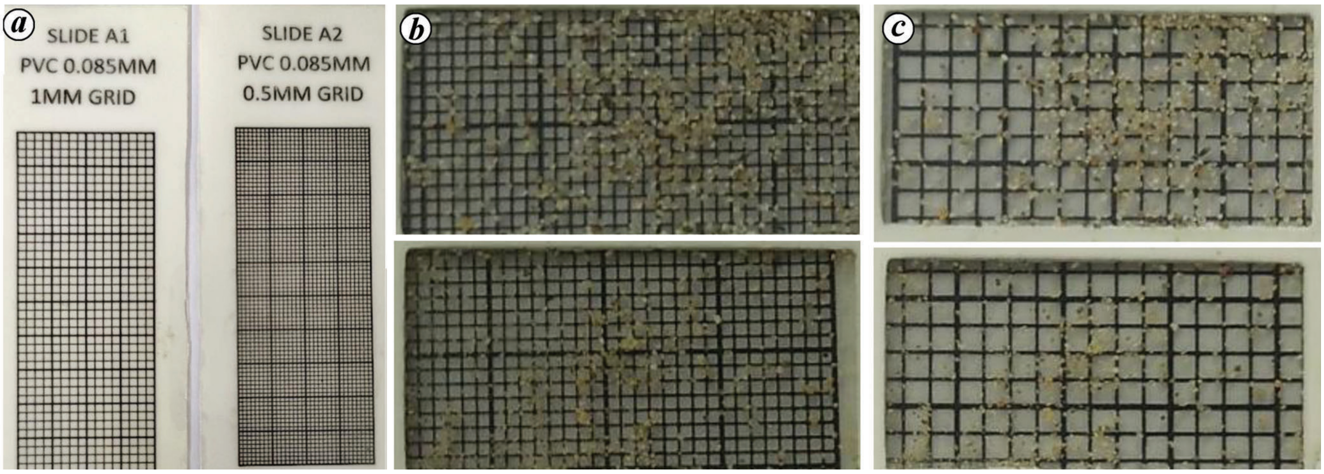

Figure 3. Photographs showing two different scale slides of the foldscope placed on the bottom of the sample slide. ***a***, Scale slide A1 with 1 mm grid lines and A2 with 0.5 mm grid lines. ***b***, ***c***, Sample slides with soil particles placed on top of A2 and A1.

Once the sample slide was prepared and foldscope parts were assembled, the soil sample slide and the scale slide were inserted into the instrument. An LED magnifier that served as a light source was mounted on the back, while a cellphone camera was fixed at the front of the foldscope. Finally, by panning exercise and focusing the foldscope magnification ramp back and forth, the sample images were taken. The LED magnifier increases the visibility of both grid lines and soil particles. Figure 4 shows the foldscope image of the four test samples (chosen in this study).

Image detection in JEOL SEM

The JEOL SEM was also used to capture the soil particle images in the present study. The results obtained were compared with the foldscope data. First, in the specimen preparation stage, 20–30 g of dry sand samples were taken and kept under desiccation for a day. Next, the sand particles were firmly fixed to the specimen mount (metal plate) by a conductive double-sided adhesive tape (Figure 5 *a*). The specimen surface was then coated with a thin metal film to make it more conductive. A noble metal, i.e. gold (Au), was used as the coating material (a couple of nanometres to 10 nm) in this study. Gold is stable and has a high secondary electron yield; thereby high-magnification observations can be made. Figure 5 *b* shows the image of a gold-coated specimen (sand particles). Finally, before the specimen mount was loaded to the SEM stage for imaging, it was ensured that the SEM machine was clean, dry and not outgassed. Figure 6 presents SEM images of the four test samples used in this study.

Image analysis

All the captured images were transferred to ImageJ for image processing to determine the particle shape parameters. ImageJ is an open-source, Java-based image processing and analysis program developed in 1997 by Wayne Rasband at the National Institutes of Health, USA[13]. It can provide the most promising results for particle shape analysis compared to the other commonly available software packages for digital image processing, like SigmaScan Pro, Matlab, etc.[14]. For image analysis, the captured images were first loaded into the software. Image dimensions (pixels) were then calibrated using a scale factor and the images were converted into binary images (black and white). Figure 7 shows the original and binary images of two different types of soil samples. The necessary processing operation can be accomplished using certain commands such as threshold, erode, dilate, fill holes, fit ellipse, etc. More details can be found in the ImageJ User Guide[13].

The thresholding of an image is a critical factor in any digital image analysis, which is essentially choosing a cutoff value for delineating the objects (foreground) from the non-objects (background). In this study, the auto-thresholding function was used in converting grayscale to binary for all the images. It was found that among all the auto-thresholding methods preinstalled in ImageJ (e.g. Huang, Entropy-based, Otsu, Shanbhag, Triangle, etc.), Otsu's method gave satisfactory and reproducible results. After image thresholding in ImageJ, the 'set measurements' function was used to choose the desired parameters and finally, the 'analyse particles' plugin was run.

Several shape descriptors such as form, roundness, irregularity, sphericity and shape factor have been introduced in the past to describe the extrinsic geometric property of a particle[2,9,15]. In the present study, roundness, circularity and aspect ratio have been considered. Table 1 illustrates these shape parameters, as defined in ImageJ.

Circularity, with a value of 1, indicates a perfect circle. As the value approaches 0, it indicates an increasingly elongated shape. Likewise, roundness relates to the sharpness of corners and edges of a particle. It depends on the radius

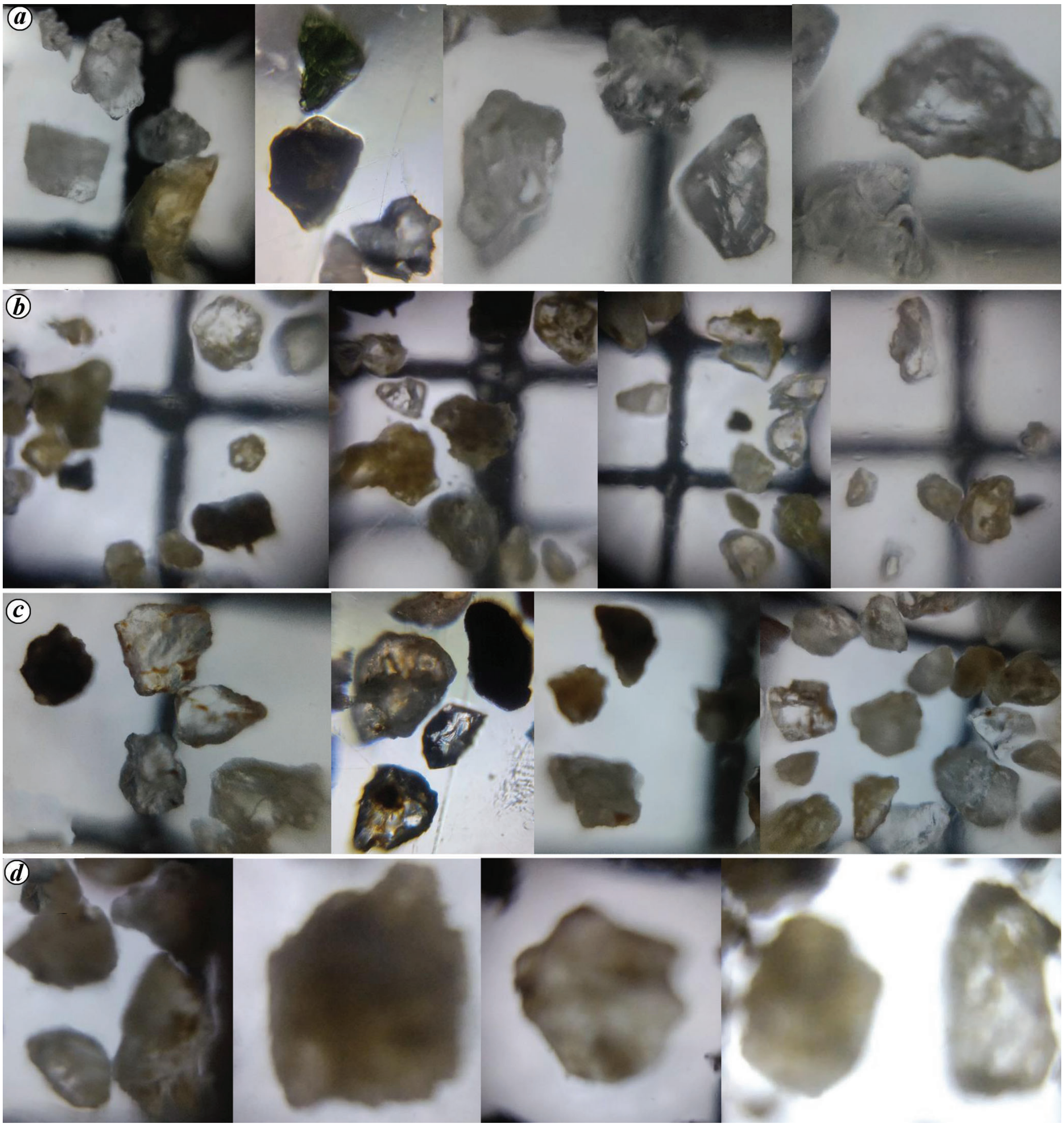

Figure 4. Foldscope images of four test samples obtained using 64 and 6 MP mobile cameras attached to the instrument. ***a***, Brahmaputra river sand; ***b***, Tripura surface liquefied sand; ***c***, Manu river sand, captured with Realme-XT 64 MP; ***d***, Kalpakkam soil captured with Redmi 4a 6 MP camera.

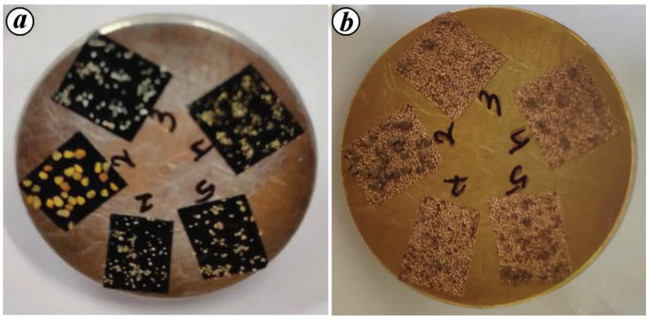

Figure 5. Sample preparation for SEM imaging under JEOL SEM. ***a***, Specimen mount on which sand particles were fixed by a double-sided adhesive tape without any coating material. ***b***, Sand samples with a coating material (gold-coated).

of the curvature of corners of a particle. Roundness value of 1 indicates a round object and its value approaching 0.12 indicates sharp corners and edges.

Results

Influence of randomly selecting a different number of particles on the shape parameter

One limitation of any quantitative method is the time taken to measure particle shape to analyse the maximum number of particles. On the other hand, qualitative methods permit studying many particles in a given timeframe, though they

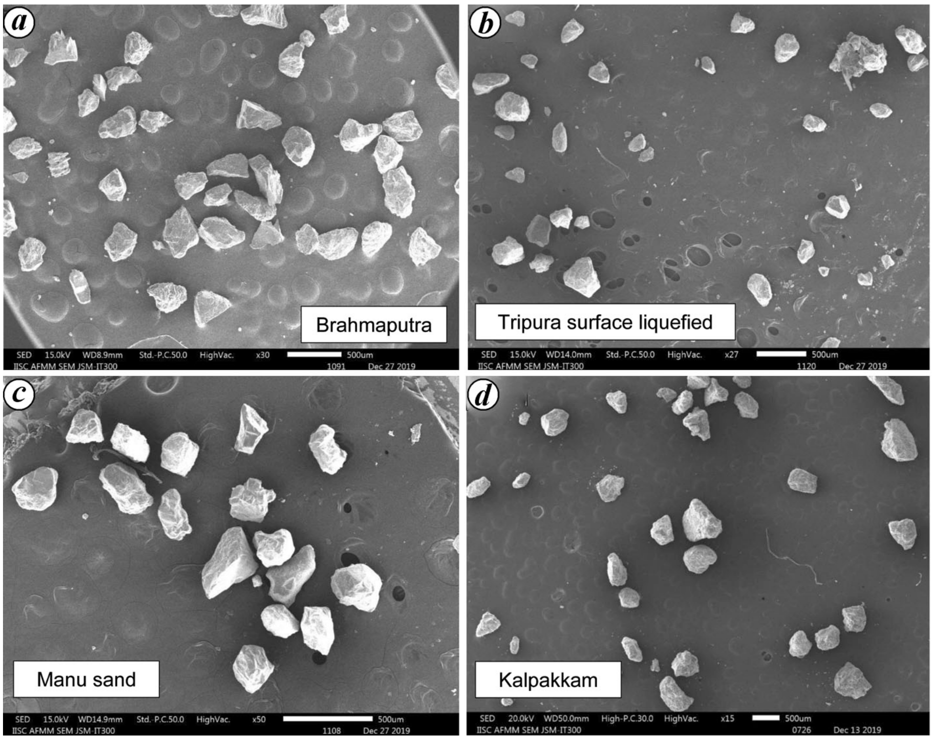

Figure 6. SEM images of the four test materials used in this study. ***a***, Brahmaputra river sand; ***b***, Tripura surface liquefied sand; ***c***, Manu river sand; ***d***, Kalpakkam soil.

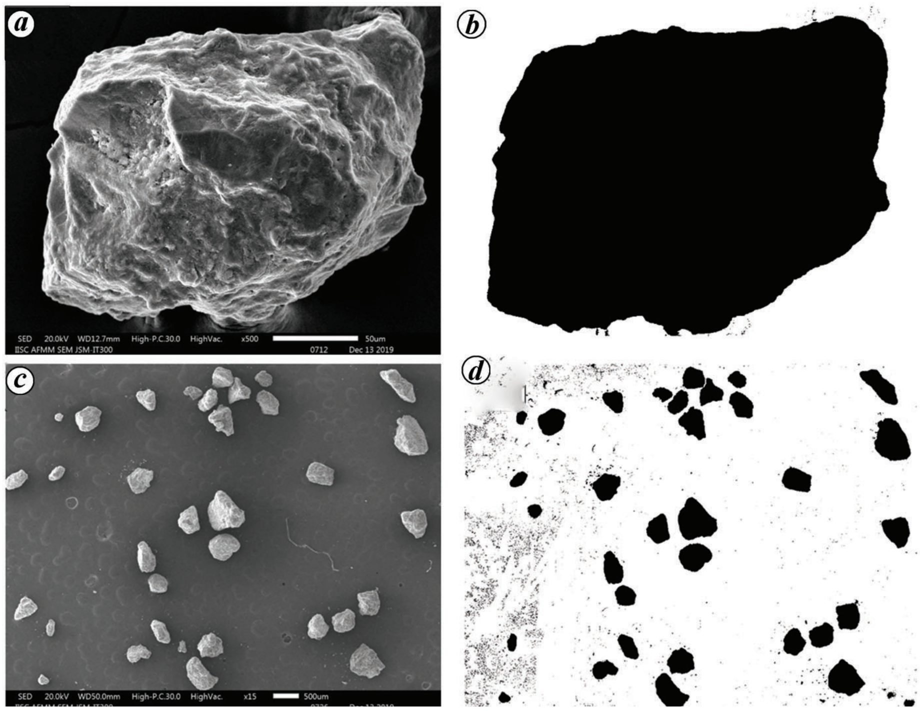

Figure 7. Image analysis: thresholding in ImageJ. ***a*** and ***c***, Examples of the original images of two soil samples. ***b*** and ***d***, The thresholded binary images of these samples.

are less accurate. Previous studies have considered a different number of particles for shape analysis (Table 2). There is no consensus about the minimum number of particles to be selected for analysis, which can yield repeatable results. Hence, in the present study, a set of 40, 80, 120 particles were randomly selected (from an ensemble of sand

Table 1. Definition of shape parameters in ImageJ

Perimeter	Aspect ratio	Roundness	Circularity (2D)
Length of the outside boundary of the selection (of a particle). Calculated based on the differential method.	$\frac{\text{Major axis}}{\text{Minor axis}}$	$4 \times \frac{\text{Area}}{\pi \times (\text{major axis})^2}$	$4\pi \times \frac{\text{Area}}{(\text{perimeter})^2}$

Table 2. Number of particles chosen by different authors for shape definition and quantification

Reference	Soil type	Number of particles considered	Instrument used
21	Uniformly graded natural sand and angular sand	20	Quantimet 570, image analyser
9	Uniform sand	25	Light microscope
2	Various types of sand	30	Stereomicroscope (Leica MZ6)
4	Eleven different sand types	30	Optical microscope
15	Missisippi river sand	50	Binocular microscope
22	River sand origin	50	Scanning electron microscope (SEM)
14	Quartz filtration sand	150	2D scanner Hp Scanjet 300
16	Standard silicaceous and natural carbonate sand	260	SEM

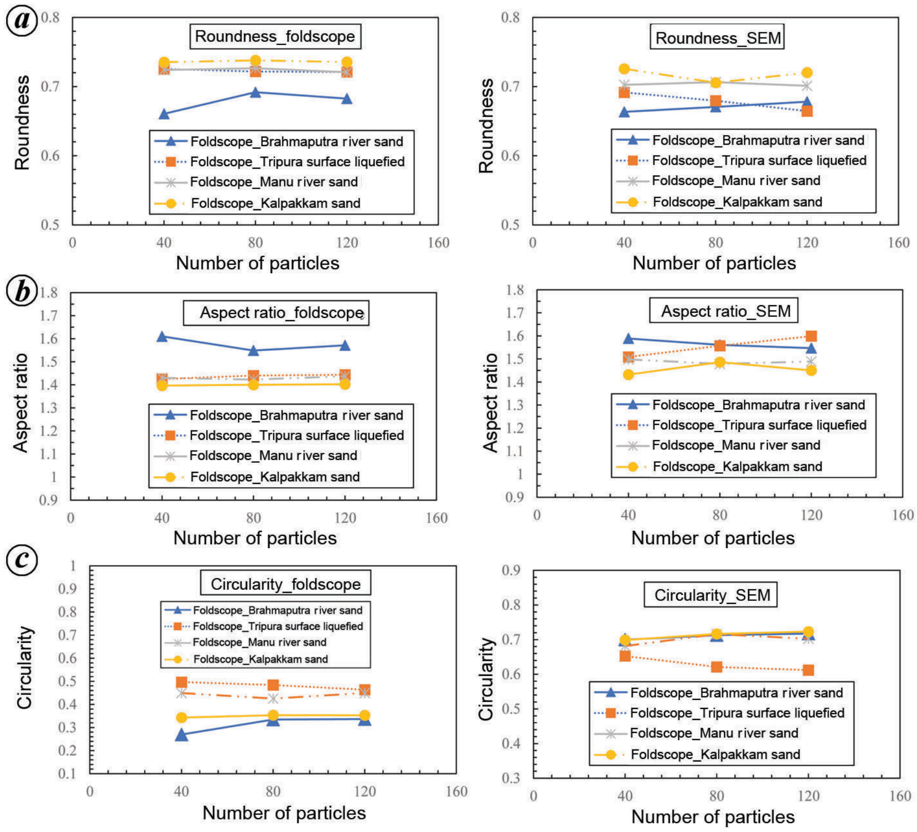

Figure 8. Influence of random selection of various number of particles on shape parameters and comparison of foldscope and SEM results of different shape descriptors obtained using ImageJ for four tested samples. ***a***, Roundness parameter; ***b***, Aspect ratio; ***c***, Circularity parameter.

grains) for shape analysis. Results obtained were compared to analyse the influence of selecting a different number of particles on the shape parameters.

Four different types of natural sand grains, viz. Brahmaputra river sand, Manu river sand, liquefied sand of Tripura and Kalpakkam sand were chosen for this study. Imaging of sand particles for all four samples was done with the foldscope and SEM, following the procedure described above. Only untouched or separated particles were selected for image analysis using ImageJ. The roundness, aspect ratio and circularity parameters were compared using ImageJ (Figure 8).

Table 3. Comparison of results between foldscope and SEM for Brahmaputra river sand

Number of particles	Roundness		Percentage error	Aspect ratio		Percentage error	Circularity		Percentage error
	R_SEM	R_foldscope		AR_SEM	AR_foldscope		C_SEM	C_foldscope	
40	0.66345	0.66063	0.425805	1.5887	1.610425	1.36747	0.6997	0.26965	61.4593
80	0.67066	0.6919	3.16664	1.560988	1.548913	0.773549	0.7127	0.334375	53.08581
120	0.68257	0.682575	0.65622	1.546925	1.5714	1.58217	0.7174	0.3368	53.04996

Table 4. Comparison of results between foldscope and SEM for Tripura surface liquefied sand

Number of particles	Roundness		Percentage error	Aspect ratio		Percentage error	Circularity		Percentage error
	R_SEM	R_foldscope		AR_SEM	AR_foldscope		C_SEM	C_foldscope	
40	0.691625	0.72545	4.89066	1.508725	1.4252	5.536132	0.652575	0.496875	23.85933
80	0.6795	0.721713	6.21229	1.557188	1.440363	7.502308	0.621113	0.483775	22.11153
120	0.664583	0.721083	8.50157	1.598942	1.444017	9.689222	0.611975	0.463558	24.25208

It can be observed from Figure 8 *a* (left panel) that when the results of 40, 80 and 120 particles were compared, the roundness value determined by foldscope for the four samples provided the closest value. A small difference was found for Brahmaputra river sand with roundness values of 0.660625, 0.6919 and 0.682575 respectively. As shown in Figure 8 *a* (right panel), the SEM results also reveal that an increase in the number of particles does not cause a large variation in the roundness value for the chosen sand samples.

Figure 8 *b* shows the corresponding aspect ratio values extracted from the foldscope and SEM. The results show that the aspect ratio is independent of the number of particles in both foldscope and SEM approaches. Figure 8 *c* shows the circularity parameter obtained from both approaches. These results also reveal that an increase in the number of particles does not affect the circularity parameter of four chosen sand samples. Thus, it is observed from Figure 8 *a–c* that the analysis of 40, 80 and 120 particles for four different sand samples show negligible influence on the roundness, aspect ratio and circularity parameter for randomly selected particles (for average grain size diameter range 0.19–0.47 mm).

Further, it is interesting to note that there is a significant difference in the circularity results between the foldscope and SEM approaches (Figure 8 *c*), which is not the case for roundness and aspect ratio. As can be seen, the foldscope values of circularity (Figure 8 *c*, left panel) for all the chosen sand materials fall below 0.55; in contrast, SEM results of circularity (Figure 8 *c*, right panel) fall above 0.55.

Comparison between the foldscope and SEM results

Tables 3–6 show a comparison of the results of shape parameters obtained from foldscope and SEM analysis for all four samples. It is apparent from Table 3 that differences in percentage error in roundness value for Brahmaputra river sand are minimal (less than or equal to 3) between the two approaches. The same is true for the aspect ratio, which is less than 2%. Further analysis of the roundness and aspect ratio of the other three samples indicates no significant differences in the data between the two methods (Tables 4–6). The maximum percentage error observed for the roundness parameter for Manu river sand, Kalpakkam sand and Tripura liquefied sand was 3, 4.5 and 8 respectively. The maximum percentage error in aspect ratio was 4.5, 5.7 and 9.6 respectively (reasonable).

There was a significant difference (more than 50%) in the circularity parameter between the foldscope and SEM results for all four samples (Tables 3–6). Foldscope underestimates the circularity value for all the chosen sand materials. This can be attributed to the pixel-based digital image processing technique or due to the influence of resolution.

Effects of resolution on the results of the shape parameter

As mentioned above, the variation in circularity between the foldscope and SEM results is due to the difference in image resolution. To examine this aspect further, particle images were captured using two cellphone brands (Redmi-4a and Realme-XT) of different configurations (8 and 64 MP rear camera), which will give images with varying pixels. Figure 4 shows the foldscope images of the sand particles captured with the two cellphones. The image particle analysis was carried out in ImageJ. The results obtained were compared to examine any changes in the shape parameters. Two sets of data containing 40 randomly selected particles were chosen for two types of sand grains (Brahmaputra and Manu river sand). Table 7 gives the configurations of the cellphones with their image type and other details. Particle images were captured and stored in the mobile memory in JPEG format (by default). The image sensors fitted inside

Table 5. Comparison of results between foldscope and SEM for Manu river sand

Number of particles	Roundness		Percentage error	Aspect ratio		Percentage error	Circularity		Percentage error
	R_SEM	R_foldscope		AR_SEM	AR_foldscope		C_SEM	C_foldscope	
40	0.7026	0.723975	3.04227	1.498175	1.430625	4.508819	0.68155	0.4495	34.04739
80	0.70645	0.726513	2.8399	1.478838	1.422938	3.779996	0.715813	0.4253	40.585
120	0.701117	0.720742	2.79911	1.4893	1.437458	3.480942	0.702567	0.449558	36.012

Table 6. Comparison of results between foldscope and SEM for Kalpakkam soil

Number of particles	Roundness		Percentage error	Aspect ratio		Percentage error	Circularity		Percentage error
	R_SEM	R_foldscope		AR_SEM	AR_foldscope		C_SEM	C_foldscope	
40	0.7258	0.73535	1.31579	1.4322	1.3971	2.450775	0.69875	0.34305	50.90519
80	0.705563	0.737863	4.57791	1.486225	1.400038	5.799088	0.7164	0.35335	50.677
120	0.72017	0.73564	2.1481	1.45065	1.40267	3.307483	0.72309	0.35274	51.21769

Table 7. Configuration of two different cellphones used in the study and resolution of SEM

Instrument/gadget used	Rear camera	Resolution (pixel)	Memory size (MB)	Image type
SEM	JSM-IT300	1280 × 1024	5.03	TIFF (uncompressed)
Realme-XT	64 MP	3456 × 4608	2.10–3.90	JPEG
RedMi-4a	8 MP	4160 × 3120	0.49–0.863	JPEG

Table 8. Influence of resolution on shape parameters obtained using two different cellphones

Sample	Number of particles	Roundness		Percentage error	Aspect ratio		Percentage error	Circularity		Percentage error
		RedMi-4a (8 MP)	Realme-XT (64MP)		RedMi-4a (8 MP)	Realme-XT (64 MP)		RedMi-4a (8 MP)	Realme-XT (64 MP)	
Brahmaputra river sand	40	0.660625	0.683075	3.3983	1.610438	1.57069	2.468153	0.26965	0.238	11.73744
	40	0.663925	0.66063	0.496291	1.587624	1.610425	1.43616	0.34165	0.26965	21.0742
Manu river sand	40	0.7092	0.698676	1.483971	1.4665	1.512709	3.15099	0.498075	0.287324	42.31304
	40	0.7092	0.715316	0.86235	1.506759	1.494704	0.800096	0.498075	0.209921	57.85353

the camera, colour filters, lenses, size of the aperture, image processing software installed on both cellphones, etc. were different. Between the two cellphones used, Realme-XT gave sharper images.

In digital image analysis, imaged particle are processed on a thresholded binary image rather than the greyscale image. Threshold helps eliminate unwanted background information in an image and leaves behind only the particles (Figure 7). In most cases, this thresholding is chosen manually. Thus, it is subjective and sometimes may lead to human error. In this study, a constant threshold (auto-thresholding method) was chosen for all fields of view to minimize this error, and analysis was carried out. Table 8 shows the data obtained using two different cellphones for two different resolutions and two different sand samples. The most striking result emerging from this table is that there is no significant difference in roundness and aspect ratio parameters for the two different image resolutions (pixels). The percentage error was less than 3.5 for both shape parameters. A large percentage error (greater than 50) was found in the circularity parameter (similar results as mentioned above, between the foldscope and SEM results) due to differences in image quality used in this study.

Discussion

The primary objective of this study was to evaluate the usefulness of the inexpensive foldscope in quantifying the shape parameter of sand materials. For this, a large number of individual particle images (more than 1100 particles) were captured using the foldscope and JEOL SEM for four different types of natural sand grains. The results obtained for the two approaches were compared. In this study, three shape descriptors, viz. circularity, roundness and aspect ratio were considered.

A fundamental question that arises while quantifying the particle shape descriptor is the number of particles required for a representative sample. The number of particles considered by different authors ranged from 20 to 260 (Table 2). Bowman *et al.*[16] suggested that a minimum of 200 grains can be chosen for statistical analysis (silica and carbonate sand), while Cox and Budhu[9] claimed that 25 grains should be sufficient for a representative sample if it is uniform sand. In the present study, based on the data presented herein, 80 particles are adequate to yield a consistent result for poorly graded sands (Figure 8).

A comparison of the shape descriptors between the foldscope and SEM approaches revealed that the percentage variation in roundness and aspect ratio was minimal (less than 5) for all the chosen sand samples except for the Tripura surface liquefied sand (maximum variation was about 9). This is because of the appreciable number of small-sized particles present in the liquefied sand of Tripura. This deviation in the shape parameters increased for small-sized particles (which can be expected) because of maintaining a constant threshold value for all the fields of view. However, the percentage error in circularity was more than 50. This variation in circularity parameter can be attributed to the pixel-based digital image processing techniques or the influence of different pixel sizes (resolution).

In the digital image analysis, curved circular shapes or the corners and edges of the particles are determined using the pixel-based approximation approach. As a result, there may be a variation in shape dimensions at the points. Thus, it can influence the calculation of perimeter values[17]. Since circularity depends on the perimeter of a particle (Table 1; equation of circularity), a large percentage error in the circularity parameter was observed. However, particle roundness is independent of circularity. It depends on the area and long axis of a particle. The area can be nearly correct in the digital image analysis. The perimeter may vary based on the number of pixels that represent the particle. Thus, significant variation in circularity was noticed for most of the sand samples.

Nevertheless, changes in roundness and aspect ratio values were reasonable. Therefore, based on the data obtained using the two cellphones and SEM results presented in this study, it can be concluded that resolution can significantly impact on circularity parameter. These results align with those of previous studies[14,17].

The present study is not intended to solve the resolution problem (or image quality issues) that remains partly unresolved in the image analysis technique, despite many technological advancements, but rather to assess the ability and usefulness of the inexpensive foldscope in determining particle shape measurements. Indeed, it can match the SEM results in measuring aspect ratio and roundness (except circularity). Thus, it can be recommended that the ultra-low-cost foldscope can be used as a scientific tool for particle shape measurements and microscopic imaging in various other fields. Nevertheless, future studies must be taken up to examine if the object-based approach is better than the pixel-based approach for solving issues associated with resolution. Several previous studies have revealed the superiority of the object-based approach over the pixel-based approach, especially in the field of agricultural landscapes and remote sensing imagery studies[18,19]. In contrast, Berhane *et al.*[20] concluded that the pixel-based (random forest) approach is far more effective in the case of assessing and mapping wetland-dominated landscapes[20]. Therefore, this needs further studies.

Advantages of the foldscope and its limitation

One interesting feature of the foldscope (over other ordinary microscopes) is that it can be directly connected to a cellphone camera. Images can be captured by adjusting different scale slides. However, in this study, after imaging about 150–200 particles with one foldscope, it stopped producing clear images as the thickness of the focus ramp was reduced by softening due to multiple usages. Also, the instrument has a relatively small focus range and a small surface area due to which there is a limit on the number of particles that can be taken in one snapshot. Its resolution is comparatively low and often, imaged particles are blurry, with difficulty in achieving fine focus. Nevertheless, foldscope is inexpensive, pocket-portable, easy to handle and affordable. One foldscope costs about 3 USD, which is extremely inexpensive compared to commercially available SEMs or other image scanners. Both sample preparation and imaging in a foldscope can be accomplished in less than 1 h, whereas SEM imaging is tedious and time-consuming.

Conclusion

This study presents a foldscope-based low-cost imaging technique for quantitative evaluation of the shape of sand particles. The proposed method matches the SEM results in measuring shape descriptors such as roundness and aspect ratio. However, a significant variation in the circularity value (more than 50%) was observed between the foldscope and SEM results. This can be attributed to the influence of resolution (different pixel sizes) or pixel-based digital image processing techniques used in the study. This is an important issue for future research to evaluate if the object-based approach is better than the pixel-based approach for solving issues associated with resolution.

Nevertheless, this study suggests that the foldscope can be a simple and economical method of measuring and quantifying the particle shape of granular soils. Further studies are required to explore the potential usefulness of this instrument in other geologic materials and various fields, including measuring and quantifying the convexity feature for geotechnical applications. This study also shows that the shape parameters are not sensitive to the number of particles considered for determining the averages and recommends that 80 particles are adequate for shape analysis while dealing with poorly graded sands.

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