Estimating the size composition of sediment surfaces through image analysis

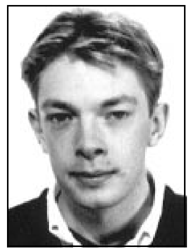
I. K. McEwan, BSc, PhD, CEng, MICE, T. M. Sheen, BEng, PhD, G. J. Cunningham, BEng and A. R. Allen, BSc, DPhil, CPhys, MInstP

Proc. Instn Civ. Engrs Water & Mar. Engng, 2000, **142**, Dec., 189–195

Paper 12069

Written discussion closes 27 January 2001

I. K. McEwan, Department of Engineering, University of Aberdeen



T. M. Sheen, Department of Engineering, University of Aberdeen

G. J. Cunningham, Department of Engineering, University of Aberdeen

A. R. Allen, Department of Engineering, University of Aberdeen

■ **This paper describes a technique to extract grain size information from areal images of sediment surfaces. An edge-detection algorithm is used to obtain the particle boundaries and segment the image into individual grains. Further processing of the segmented image can result in detailed information about grain size, position, orientation and, depending on the type of image, exposure. The images analysed in this paper were obtained by laser altimeter scans of sediment surfaces in laboratory conditions. Further development of the method could harness photogrammetric methods which are currently under development as a means of obtaining suitable images. Alternatively, carefully lit photographs have the potential to provide sufficient contrast at grain edges for the successful implementation of the image-processing technique. Therefore, this paper can be regarded as an interim step towards the provision of an improved method for estimating surface sizes and composition. The results presented are sufficiently encouraging to make field trials, probably with other image types, an attractive possibility.**

Keywords: coastal engineering; research & development; river engineering

Introduction

In order to understand and predict the physical processes which regulate the transport of graded sediments, it is necessary to be able to quantify the nature of the surface layer. A variety of methods exist in the literature for obtaining the surface size composition. Kellerhals and Bray[1] examined a number of these and evaluated their equivalence to volumetric sieving by means of an idealized cube of mixed-size sediment grains. They concluded that the grid by number technique, introduced by Wolman,[2] produced results that were directly equivalent to grain size distributions originating from a volumetric sieve analysis. More recent work has generally endorsed this finding.[1,3,4] In this method, the sample is obtained by collecting particles which are found under the nodes of a regular square grid, and the number of particles in the various size classes is used to form the size distribution. This paper describes an adaptation of this method which draws on recent advances in image processing to automate the basic process of obtaining grain sizes from the analysis of plan view images. Herein the term image is used in a broad sense to describe laser altimeter data,[5] photogrammetric data, digital photographs and scanned photographs. In principle, the qualifying property of any image which makes it amenable to the image processing is that the grain boundaries must be strongly contrasted with other parts of the image. Whether this contrast is derived from elevational information in the case of photogrammetric data or shading effects in the case of a photograph is immaterial.

2. The image processing has, in addition to sizing particles, the capability to provide data concerning grain position and orientation which are impractical or impossible to obtain with other standard techniques. The simultaneous measurement of the size and position of surface grains is timely in respect of other recent developments in sediment transport mechanics. It has generally been assumed that the composition of the surface is the dominant factor in determining its behaviour; thus most measurement techniques focus exclusively on this quantity. However, some other workers have suggested that, in addition to composition, the stability of the surface is dependent on the arrangement of the exposed grains.[6] This contention is supported by Kirchener *et al.*[7] and Buffington *et al.*,[8] who have shown that there is considerable variability in critical entrainment shear stresses for particles of like size deposited on a graded sediment surface. A natural development of their thesis is the notion that the stability of a given sediment particle in a surface is dependent on its location as well as its size. To thoroughly investigate this contention it is necessary to have measurement techniques which record the size *and position* of a given particle in the surface layer. This is beyond the capabilities of many of the traditional measurement methods which are intended as a means of measuring surface composition only, but it is relatively straightforward using image processing.

3. The development of the image-processing technique was originally driven by the desire to extract grain size information from laser altimeter scans of waterworked sediment beds.[5] These scans were made by a laser sensor which was driven over a sediment surface in a fine grid. The resulting data provided a detailed (x, y, z) description of the exposed surface of the bed. In photogrammetric terms this data can be considered as a digital elevation model (DEM). Examples of this data type are shown in Figs 3(a), 4(a) and 5(a). In the paper, the algorithms used in the image processing are described and their effectiveness is demonstrated by comparing calculated compositions with bulk sieve data for the three sediment mixtures.

Image analysis

4. Processing the images takes place in two stages. The first (low-level processing) segments the grey-level image into regions (grains). The second (high-level processing) operates on regions to generate and interpret the grain size and shape information. In order to commence image processing, a discretized map of image intensity is required in which grain boundaries tend to correspond to sharp changes in the intensity gradient. Herein, intensity refers to the image property which delineates the grain boundaries (e.g. gradients of elevation or grey level).

Low-level analysis: identifying the grains

5. The flow for the low-level image processing consists of three stages and is shown in Fig. 1. First, the edge detector generates a binary edge map for the image. Second, the morphological filtering stage (dilation and skeletonization) generates a closed segmentation of the image. Third, region labelling extracts closed region locations (grains). The implementation of these stages is illustrated visually in Figs 2(b)–2(h) and is described in detail in the following sections. Fig. 2(a) shows the initial photographic image on which the analysis was based.

6. *Edge detection.* The Canny algorithm[9] for edge detection consists of four stages. First, the gradient of image intensity is independently generated in both the x and y directions by using a convolution between the image and a one-dimensional matrix. The x convolution uses the single row matrix $[1, N]$ defined by equation (1) to generate the x component of the intensity gradient (Fig. 2(b)). A similar convolution with a column matrix $[N, 1]$, also defined by equation (1), is used to calculate the y component of the intensity gradient (Fig. 2(c)).

$$\text{gaussian}' = \frac{\mathrm{d}}{\mathrm{d}n}\exp(-n^2/2\sigma^2)\Big|_{n=-N/2}^{n=N/2} \quad (1)$$

7. The magnitude of the intensity gradient is then calculated from its x and y components by equation (2). The result is shown in Fig. 2(d).

$$G_{(x,y)} = \sqrt{(G^2_{x(x,y)} + G^2_{y(x,y)}} \quad (2)$$

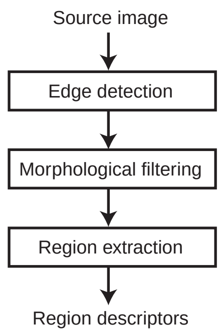


Fig. 1. The flow for the low-level image processing for grain recognition

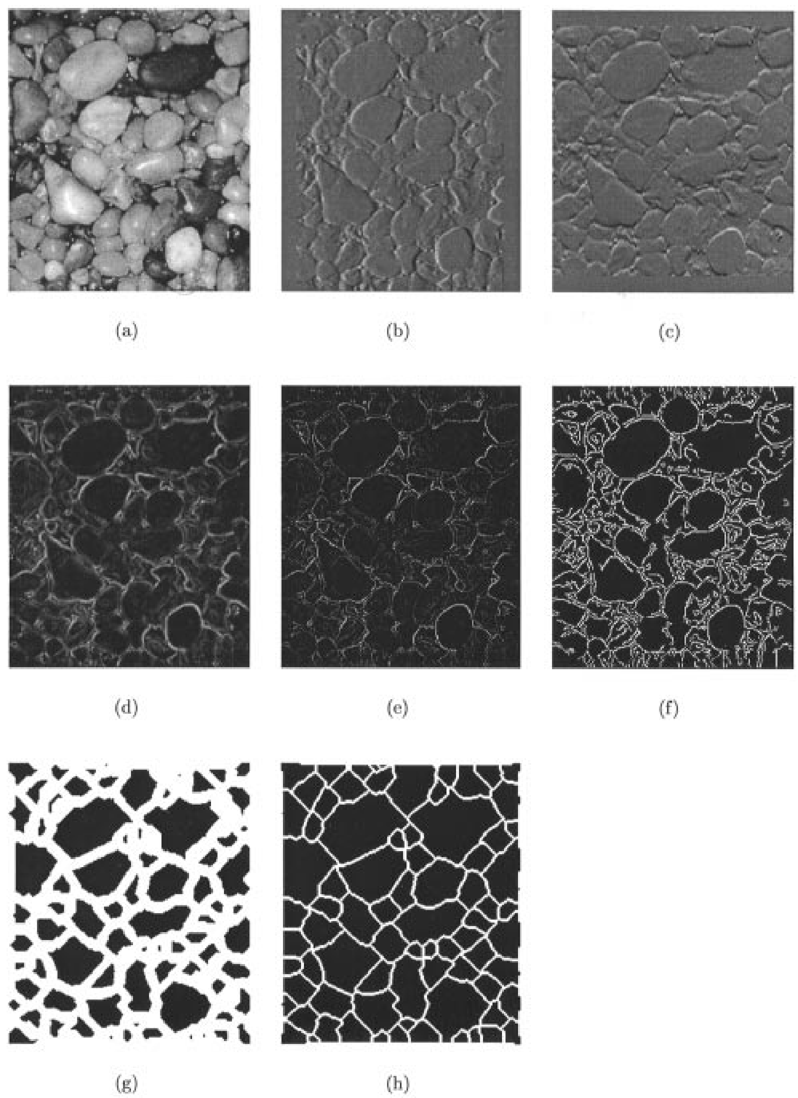


Fig. 2. The implementation of the image processing in visual form: (a) a 20 × 20 mm section of a scanned photograph; (b,c,d) the x and y components and magnitude of the image intensity gradient respectively; (e) the potential edge points found by non-maximal suppression of the intensity gradient; (f) the actual edges determined by thresholding the image in (e); (g) the dilation of the edges; (h) the final skeletonization

8. Potential edge points or grain boundaries are isolated using non-maximal suppression (Fig. 2(e)). This operation is akin to finding ridges in the intensity gradient map. Only points which are local maxima along a line perpendicular to the edge direction are considered as potential edge points.

9. Once potential edge points have been found, the actual edges must be generated. This is done by thresholding the edge image. In order to reduce the number of noise-lines but maintain edge connectedness, a hysteresis threshold is used. This seeds lines on all points with gradient magnitudes above an upper threshold and then extends the lines until the magnitude falls below the lower hysteresis threshold (Fig. 2(f)).

10. *Morphological filtering*. Even using the widest tolerance for the thresholding stage, the edge image is not well connected. Connected regions are formed by dilating the edge image. Dilation is equivalent to a binary convolution with a circular mask, with a radius equal to the dilation width.

11. The mask size is not critical; it must be large enough to close the majority of regions, while not being so large as to remove the smallest regions. A radius of 2–3 pixels was found to perform quite well (Fig. 2(g)).

12. In order to produce correct grain boundaries from the dilated edge map, the edges must be thinned. There are many skeletonization algorithms with different properties and different trade-offs such as efficiency, complexity, and skeleton shape. In the present application, speed is not critical; however, an unbiased skeleton is highly desirable. It is not necessary to generate a true skeleton, as we are only interested in closed regions, so it does not matter if branches are eroded. Thus a simplified version of the algorithm of Davies[10] is used. The resulting skeleton image is shown in Fig. 2(h).

13. *Region extraction*. After morphological filtering, the image consists of pixels in two categories: those with value 1 are edge pixels and those with value 0 are region pixels. A three-stage algorithm is used to extract regions. The image is searched in the x and y directions. When a new region is found (i.e. a pixel with value 0), it is used to seed a flood fill of the region, which is then relabelled 2, to denote it as the current region. From the seed pixel, a line is extended until the region boundary is found. The boundary is then traced round the flooded region and it is marked as finished by setting all pixels within the region to 3. The boundary-tracking algorithm maintains a history of two boundary points to prevent backtracking. Tracking is achieved by selecting a pixel adjacent to the current pixel which is also adjacent to the current region. Adjacency of edge pixels is defined to be '8 connected', that is any of the pixels surrounding the current one are permitted.

High-level processing: extracting the grain geometry

14. Once the regions have been extracted from the image, the shape of the grains must be analysed. This is done by extracting the grain geometry in terms of the major and minor axes of the grains in the plan view.

15. Given a set of edge points P for a closed region (or grain), the major axis is defined by the two points $P(x_a, y_a)$ and $P(x'_a, y'_a)$ which are chosen so that they maximize the length, $\sqrt{[(x_a - x'_a)^2 + (y_a - y'_a)^2]}$.

16. The major axis is used to divide P into two sets, the first set (M) consisting of the points on the clockwise boundary between $P(x_a, y_a)$ and $P(x'_a, y'_a)$ and the second (N) containing the remaining points on the anti-clockwise boundary. The minor axis is defined as the maximum dimension of the grain perpendicular to the major axis and is defined by the points $P(x_b, y_b)$ and $P(x'_b, y'_b)$. If the gradient of the major axis is $s = (y_a - y'_a)/(x_a - x'_a)$, then the minor axis will have a gradient of $-(1/s) = -(x_a - x'_a)/(y_a - y'_a)$. For each point in M, a corresponding point in N is selected, so that the gradient between the pair is closest to $-(1/s)$. The minor axis is then determined as being the maximum length between any particular pair of these points.

17. The only significant caveat for the algorithm is the assumption that the grain boundary is largely convex, so concavity along the major axis is not a problem; however, behaviour of the algorithm when there is concavity along the minor axis is not well defined. In practice, with the images analysed in this paper, this is not a problem, as significant concavity of the grain boundaries is rare. Nevertheless, it is potentially important should the technique be applied to other sediments, especially if significant grain imbrication has occurred.

Obtaining surface size composition from areal images

18. Kellerhals and Bray[1] concluded that the grid by number technique produced surface size composition data which are equivalent to those obtained by a volumetric sieve analysis. The present technique can readily be adapted to automate the grid by number technique where the sample has been recorded via an areal image. The 'grid' may be imposed numerically at a later stage, provided that a suitable scale has been incorporated in the image.

19. Figure 3(a) shows a section from a laser altimeter scan (80 by 80 mm). The calculated grain boundaries are also shown for each grain in Fig. 3(b). Visual comparison of the figures suggests that, at least for this type of image,

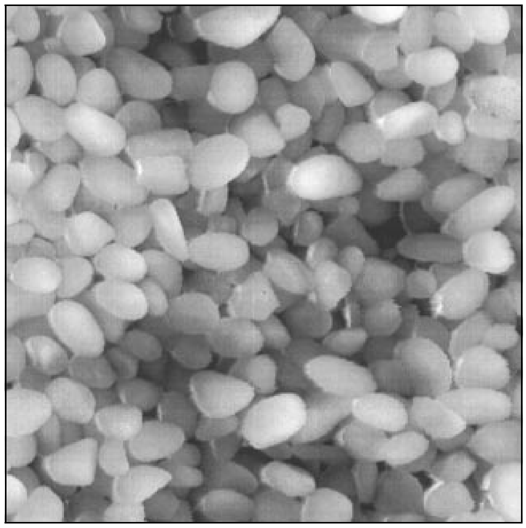
the low-level processing (grain boundaries) has performed reasonably well. In the results presented in this paper, it is assumed that the minor axis obtained from the plan image is equivalent to the *b*-axis of the particle.[11] The limitations introduced through this assumption are discussed later. Fig. 3(c) shows the size composition found from analysing the image using the grid by number method together with the composition found by volumetric sieving. Encouragingly, the two size distributions have similar values of d_{50}, although there is some over-representation of the finer grain sizes by the image-processing technique.

20. In order to demonstrate that the technique is reasonably robust, it was tested with two other sediment distributions. One of these was a unimodal sediment with a d_{50} of 4·6 mm, while the other was a bimodal mixture with modes between 1–2 mm and 5–6 mm in the ratio of 40:60 by weight of fine/coarse particles. The basic images for these two sediments are shown in Figs 4(a) and 5(a), the respective segmentations in Figs 4(b) and 5(b), and the comparison of the calculated and sieved distributions in Figs 4(c) and 5(c). Note that for the purposes of comparison, the sieved size distribution for the unimodal sediment has been truncated at its lower end because grains less than 2 pixels (in this case 1 mm) cannot be resolved by the image-processing technique. This does not apply to the other two mixtures, as in each case the minimum grain size was greater than twice the scanning resolution. Thus, mixture descriptors for the unimodal sediment presented here are derived for truncated distributions. For this mixture, it was found by sieving that d_{16}, d_{50} and d_{84} were 3·25, 4·68 and 7·70 mm respectively, with a standard deviation of 1·54 mm. The corresponding values d_{16}, d_{50} and d_{84} for the grid by number image-processing technique were 3·13, 5·34 and 8·10 mm respectively, and the standard deviation was 1·61 mm.

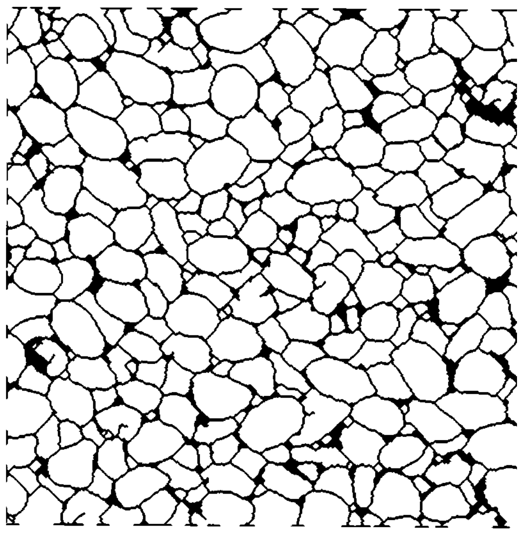
21. In short, the technique performs well for all three cases, which together represent a reasonable range of sediment types. Note that all three sets of results are for non-waterworked beds. This is not a limitation of the image processing. Rather, this condition has been chosen because waterworking would have introduced significant sorting to the surface, making comparison with bulk sample sieve data less meaningful.

Discussion

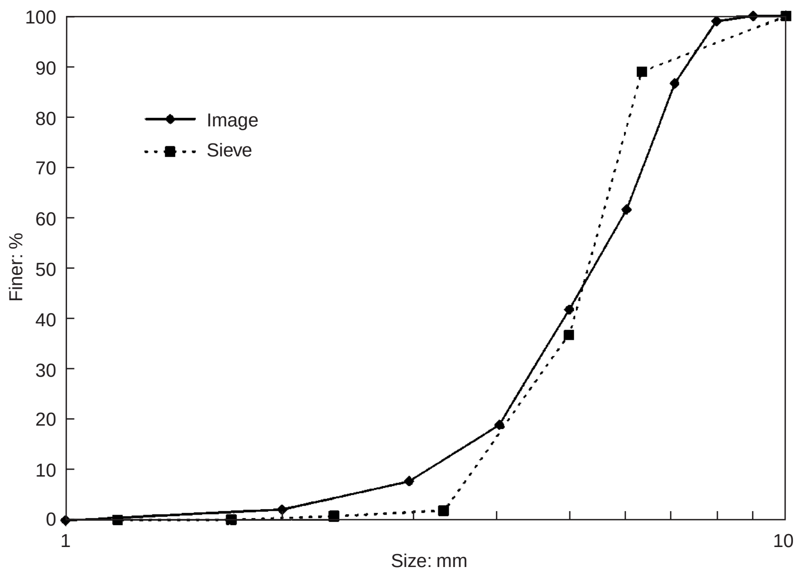
22. It has long been recognized that the surface plays an important role in regulating the behaviour of sediment systems. Because of this, much effort has been put into producing reliable and practical tools for measuring surface size composition and evaluating their suitability for elucidating surface phenomena.



(a)



(b)



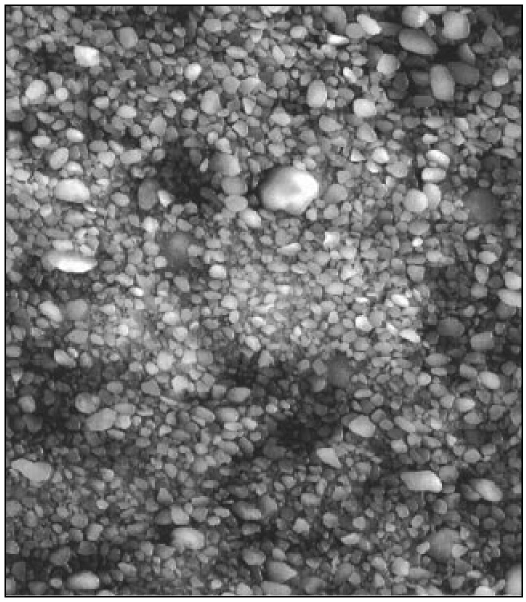
(c)

Fig. 3. (a) A laser altimeter scan of a sediment bed (80 by 80 mm). The bed has not been waterworked and contains a well-sorted sediment with a d_{50} of 5·3 mm. In this image, the elevation is represented as a grey level. (b) The segmentation of the image obtained by image processing. (c) A comparison of the composition obtained from image processing with that from a sieve analysis of the bulk sediment

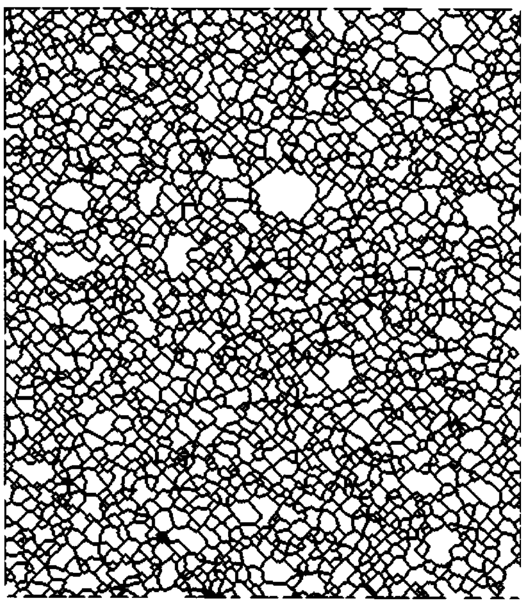
The technique introduced in this paper is a logical extension of the grid by number technique, which has been favoured by a number of investigators because it produces data which are directly equivalent to bulk sample sieve analysis.[3,4,12,14]

23. The general usefulness of the technique is limited in a number of ways. Some of these are methodological matters and can be overcome with careful implementation. However, at a fundamental level the technique is limited by the nature of an areal plan view and what can and cannot be recorded in it. Only two axes of the grain can be measured from an areal image. The analysis in this paper is based on the assumption that the largest visible dimension of the grain is its *a*-axis and that the grain's *c*-axis is orthogonal to the plane of the image. Thus the minor axis in the plan image of the grain is assumed to be the *b*-axis. Adams[11] quantified this relationship for a number of sediments and found that it was a very reasonable assumption. However, in general terms, its validity will vary according to the shape of sediment and the manner in which it is packed. Visual inspection of the photographic image will reveal the degree of partial shielding that is occurring between surface particles. Clearly, imbricated surfaces will not be sized correctly by this method. Moreover, coarse grains will be particularly susceptible to being wrongly sized, as they are more likely to be partially covered so that a reduced section is visible which cannot be used to accurately calculate the true particle dimension. The original grid by number technique was limited, at small scales, by the size of particle that could be reliably detected by a human operator. Kellerhals and Bray[1] suggested a lower limit of 8 mm, while Leopold[13] used 2 mm. The limits of the present technique are not determined by human factors but by the resolution and quality of the initial image.

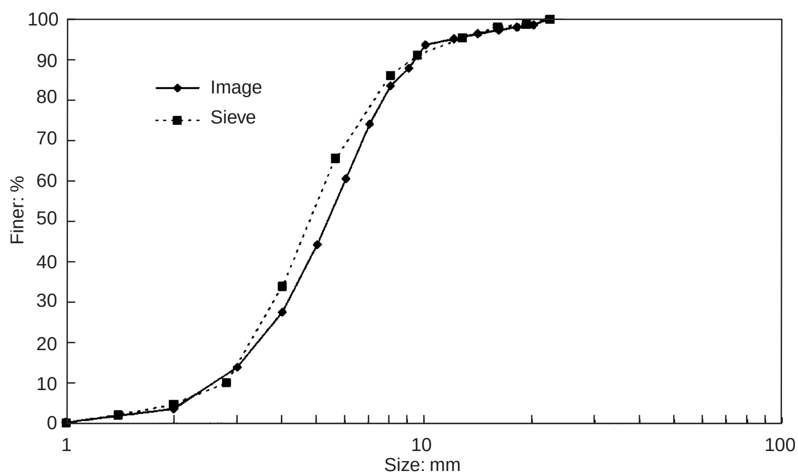
24. One clear advantage of the image-processing technique is that it is simple to implement and is likely to prove less labour-intensive than most other methods. In fact, it has the potential to be extended to photographic data which can be recorded easily. The higher-level processing relies on the segmentation being accurate. This is only possible when the boundaries between grains in an image are well defined, that is the areal image must be sharp and have good contrast. In order to achieve accurate edge detection, photographic images would, as far as possible, have to be free from lighting artifacts such as shadows and uneven illumination. Although not reported in the results discussed in this paper, some partially successful attempts at analysing such photographs have been made. These photographs were illuminated with a vertical circular flash, as it is not appropriate to side-light



(a)



(b)



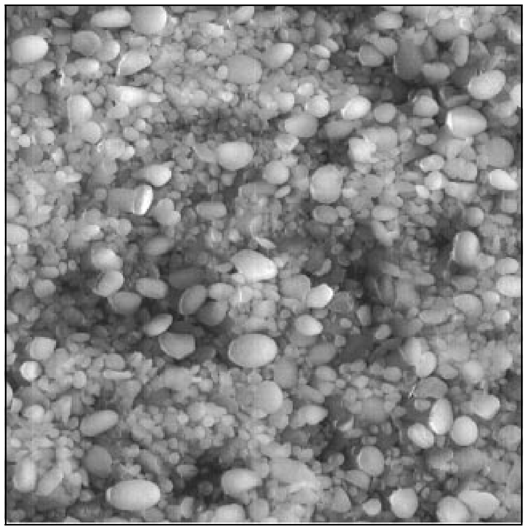
(c)

Fig. 4. (a) A laser altimeter scan of a sediment bed (256 by 256 mm). The bed has not been waterworked and contains a well-graded sediment with a modal diameter of 4·68 mm. (b) The segmentation of (a) obtained by image processing. (c) A comparison of the composition obtained from image processing with that from a sieve analysis of the bulk sediment

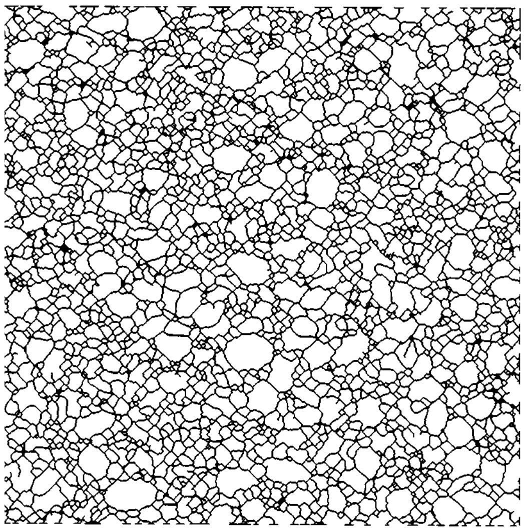
photographs, because the most rapid changes in image contrast tend to occur towards the summits of grains rather than at the grain boundary. In practice, it was found that tonal imperfections on the surface of grains caused some problems in the image processing, and the segmentation was not as 'clean' as with the laser altimeter data. This problem is almost certainly surmountable with a slightly more sophisticated algorithm for eliminating such spurious 'edges' but it will not be considered further here.

25. One of the most interesting aspects of the new technique which has not been emphasized is its capability to produce data on grain location and orientation. The availability of a technique to acquire this information opens up a number of possibilities, each with considerable potential to improve the understanding of sediment mechanics. For instance, it would be relatively straightforward to examine the formation of static armour layers by examining spatial and temporal development of stable formations of particles on the bed through a time series of photographs. Similarly, the exchange of particles between the bed load and surface could be monitored by analysing a time series of photographs under conditions of equilibrium transport rate. This would lead to an increased understanding of entrainment and deposition during bedload transport, permitting analysis of the fundamental relationships between processes. Moreover, collecting images is non-destructive, in contrast to most other surface-sampling methods (e.g. using adhesives). Thus, in laboratory conditions, samples can be collected during experiments without removing sediment from the bed.

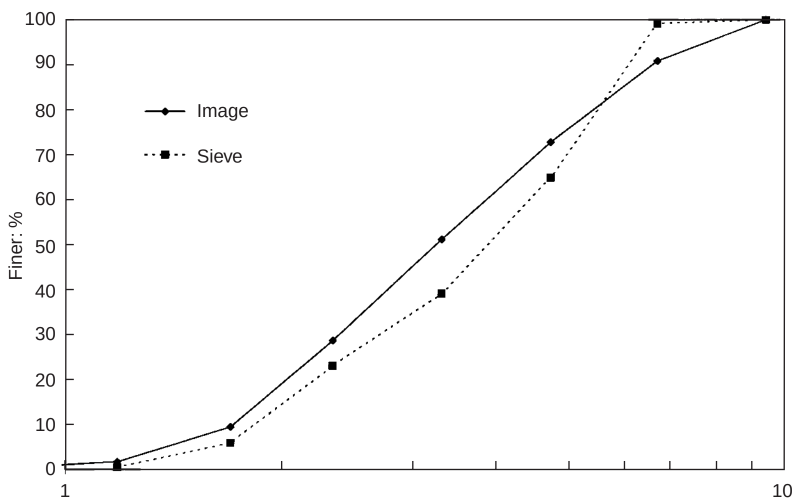
26. It is important to set this alternative method for obtaining surface composition in its wider context. Physically, the surface composition plays an important role in regulating transport rate, particularly in graded sediments. Thus reliable and efficient methods are required for the prediction of sediment transport rates and subsequent morphological behaviour. Moreover, in mobile bed channels there is usually significant variation in surface composition at different scales, which makes the appropriate use of surface sampling difficult. In practice, the difficulty in measuring and representing this heterogeneity may set limits to the accuracy of modelling predictions—in effect, the initial conditions are poorly defined. This paper does not contribute to the solution of this problem, except in the sense that an image-analysis-based method is likely to be cheaper to implement than more conventional methods and so may enable more samples to be collected. The problem of how this additional data would be used in modelling remains.



(a)



(b)



(c)

Fig. 5. (a) A laser altimeter scan of a sediment bed (120 by 120 mm). The bed has not been waterworked and contains a bimodal sediment with the modes in the range 1–2 mm and 5–6 mm in the ratio by weight of 40:60, fine to coarse. (b) The segmentation of (a) obtained by image processing. (c) A comparison of the composition obtained from image processing with that from a sieve analysis of the bulk sediment

27. The motivation of this paper has been to introduce an alternative technique and evaluate its reliability in estimating the composition of sediment surfaces. Because of the importance of obtaining surface composition, other measurement methods have received much attention in the literature.[4] Thus, a variety of surface sampling methods exist, each having different characteristics and producing samples which are not directly comparable to samples taken with another technique. The authors are aware that the introduction of another technique to the literature is not necessarily a step forward. The principal recommendation of an image-processing technique for surface sampling is that it would be reasonably cheap to implement in field conditions. Currently, we are a little way from attaining this goal; however, the deployment of photogrammetry in the field[14] is being actively investigated and, in association with image processing, may move us further towards it.

Conclusions

(*a*) The application of automated analysis methods to images of sediment beds provides a reliable means of determining surface size composition.
(*b*) The surface size composition determined by the automated grid by number technique is directly equivalent to that obtained by sieving of bulk sediment.
(*c*) Many standard surface sampling techniques were developed to measure surface composition only. As well as measuring surface composition, the image-processing technique is capable of providing information on particle location and orientation. Thus the technique may well provide the catalyst towards obtaining an improved understanding of some fundamental aspects of sediment transport mechanics.

Acknowledgements

The authors acknowledge the funding of the Engineering and Physical Sciences Research Council of the UK, which supports the experimental programme with which this work is associated.

References

1. Kellerhals R. and Bray D. I. Sampling procedures for coarse fluvial sediments. *Journal of the Hydraulic Engineering Division, ASCE*, 1971, **97**, No. 8, 1165–1180.
2. Wolman M. G. A method of sampling coarse river-bed material. *Transactions of the American Geophysics Union*, 1954, **35**, No. 6, 951–956.
3. Church M. A, McLean D. G. and Wolcott J. F. River bed gravels: sampling and analysis. In *Sediment Transport in Gravel-bed Rivers* (Throne C. R., Bathhurst J. C. and Hey R. D. (eds)). Wiley, New York, 1987, 43–79.
4. Diplas P. and Sutherland A. J. Sampling techniques for gravel bed sediments. *Journal of the Hydraulic Engineering Division, ASCE*, 1988, **114**, No. 5, 484–501.
5. Willetts B. B., Pender G. and McEwan I. K. Experiments in graded sediment transport. *Proceedings of the Institution of Civil Engineers, Water Maritime & Energy*, 1998, **130**, 217–225.
6. Tait S. J., Willetts B. B. and Maizels J. Laboratory observations of bed armouring and changes in bedload composition. In *Dynamics of Gravel Bed Rivers* (Billi P., Hey R. D., Throne C. R. and Tacconi P. (eds)). Wiley, New York, 1992, 205–225.
7. Kirchener J., Dietrich W., Iseya F. and Ikeda H. The variability of critical shear stress, friction angle and grain protrusion in water worked sediments. *Sedimentology*, 1990, **37**, 647–672.
8. Buffington J. M., Dietrich W. E. and Kirchner J. W. Friction angle measurements on a naturally formed gravel streambed—implications for critical boundary shear stress. *Water Resources Research*, 1992, **28**, No. 2, 411–425.
9. Canny J. A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1986, **8**, No. 6, 679–698.
10. Davies E. R. *Machine Vision: Theory, Algorithms, Practicalities*. Academic Press, New York, 1990.
11. Adams J. Gravel size analysis from photographs. *Journal of the Hydraulic Engineering Division, ASCE*, 1979, **105**, 1247–1255.
12. Hey R. D. and Thorne C. R. Accuracy of surface samples from gravel bed material. *Journal of the Hydraulic Engineering Division, ASCE*, 1983, **109**, No. 6, 842–851.
13. Leopold L. B. An improved method for size distribution of stream bed gravel. *Water Resources Research*, 1970, **6**, No. 5, 1357–1366.
14. Butler J. B., Lane S. N. and Chandler J. Assessment of DEM quality characterizing surface roughness using close range digital photogrammetry. *Photogrammetric Record*, 1998, **16**, 271–291.

Please email, fax or post your discussion contributions to the secretary: email: wilson_l@ice.org.uk; fax: +44 (0)20 7799 1325; or post to Lesley Wilson, Journals Department, Institution of Civil Engineers, 1–7 Great George Street, London SW1P 3AA.