Chesil Beach grain-size report

A technical report on the impact of beach management works and evaluation of the Sedimetrics® Digital Gravelometer^{tm} software

A report for the Environment Agency

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A technical report on the impact of beach management works and evaluation of the Sedimetrics® Digital Gravelometer^{tm} software

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Date	Comments

EXECUTIVE SUMMARY

- In the light of the exceptional geological importance of Chesil Beach, and following extensive remedial work to prevent it being breached during the winter storms of 2013/2014, the Environment Agency commissioned this report to evaluate the current sediment-size properties of the eastern end of the beach. The aims of the work were:
    - to evaluate the effectiveness of photographic sampling, combined with analysis using Sedimetrics® Digital Gravelometer™ software, in beach monitoring projects;
    - to determine whether the beach management interventions have significantly modified the grain-size structure of the beach; and
    - to obtain baseline data against which future surveys can be compared.
- Grain size measurements were made on 28 transverse profiles along a 2.9 km length of the beach stretching between Chesil Cove (to the east) and the Chesil Beach Visitor Centre (to the west). This included the approximately 1 km length of beach subject to remediation works in 2014. The majority of the samples were collected photographically and processed using the Sedimetrics® Digital Gravelometer™ software to extract grain-size information. Additional samples were collected using the conventional 'Wolman' sampling method for data validation and quality control purposes.
- The project generated a dataset of c. 1000 images collected at 189 discrete locations, and for which detailed grain size information is available. There are an additional 27 detailed grain-size distributions collected via conventional 'Wolman' sampling.
- A sharp progressive decrease in grain size was observed over the first c. 0.5 km from the eastern limit of the beach at Chesil Cove. The rate of decrease gradually levelled off in a westerly direction, until little there was little longitudinal change in grain size over the most westerly 0.5 km of the studied beach. There were some systematic longitudinal changes in the overall 'shape' of the grain size distributions (as measured by sorting, skewness and kurtosis), but these were of a very small magnitude. Some evidence of a slight decrease in grain size from the landward to seaward side of the beach was observed.
- There is little evidence that the beach management interventions undertaken during 2014 have had a significant impact on the grain-size structure of the beach. Although the interventions occurred in the part of the beach with the steepest longitudinal grain-size gradient, there is no evidence of a discontinuity in grain size between the modified and unmodified parts of the beach. There are some differences in the 'shape' of the grain-size distributions between the modified and unmodified parts of the beach, but the magnitude of these is very small and unlikely to be identified by the casual observer. There are also some small cross-beach variations in grain size in the modified area. Whilst it may be inferred that these differences result from the beach management works, it is possible that they simply reflect the more dynamic nature of this part of the beach or its natural recovery following the storms.

- Photographic sampling, combined with the use of Sedimetrics® Digital Gravelometer™ software for extracting grain-size information, proved an effective means of data capture. Photographic data collection time was less than 5 minutes per sample (versus 20-30 minutes for a conventional 'Wolman' sample).
- Some tuning of the image processing parameters used to extract grain-size information from the images was required to optimise them for the Chesil Beach environment, and calibration was required to correct for systematic biases. Following calibration, the uncertainty in key size indices was around 5% (RMS error expressed in millimetres), which is comparable to that achieved from conventional sampling methods.
- Given the success of the photographic sampling method at Chesil Beach, it is anticipated that it may find wider application in beach monitoring studies. It is recommended that a similar tuning and calibration procedure be applied in any future applications, at least until a transferable set of processing and calibration parameters have been established via work at a variety of sites. Field and processing operatives should be appropriately trained to ensure the reliability and consistency of results.

BACKGROUND

Chesil Beach is renowned for its longitudinal grading of sediment size, with smaller grains at the western end and larger grains to the east. During the exceptional period of storms during the winter of 2013/2014, remedial work was undertaken at the extreme eastern end of the beach to prevent its breaching and flooding of the properties behind it. This work involved movement of material from the lower part of the beach to create an artificial berm higher up the beach, with possible implications for the pattern of sediment grading now and in the future. Due to the significant environmental considerations and the important historical aspect of the beach formation, following the significant intervention in the winter of 2013/2014, the Environment Agency approached the authors of this report to undertake a survey of the sediment grain-size distribution along beach profile (transverse) cross-sections within the modified section of beach and adjacent unmodified section.

The aims of this work were:

- to evaluate the effectiveness of photographic sampling, combined with analysis using Sedimetrics® Digital Gravelometer™ software, in beach monitoring projects;
- to determine whether the beach management interventions have significantly modified the grain-size structure of the beach; and
- to obtain baseline data against which future surveys can be compared.

The fieldwork upon which the report is based was undertaken between 27 February and 6 March 2015.

METHODS

Units, notation and sampling protocol

Grain-size frequency distributions tend to have an approximately lognormal distribution. It is therefore conventional to use a logarithmic size scale to simplify statistical analyses (Bunte and Abt, 2001). This report uses the Psi (ψ) scale, which is convenient for gravel-sized material because particles larger than 1 mm have positive values in ψ-units. ψ-units are computed from particle size D in units of mm by $\psi = \log_2(D)$.

Particle size-frequency distributions are commonly described in terms of size percentiles, representing the proportion of a sample smaller than a given size. The median grain size – the most commonly used measure of the 'average' grain size – is represented by ψ_{50}, the size that 50% of the grains are smaller than (ψ-units). Percentiles are derived from a grain-size distribution, which is constructed from the measured proportion of a sample in a series of consecutive grain size classes. To improve the quality of derived percentiles half-ψ size classes are typically used, in which the class boundaries correspond to 0.5 ψ increments (e.g. 2^4=16.0 mm, $2^{4.5}$ = 22.6 mm, 2^5=32.0 mm, $2^{5.5}$=45.3 mm, 2^6= 64.0 mm etc.).

In addition to the median grain size, grain-size distributions are commonly characterised using three additional descriptive statistics. Sorting (equivalent to the standard deviation) describes the width or spread of the distribution. Skewness measures the deviation from a symmetrical (normal) distribution. Kurtosis is a measure of the flatness or peakedness of the distribution. This report uses the most commonly-presented measures of sorting, skewness and kurtosis, which were developed by Folk and Ward (1957):

Sorting: $$s_{f\&w} = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_{5}}{6.6}$$

Skewness: $$sk_{f\&w} = \frac{\varphi_{16} + \varphi_{84} - 2\varphi_{50}}{2(\varphi_{84} - \varphi_{16})} + \frac{\varphi_{5} + \varphi_{95} - 2\varphi_{50}}{2(\varphi_{95} - \varphi_{5})}$$

Kurtosis: $$ku_{f\&w} = \frac{\varphi_{95} - \varphi_{5}}{2.44(\varphi_{75} - \varphi_{25})}$$

Care must be taken when comparing data from different studies that they are presented in the same way. Data obtained from the surface layer are not directly comparable with those collected by bulk sampling of a subsurface volume. Data analysed by grain counts are not directly comparable with those analysed by weight (because weight is proportional to the cube of size). Similarly, data collected using a grid sample (where the probability of sampling a grain is proportional to its exposed area) are not directly comparable with those collected by sampling the grains within a given area (where the probability of sampling all grains is the same). In this study, all data were obtained by sampling the surface layer and were obtained in (or converted to) grid-by-number format (grains collected on a regular grid and aggregated based on the number of grains in each size class). These methods were appropriate because they do not require the sediment to be dug up or removed (particularly important for this protected site), they can be undertaken using simple field equipment, and they facilitate the application of rapid photographic sampling and analysis methods.

Sampling strategy

Sediment grain-size distributions were determined along 28 predefined transverse profiles across the beach between Chesil Cove and the Chesil Beach Visitor Centre, a total distance of 2.9 km (Fig. 1; Appendix 1). These profiles represent a subset of those used by the South West Regional Monitoring Programme for monitoring of the beach morphology. The first 20 profiles, between Chesil Cove (profile 109) and the outflow of the flood alleviation channel (profile 148), had an average spacing of 90 m. This included 12 profiles (109 – 131) within the area subject to remedial work during 2014. The remaining profiles had an average spacing of 150 m.

The location of each profile was identified in the field with reference to a printed topographic map on which the profile lines were marked (based on the OSGB coordinates and bearings provided by the Environment Agency). Where possible, the inland end of each profile was identified from its known coordinates using a consumer grade GPS. A magnetic compass was then used to place two markers to indicate the line of the profile. Where the start of the profile was not accessible, the point at which the profile crossed the beach crest was identified by triangulation from visible map features using a magnetic compass, and markers placed as before. It is estimated that this process resulted in the position of each surveyed profile being within ±10m of the desired position.

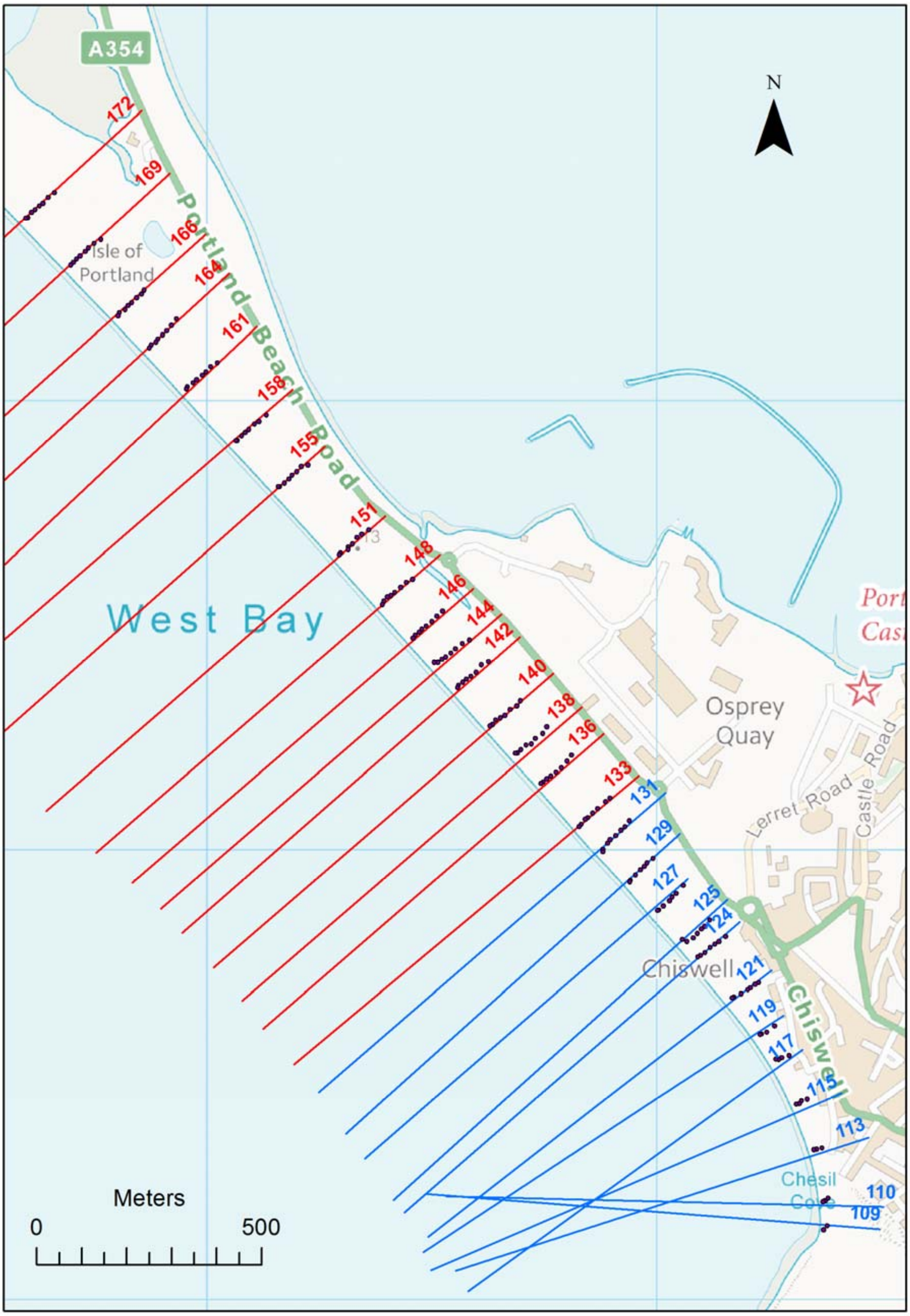


Figure 1: The surveyed profiles and sample locations (purple dots). Blue lines represent profiles that were affected by remedial work during winter 2013/14; profiles indicated by red lines were not affected. Profile numbers reference the last three digits of the Environment Agency profile identifiers. Contains OS data licensed under the Open Government Licence v3.0 © Crown copyright (2015).

Along each profile, sediment grain-size measurements were made at up to 8 positions, as outlined in Table 1 (and illustrated in Fig. 2), designed to capture the main morphological components of the beach. Sampling morphological features rather than specific points in space is sensible given the dynamic nature of the beach face and the desire to monitor the beach over time. The number of measurements on each profile reflected the morphology of the beach at that position. The coordinates of all sampling positions are given in Appendix 1.

Table 1: Morphological locations of samples

	Morphological unit	Identifier
Land ↑	Break of slope at base of beach crest (landward side)	a
	Halfway up landward face of beach crest	b
	Beach crest	c
	Profiles 110 – 131: Top of artificial berm 1 Profiles 133 – 172: Break of slope at base of beach crest (seaward side)	d
	Halfway between d and f	e
	Top of main (natural) berm	f
	Top of lowest berm	g
↓ Sea	On seaward face of lowest berm (just above low water swash zone)	h

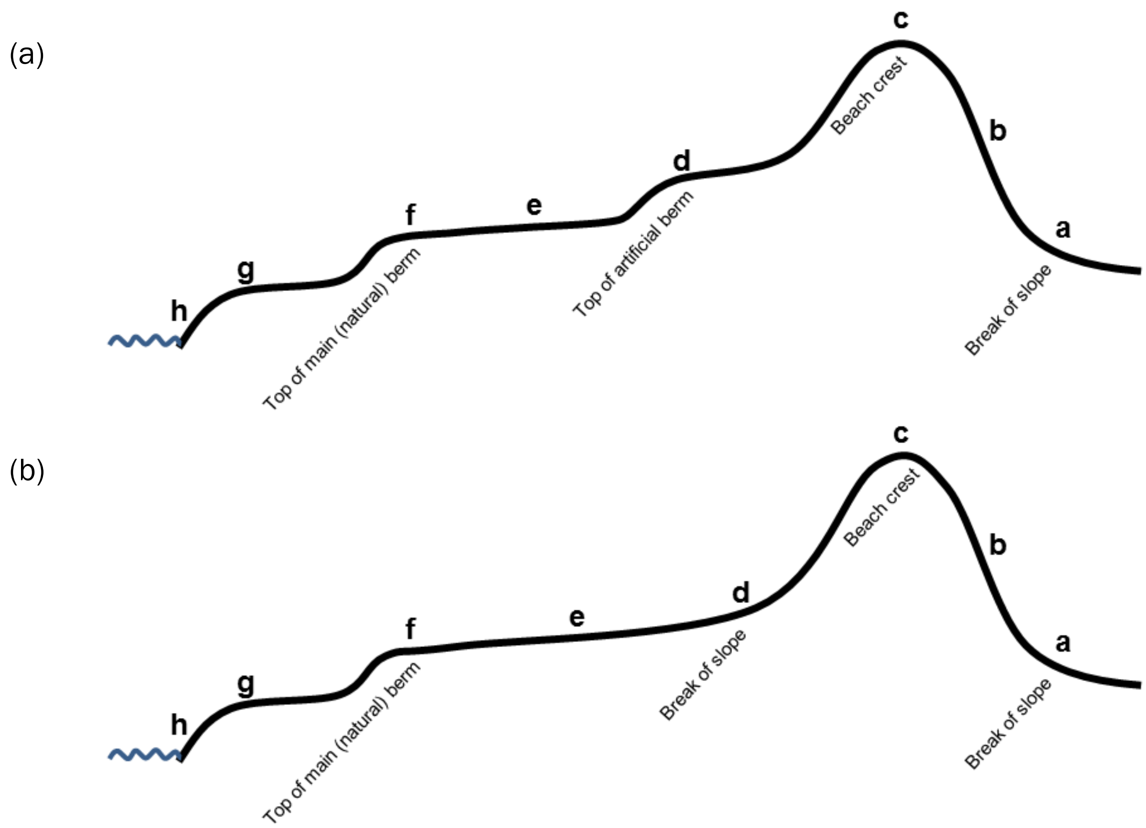


Figure 2: Schematic transverse profiles across Chesil Beach showing the morphological locations of samples. (a) Profiles 109-131, incorporating a sample on the artificial berm. Not all morphological elements were present in every profile in this section of beach. (b) Profiles 133-172. Note: not to scale.

Control data sampling

In order to provide validation data for the photographic sampling, and for direct comparison with existing data, one sample was collected on each profile using a traditional grid-by-number sampling technique ('Wolman' sampling; Bunte and Abt, 2001). These samples were collected on the top of the main berm on each profile (position f). Grains were selected for measurement on a regular grid with node spacing greater than 2 times the maximum grain size. The grid was established using a 30 m tape (Fig. 3a). Care was taken to sample the particle directly beneath each grid node, even if this lay within the interstices of the surface grains. 200 grains were sampled at each location using this method. This is less than the sample size of 300 grains recommended by Rice and Church (1996) to adequately capture the tails of the grain-size distribution in typical fluvial environments, but because optimal sample size increases with the spread of the grain size distribution and these beach sediments are well sorted, a sample of 200 was reasonable compromise between accuracy and effort. Grains were sorted into standard half-ψ *size classes* using a square-hole gravel template ('gravelometer'; Fig. 3b) and counted.

To enable subsequent comparison between measurements from the photographs (where the grain b-axis measurements are equivalent to those made using a ruler) and the gravel template (where grain flatness affects the apparent b-axis size as a result of grains passing through the square holes along the diagonal), the mutually orthogonal a-, b- and c-axes of 20 grains were measured using a ruler to enable a mean flatness index (c/b) to be calculated.

(a) (b)

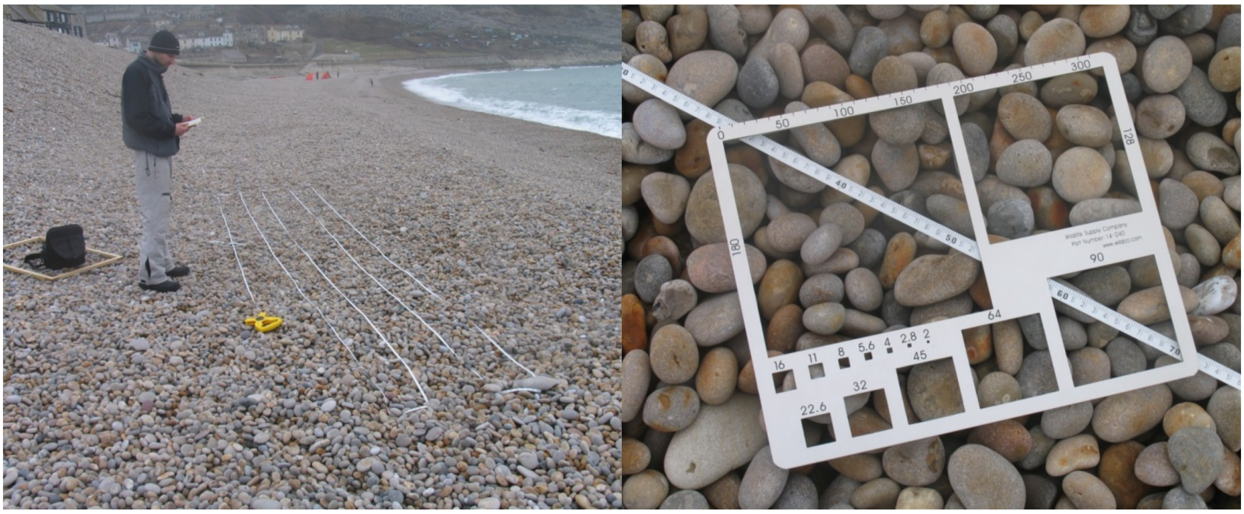


Figure 3: Control data collection. (a) The establishment of a grid for 'Wolman' sampling using a 30 m tape. (b) Gravel template used for determining the size of sediments in the field.

Control data analysis

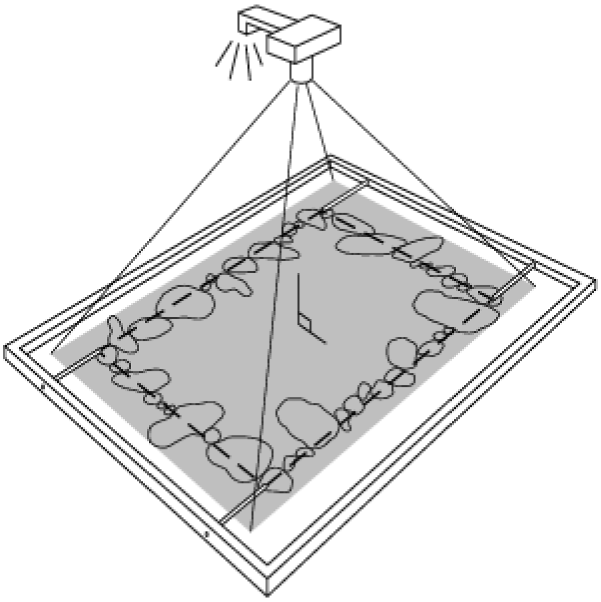
The tallied data from the 'Wolman' samples were converted into cumulative grain-size distributions on a 'percent finer' basis (as is conventional in the UK). Grain size percentiles were estimated by using spline interpolation to fit a smooth curve through the data points. Key descriptive statistics for each distribution (sorting, skewness, kurtosis) were calculated using the inclusive graphical measures of Folk and Ward (1957).

Photographic sampling

The primary method of data collection was via photographic sampling (Fig. 4). The ends of metal pins attached to a wooden frame were used to define a controlled area of 600 mm by 400 mm (0.24 sq m) on the surface to be sampled. The area was then photographed from above using a Canon Powershot Pro 1 with an externally mounted flash. This is an 8MP consumer grade compact camera with a fold out display that aids the composition of shots. The camera was held at shoulder height and arm's length. Images were stored at the highest resolution and lowest compressionlevel supported by the camera. The photographic procedure adhered to the recommendations of the Sedimetrics® Digital Gravelometer^{tm} image collection checklist (Appendix 2). Particular care was taken to ensure that lighting conditions were optimised. Direct sunlight is known to degrade the quality of the resulting data (because only the sunlit parts of grains are measured; Graham *et al.* 2005b), so the sample areas were shaded from direct sunlight when necessary. Given the relatively low sun elevation at the time the work was undertaken, this was achieved using the body and clothing of the operator and an assistant. A large umbrella or sheet of fabric on a lightweight frame has been successfully employed on other occasions. The external flash ensured that the surface of each grain was brightly and evenly illuminated, with their edges picked out by the shadows cast in the interstices.

Each sample consisted of five photographs collected from immediately adjacent areas. This increased the sampling area (to 1.2 sq m) to ensure the collection of a representative sample, and allowed for the rejection of poor quality images at the analysis stage.

(a)



(b)

Figure 4: Schematic representation of the photographic method. (a) Frame laid on the ground and photographed from above. The shading represents the photographed area. The dashed line represents the controlled area of known dimensions and indicated by metal rods protruding from the frame. The camera has an externally-mounted flash to provide illumination. (b) The frame used in this study. The ends of the metal rods define an area of 600 by 400 mm.

Photographic data analysis

Photographs were processed using the Sedimetrics® Digital Gravelometer[tm] software (http://sedimetrics.com). This software identifies the grain boundaries for the sediment contained within each image (segmentation), measures the dimensions of the resolved grains and then aggregates the measurements to yield a grain size distribution. An example, showing the original and segmented images are presented in Figure 5. A full description of the image processing procedures are contained in Graham *et al.* (2005a; 2005b).

(a)

(b)

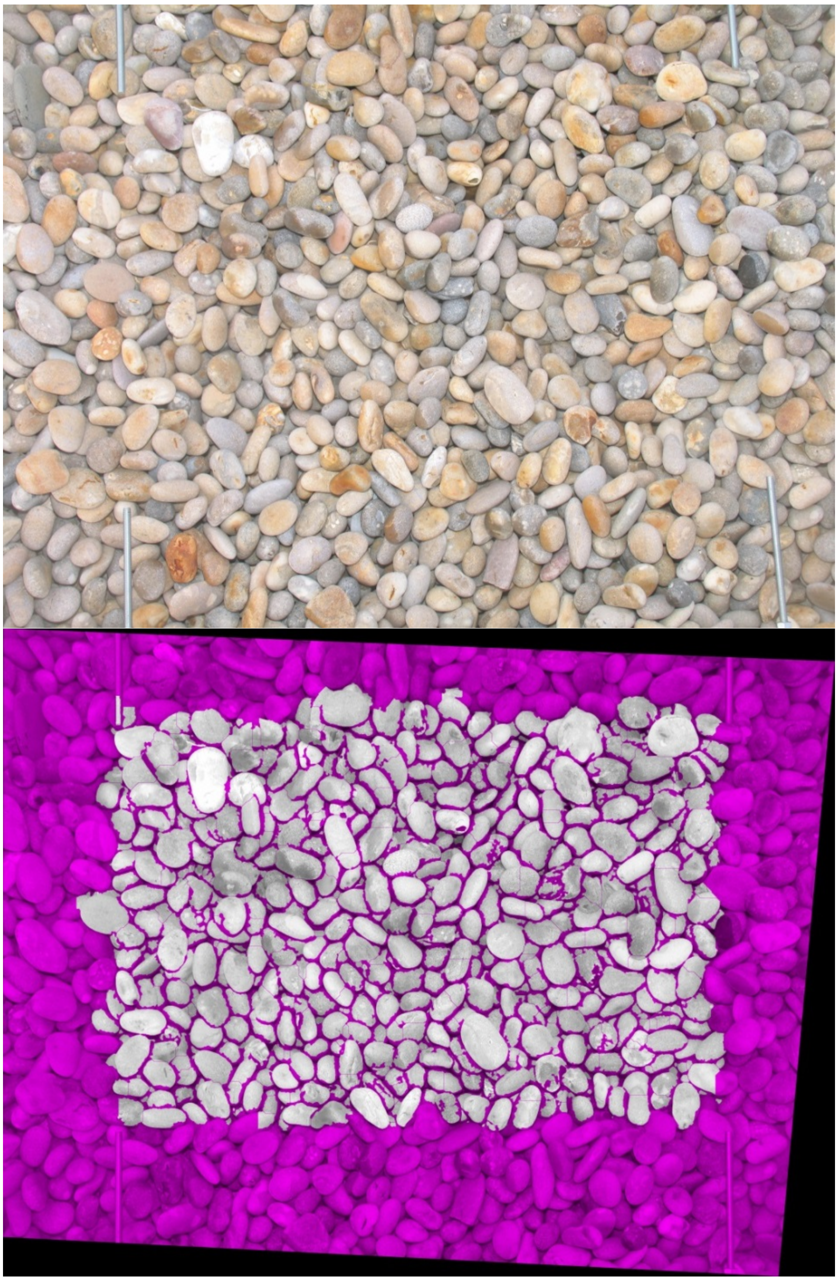


Figure 5: Example images illustrating the segmentation within the Digital Gravelometer software. (a) Original photograph. The ends of the metal pins define an area of 600 mm by 400 mm. (b) Processed image. Grain boundaries (purple) are overlaid on the original image. The segmentation in this image is considered good, even though a few grains are over-segmented and others merged.

The data flow for each image was as follows:

1. Input of image to software with manual digitisation of the four points that define the known area within each image.
2. Processing of image to determine grain boundaries and measure the size of each grain.
3. Visual inspection of the segmented image and rejection if the segmentation was not deemed satisfactory.
4. Once all of the images comprising a single sample had been processed, generation of a grain size report for the sample.

At stage 3, 62 images were rejected out of a total of 948 (6.5%). A list of the accepted and rejected images is presented in Appendix 3).

As the software was developed for fluvial environments, experiments were undertaken to determine optimal processing parameters for the more rounded and sorted sediments encountered on Chesil Beach, rather than relying on the default values. The parameters utilised are presented in Table 2. It is beyond the scope of this report to explain each of these parameters, but further information was presented by Graham et al. (2005a; b) and in the software documentation (http://sedimetrics.com/documentation/introduction.html).

Table 2: Principal processing parameters applied

Parameter	Values applied	Default values
Median filter size	10 pixels	5 pixels
Bottom-hat filter structuring element size	15 pixels	15 pixels
Segmentation thresholds	2%, 25%	1%, 35%
Watershed minima suppression value	1	1

Grain-size reports were prepared in grid-by-number format to permit direct comparison with the control data collected by 'Wolman' sampling. Cumulative grain-size curves and percentiles were prepared on a 'percent finer' basis. To avoid noise associated with over-segmentation of the images and improve the precision of the percentile estimates, a lower truncation of 4 ψ (16 mm) was applied, which was smaller than the smallest grain encountered in the Wolman sampling. In this case, truncation simply removed the possibility that spurious small grains were introduced by the software (for example by identifying holes between large grains as small grains). A square-hole correction (calculated from the mean grain flatness measured in the field) was applied to make the data equivalent to the control data, in which the grains were measured using a square-hole template.

RESULTS

Calibration of photographic data

The grain-size distributions derived from the Digital Gravelometer software are subject to a number of errors associated with the structural characteristics of the surface being measured (partial grain burial, overlapping and imbrication), and limitations of the image-processing procedures themselves (over- and under-segmentation). The software was developed and optimised using data from fluvial environments, where the sediments are relatively poorly sorted. In fluvial environments it has been shown that these errors tend to cancel one another out, resulting in grain-size percentile estimates with a similar precision to those obtained from conventional measurement methods (Graham *et al.* 2010).

The software has not previously been applied to beach environments, which are commonly characterised by better grain-size sorting than fluvial environments. During the analysis of the photographic data, it became apparent that the combination of errors (particularly over-segmentation and partial grain hiding/burial) were having a significant effect on the derived grain-size distributions. In particular, the proportion of finer grains was significantly overestimated, resulting in underestimation the value of lower grain-size percentiles.

To improve the precision of derived grain-size percentiles, a calibration was calculated using the 'Wolman' sample control data collected on the top of the main berm (position f, n=27). This was achieved using linear least-squares regression between the Wolman and photographic ψ_{16}, ψ_{50} and ψ_{84} percentiles. The results of this modelling are presented in Fig. 6 and the data are in Appendix 4.

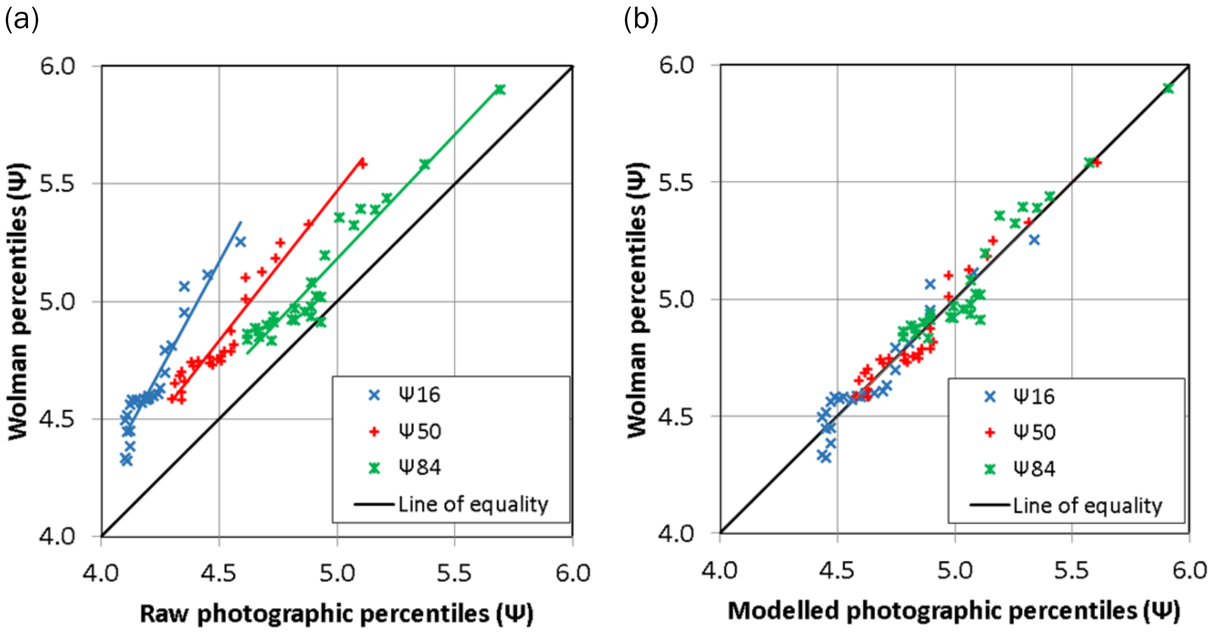


Figure 6: Covariant plots of key percentiles derived by photographic and 'Wolman' sampling. (a) Raw (uncalibrated) photographic percentiles vs 'Wolman' percentiles and their associated linear least-squares best fit lines. (b) Calibrated photographic percentiles vs 'Wolman' percentiles.

The regression equations were significant (α = 0.001), with large coefficients of determination:

$$\psi_{16calibrated} = 1.846\psi_{16rawphoto} - 3.135 \qquad (r^2 = 0.903)$$

$$\psi_{50calibrated} = 1.270\psi_{50rawphoto} - 0.881 \qquad (r^2 = 0.935)$$

$$\psi_{84calibrated} = 1.058\psi_{84rawphoto} - 0.107 \qquad (r^2 = 0.914)$$

These equations were used to calibrate the image-derived percentile estimates presented in the remainder of this report. A summary of the errors in key percentiles before and after calibration are presented in Table 3.

Table 3: Summary of errors in photographic grain-size percentiles before and after calibration.

	RMS error (raw photographic data)	RMS error (calibrated photographic data)
ψ_{16}	0.445 ψ (=36.1% in mm)	0.069 ψ (=4.9% in mm)
ψ_{50}	0.346 ψ (=27.1% in mm)	0.063 ψ (=4.5% in mm)
ψ_{84}	0.194 ψ (=14.4% in mm)	0.078 ψ (=5.6% in mm)

Summary diagram

Figure 7 presents a summary of the spatial variability in key grain-size percentiles for the entire surveyed area in the form of an isopleth map. Key features of the longshore and cross-shore patterns of grain size are highlighted in the following sections.

Longshore variability in grain size

Figure 8 illustrates the longshore variability in key grain-size metrics. Grain-size percentiles are presented for the calibrated photographic data and the 'Wolman' samples. Sorting, skewness and kurtosis are derived from the 'Wolman' data. Profiles are ordered as if looking onshore, with profiles at Chesil Cove to the right, and the Chesil Beach Visitor Centre at profile 172. There is an initial rapid decrease in grain size with distance away from Chesil Cove (from ψ_{50} = 5.6 [48 mm] at profile 110 to ψ_{50} = 4.9 [29 mm] at profile 125), the rate of which gradually slows (to ψ_{50} = 4.6 [24 mm] at profile 172). All samples are classified as very-well sorted in the Folk and Ward (1957) classification (sorting index <0.35), although clear longshore trends are visible. The majority of samples did not exhibit skewness (skewness index -0.1 to +0.1). A single sample (121f) exhibited a slight degree of positive skew (fine skew; tail of fine particles). Sample 113f, and several samples in the centre of the studied area exhibited a slight degree of negative skew (coarse skew; tail of coarse particles). The majority of samples were slightly platykurtic (kurtosis index 0.67 to 0.9), indicating a flat distribution curve. Four samples at the southern end of the beach were mesokurtic (kurtosis index 0.9 to 0.11) , indicating a peakedness close to that of a normal distribution.

The eastern part of the beach was subject to remedial work during the 2014 storms, and profile 131 marks the western limit of the artificially created berm. There is no appreciable step in grain size between the modified and unmodified parts of the beach (the boundary is indicated by a vertical grey line in Fig. 8). There is substantially greater longshore variability in sorting, skewness and kurtosis in the modified area compared to the unmodified part of the beach. However, the magnitude of these differences is very small. On average, sediments in the modified area are slightly less well sorted but the difference (approximately 0.05 ψ) is very small and almost certainly not apparent to casual observers.

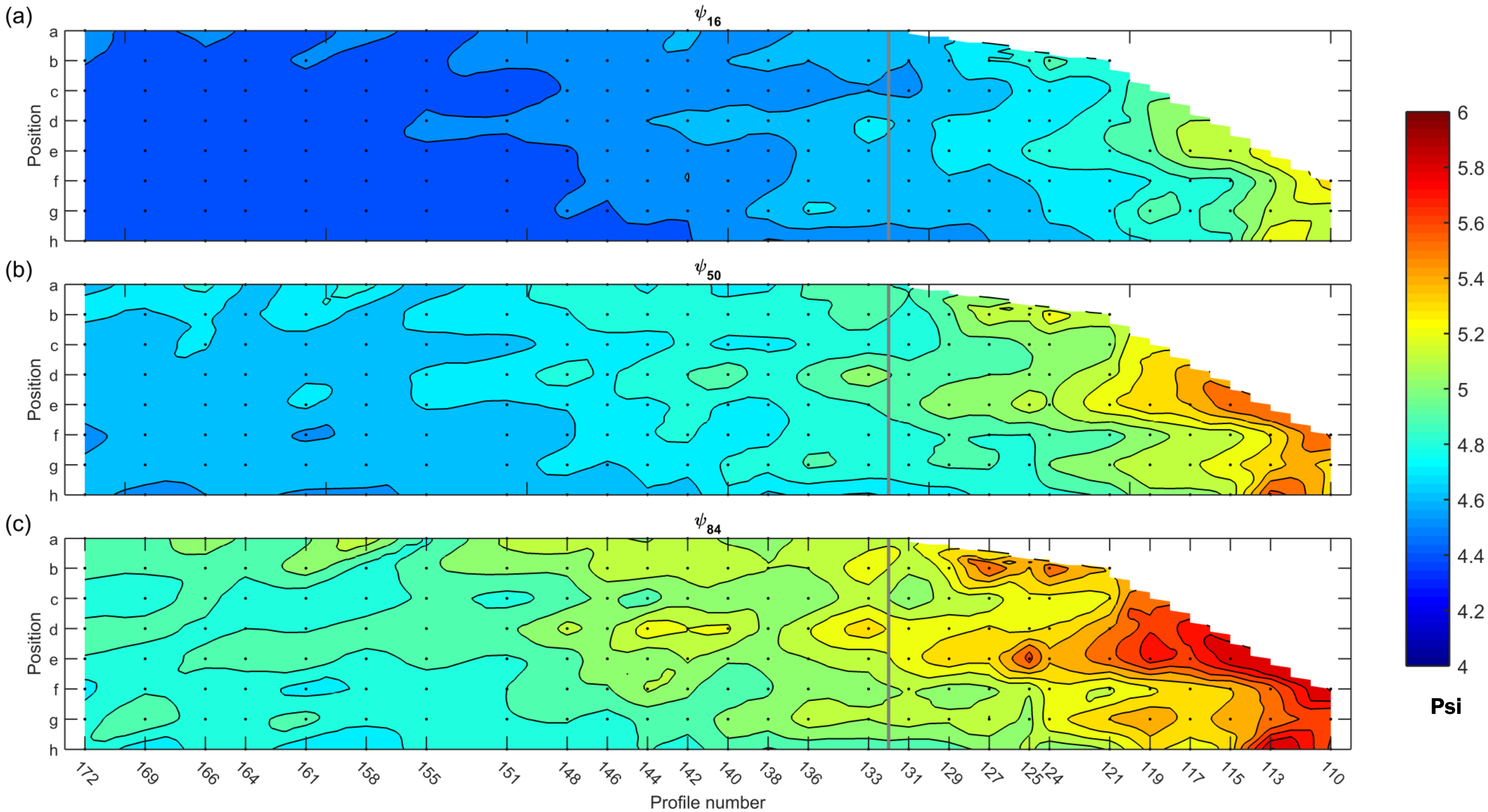


Figure 7: Isopleth map of spatial variability in key grain-size percentiles for the entire surveyed area, as measured by photographic sampling. The horizontal axis indicates position along the beach, with reference to the transverse profile numbers (which are ordered as if looking onshore). The vertical axis indicates the morphological position on the beach. Note that the horizontal and vertical axes mark relative positions and are not to scale. The vertical heavy grey line marks the boundary between the area subject to remedial works during 2014 (profiles 109-131) and the unmodified part of the beach. Dots indicate sampling positions. (a) ψ_{16}. (b) ψ_{50}. (c) ψ_{84}.

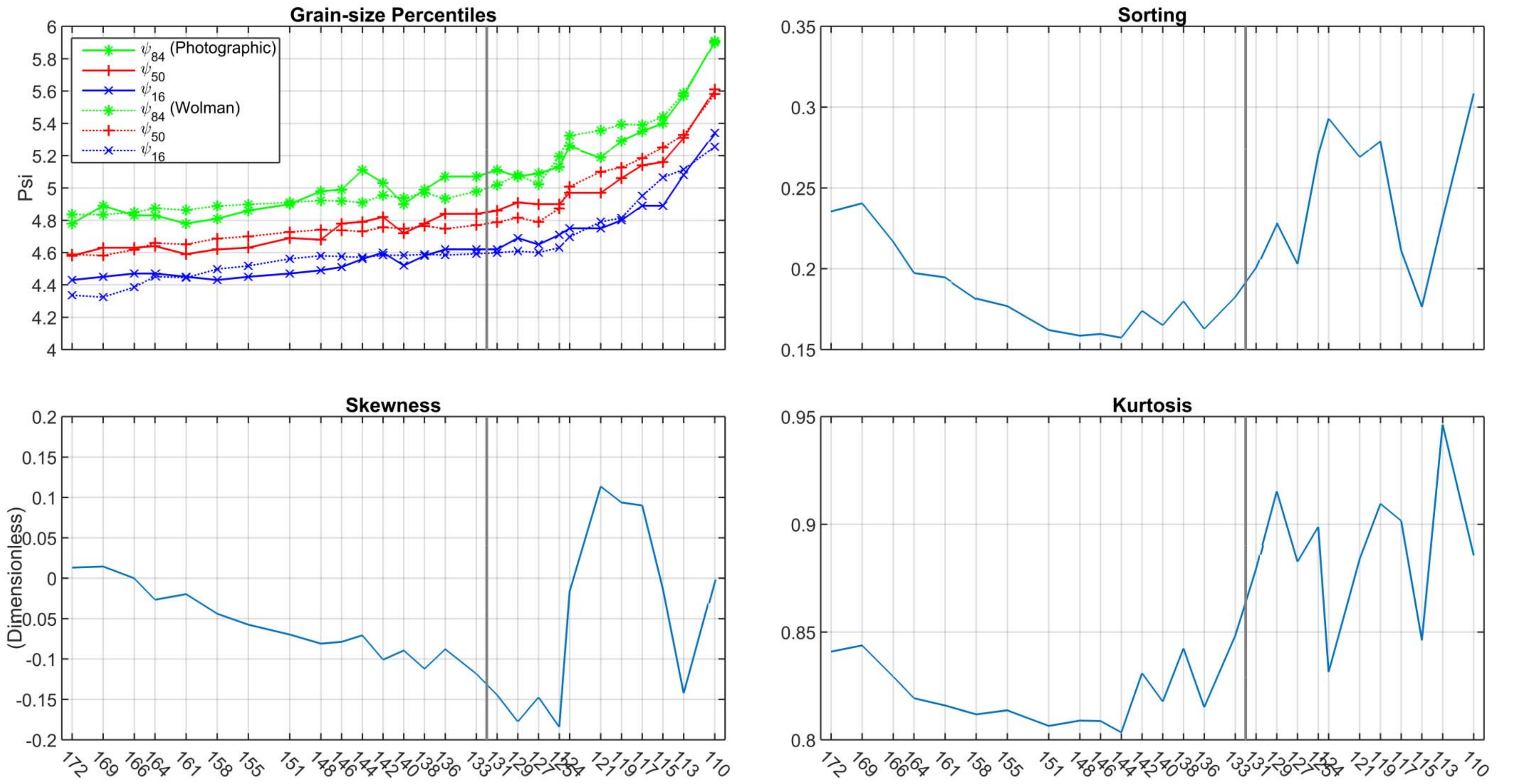


Figure 8: Longshore variability in grain-size percentiles and statistics at position f (top of main natural berm). Grain-size percentiles are presented for photographic (solid line) and 'Wolman' (dashed line) samples. Sorting, skewness and kurtosis are derived from the 'Wolman' samples. The horizontal axis indicates position along the beach, with reference to the transverse profile numbers (which are ordered as if looking onshore). The vertical heavy grey line marks the boundary between the area subject to remedial works during 2014 (profiles 109-131) and the unmodified part of the beach.

Figure 9 summarises the longshore variability in the calibrated photographic grain-size data. Once again, profiles are ordered as if looking onshore. Position h represents the seaward limit of the profiles, in the swash zone. The longitudinal pattern of grain size change is similar to that presented above with ψ_{50} on the beach face (positions e to h) declining from approximately 5.5 ψ (45 mm) to 4.5 ψ (23 mm) from east to west and without any noticeable adjustment between the modified and unmodified parts of the beach. Comparison of the cross-beach positions (a to h) indicate that the pattern of longitudinal grain size differences are generally consistent across all morphological positions on the beach. There is no appreciable step change at the limit of berm construction (marked by a vertical grey line in Fig. 9). That the lines for ψ_{16}, ψ_{50} and ψ_{84} are essentially parallel is consistent with the argument above that differences in sorting are minor along the beach.

Cross-shore variability in grain size

Figure 10 summarises the cross-shore variability in the calibrated photographic grain-size data. On most profiles there is a gradual decrease in grain size from landward to seaward. However, the absolute difference is small; the average difference between the median grain size measured at locations a and h is less than 3 mm. On most profiles the grain size at position c (top of the main sea defence ridge) is observed to be slightly smaller than those either side of it, but again this difference is small.

Within the modified section of beach (profiles 110 to 131), position e is characterised by slightly larger grain sizes than are typical for the rest of the profile. In contrast, the grain size at position f (main natural berm) is slightly lower than that typical for the profile. The average difference between the ψ_{50} grain sizes at positions e and f is 0.23 ψ (17% in mm). Whilst measurable, this amounts to an average difference of only 5.7 mm. However, there is a systematic trend in this effect, albeit with a substantial amount of variability. This is illustrated in Figure 11, which shows the difference in key grain size percentiles between locations e and f for each profile (expressed in millimetres). The same trend does not appear to be present when comparing the difference in grain size between the main artificial (position d) and natural (position f) berms.

In the absence of comparative baseline data, it is impossible to determine whether this effect is a result of the remedial work undertaken on the beach during 2014. The magnitude of the difference appears to reflect the pattern of rapidly decreasing grain size along this part of the beach and may be a naturally occurring phenomenon. However, it is notable that the difference is only present within the modified section of the beach. It should be emphasised that the absolute size of the difference is quite small, and unlikely to be noticed by the casual observer.

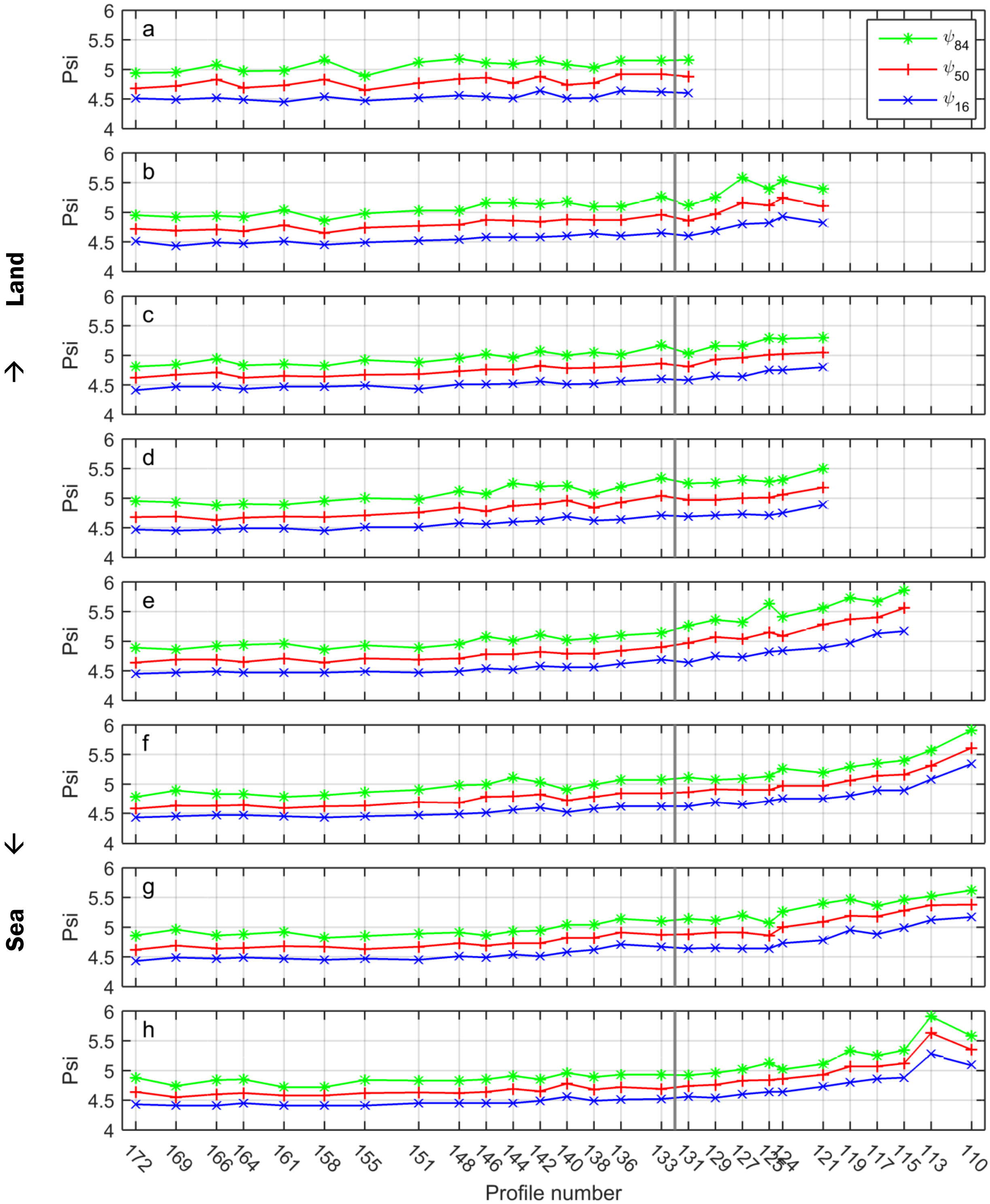


Figure 9: Longshore variability in grain-size percentiles for each of the morphological locations across the beach (a-h; Table 1), as measured by photographic sampling. The horizontal axis indicates position along the beach, with reference to the transverse profile numbers (which are ordered as if looking onshore). The vertical heavy grey line marks the boundary between the area subject to remedial works during 2014 (profiles 109-131) and the unmodified part of the beach.

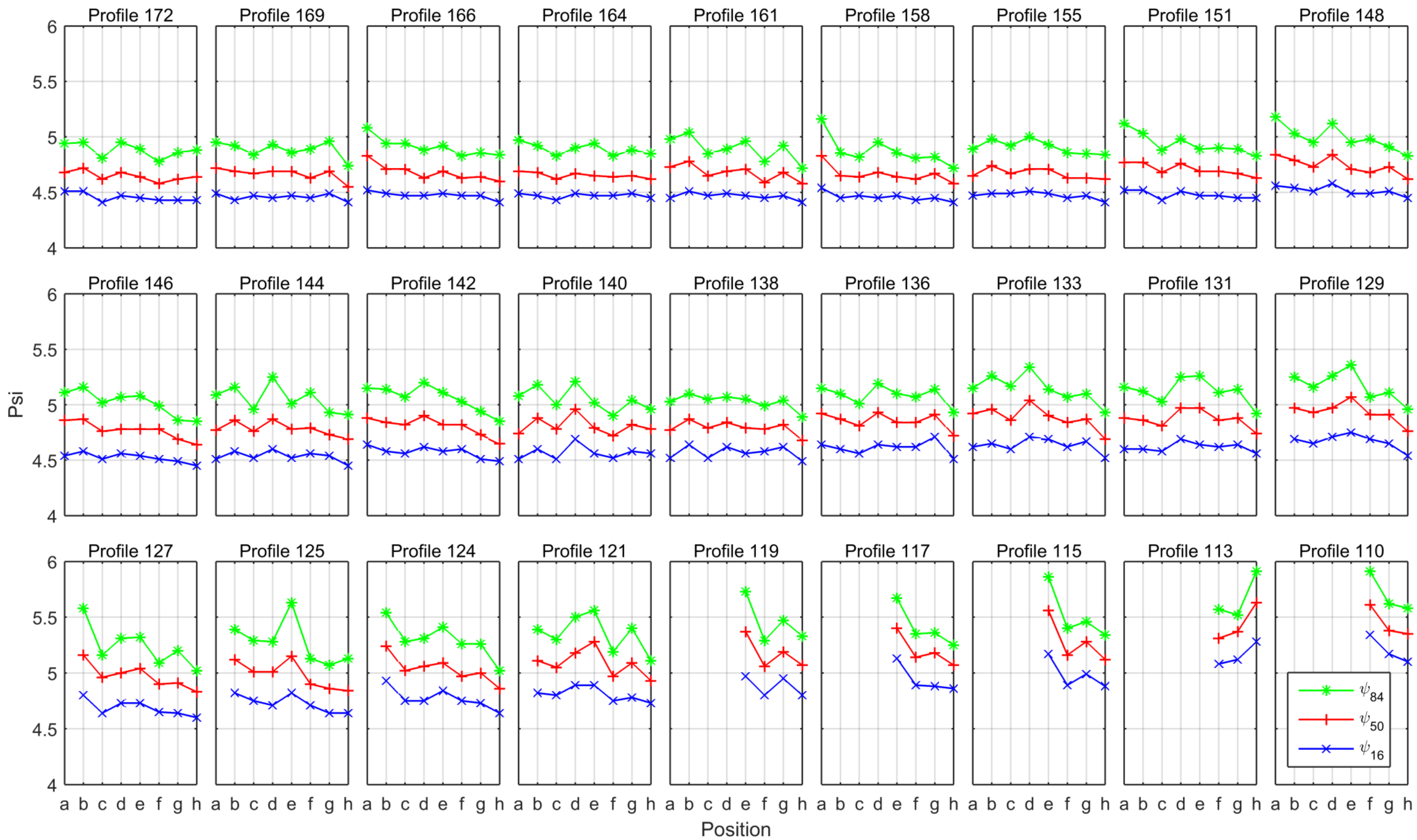


Figure 10: Cross-shore variability in grain-size percentiles, as measured by photographic sampling. Each panel represents a single transverse profile, with the horizontal axis indicating the morphological location across the beach (Table 1).

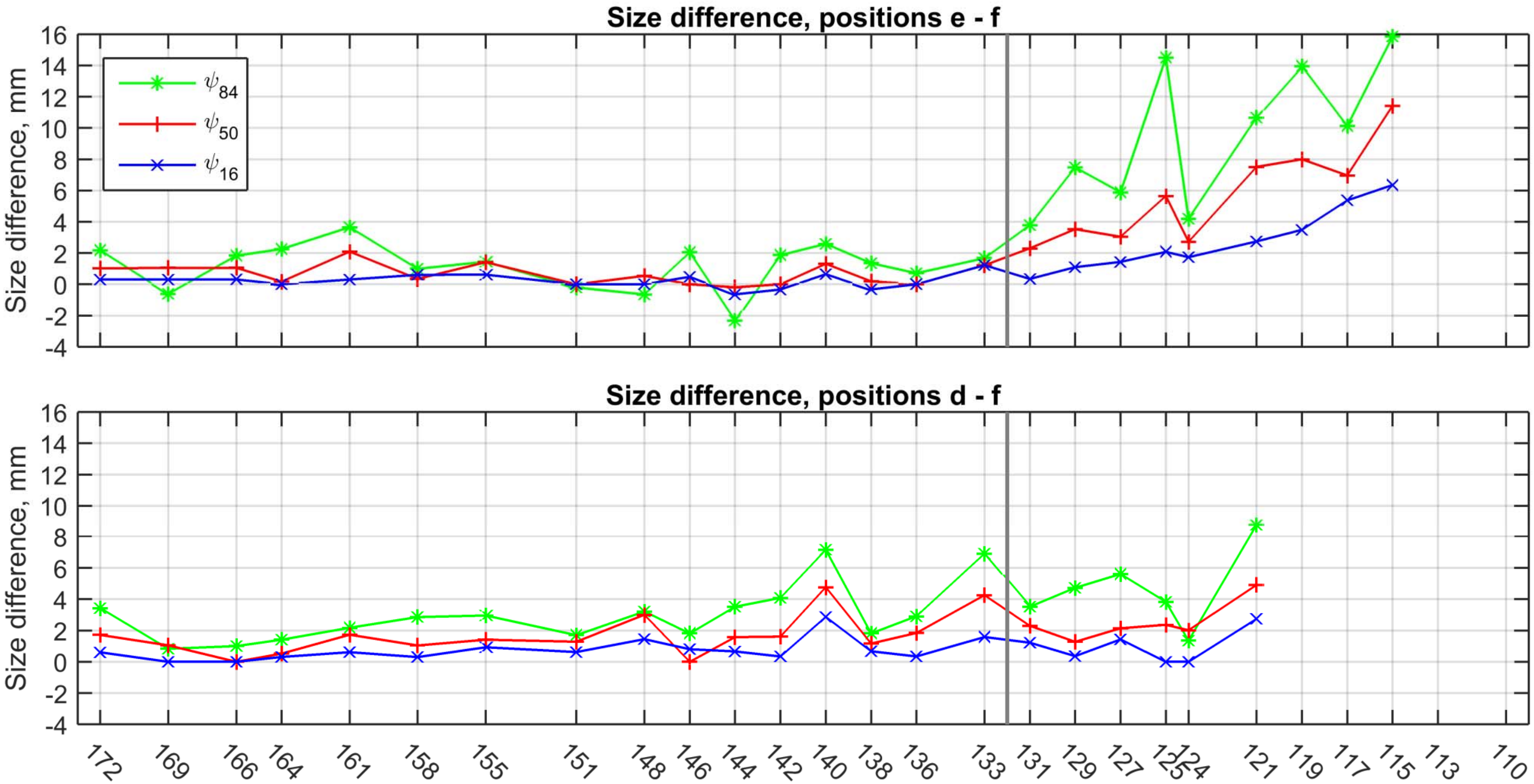


Figure 11: The difference in key grain-size percentiles measured between morphological positions e – f (natural berm) and d (artificial berm) – f. The horizontal axis indicates position along the beach, with reference to the transverse profile numbers (which are ordered as if looking onshore). The vertical heavy grey line marks the boundary between the area subject to remedial works during 2014 (profiles 109-131) and the unmodified part of the beach. The vertical scale shows the difference in grain size percentiles for the two positions, measured in millimetres.

EVALUATION OF SEDIMETRICS DIGITAL GRAVELOMETER

During development of the automated grain-sizing procedure that underpins the Digital Gravelometer software, a dataset representing a wide variety of fluvial environments was used to define the optimal algorithms and parameterisation (Graham *et al.* 2005a). It has subsequently been applied successfully within river research and management in many locations using default parameters.

As far as we are aware, this project represents the first time that the Digital Gravelometer software has been used in a study of beach gravels. During the processing of the images it became clear that the default parameters were not optimised for the Chesil Beach sediments. This resulted in excessive over-segmentation of the images. It was therefore necessary to undertake some experimentation to define a set of parameters that produced acceptable levels of over- and under-segmentation. This was defined on the basis of a visual inspection of the images by an experienced operator (David Graham).

Once all of the images had been processed, manual examination of the segmented images highlighted that – even with the adjusted parameters – there was likely to be a significant underestimation of grain-size distribution percentiles. This was a result of both oversegmentation of some grains and the measurement of grains that were partially hidden by other grains (i.e. grains that are not in the top-most layer). Some degree of over- and under-segmentation effectively cancel one another out in images of relatively heterogeneous sediment (such as those from fluvial environments). Furthermore, the errors associated with grain burial, hiding and imbrication have been shown to be a small component of the total error (and not separable from the total error) in fluvial environments (Graham *et al.* 2010). However, for the well sorted sediments present on Chesil Beach, these issues manifested themselves as relatively large errors when compared with the 'Wolman' sample control data. These were particularly evident in the lower grain-size percentiles, with the ψ_{16} having a RMS error of 0.445 ψ, equivalent to 36% when expressed in mm. Fortunately, these are systematic errors, so they can be corrected via a calibration using linear least squares regression (as described above). This reduced the RMS error to around 0.07 ψ for all key percentiles (around 5% when expressed in mm).

Although the errors in calibrated grain-size percentiles are small (Figure 6, Table 3), it was not considered appropriate to use them to derive distribution statistics (sorting, skewness, kurtosis). This is because these statistics are sensitive to errors in percentile estimates and is why we used the Wolman samples to derive them (Figure 8).

CONCLUSION

This project set out to provide a comprehensive assessment of the grain-size characteristics of the eastern end of Chesil Beach following the winter 2013/2014 storms and subsequent remediation works. It was the first project to apply photographic sampling and automated extraction of grain size information using Sedimetrics® Digital Gravelometer™ in a beach environment.

This project was established with three aims, which are considered in turn.

Aim 1: to evaluate the effectiveness of photographic sampling, combined with analysis using Sedimetrics® Digital Gravelometer™ software, in beach monitoring projects

- Photographic sampling, combined with the use of Sedimetrics® Digital Gravelometer™ software for extracting grain-size information, proved an effective means of data capture. Photographic data collection time was less than 5 minutes per sample (versus 20-30 minutes for a conventional 'Wolman' sample), representing a >400% efficiency improvement during fieldwork.
- The software was originally developed for use in river environments, and some tuning of the image processing parameters used to extract grain-size information from the images was required to optimise them for the Chesil Beach environment. Calibration was also required to correct for systematic biases. Following calibration, the uncertainty in key size indices was around 5% (RMS error expressed in millimetres), which is comparable to that achieved from conventional sampling methods.
- Given the success of the photographic sampling method at Chesil Beach, it is anticipated that it may find wider application in beach monitoring studies. It is recommended that a similar tuning and calibration procedure be applied in any future applications, at least until a transferable set of processing and calibration parameters have been established via work at a variety of sites. Field and processing operatives should be appropriately trained to ensure the reliability and consistency of results.

Aim 2: to determine whether the beach management interventions have significantly modified the grain-size structure of the beach.

- A sharp progressive decrease in grain size was observed over the first c. 0.5 km from the eastern limit of the beach at Chesil Cove. The rate of decrease gradually levelled off in a westerly direction, until there was little longitudinal change in grain size over the most westerly 0.5 km of the studied beach. There were some systematic longitudinal changes in the overall 'shape' of the grain size distributions (as measured by sorting, skewness and kurtosis), but these were of a very small magnitude.
- A slight decrease in grain size from the landward to seaward side of the beach was observed, a pattern that was consistent throughout the study area.

- Within the modified part of the beach, there was evidence of small depression in grain size on the natural berm relative to the adjacent samples. The magnitude of this effect decreased with distance from Chesil Cove.
- There is little evidence that the beach management interventions undertaken during 2014 have had a significant impact on the grain-size structure of the beach. Although the interventions occurred in the part of the beach with the steepest longitudinal grain-size gradient, there is no evidence of a discontinuity in grain size between the modified and unmodified parts of the beach. There are some differences in the 'shape' of the grain-size distributions between the modified and unmodified parts of the beach. There are also some small cross-beach variations in grain size in the modified area. However, the magnitude of these effects is very small and only detectable via detailed and systematic sampling. In the absence of pre-existing baseline data it is impossible to determine whether these differences result from the beach management works; they may simply reflect the more dynamic nature of this part of the beach or its natural recovery following the storms.

Aim 3: to obtain baseline data against which future surveys can be compared.

- Grain size measurements were made on 28 transverse profiles along a 2.9 km length of the beach stretching between Chesil Cove (to the east) and the Chesil Beach Visitor Centre (to the west). This included the approximately 1 km length of beach subject to remediation works in 2014. The majority of the samples were collected photographically and processed using the Sedimetrics® Digital Gravelometer™ software to extract grain-size information. Additional samples were collected using the conventional 'Wolman' sampling method for data validation and quality control purposes.
- The project generated a dataset of c. 1000 images collected at 189 discrete locations, and for which detailed grain size information is available. There are an additional 27 detailed grain-size distributions collected via conventional 'Wolman' sampling.
- Now that a detailed baseline dataset has been established, it is recommended that regular repeat grain-size surveys be undertaken to evaluate the long term response and recovery of the beach following the storms of winter 2013/2014. This monitoring work could be undertaken on a subset of the profiles examined in this report.

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APPENDIX 1: SAMPLE LOCATIONS

GPS easting and northing coordinates of all sampled locations.

Profile		Position															
EA code	Short code	a		b		c		d		e		f		g		h	
		E	N	E	N	E	N	E	N	E	N	E	N	E	N	E	N
6a00109	**109**													68379	73164	68370	73156
6a00110	**110**											68381	73225	68374	73220	68369	73218
6a00113	**113**											68367	73336	68354	73334	68349	73333
6a00115	**115**									68334	73445	68322	73441	68316	73435	68310	73434
6a00117	**117**									68294	73543	68277	73537	68271	73533	68265	73534
6a00119	**119**									68261	73608	68244	73595	68232	73590	68230	73589
6a00121	**121**			68226	73705	68218	73701	68207	73693	68202	73689	68187	73680	68171	73673	68167	73671
6a00124	**124**			68152	73807	68138	73796	68129	73790	68119	73783	68107	73771	68096	73765	68091	73762
6a00125	**125**			68118	73844	68106	73830	68098	73824	68090	73814	68080	73804	68067	73797	68056	73801
6a00127	**127**			68058	73921	68042	73903	68034	73896	68028	73888	68014	73876	68003	73866	68001	73865
6a00129	**129**			67992	73982	67978	73972	67972	73964	67963	73956	67952	73945	67941	73933	67940	73930
6a00131	**131**	67939	74066	67929	74053	67920	74045	67908	74032	67895	74024	67890	74016	67880	74002	67880	73996
6a00133	**133**	67895	74116	67886	74109	67868	74093	67857	74083	67847	74073	67840	74069	67832	74058	67827	74053
6a00136	**136**	67810	74211	67800	74198	67787	74184	67776	74173	67764	74166	67755	74159	67747	74152	67742	74149
6a00138	**138**	67755	74275	67746	74260	67729	74248	67721	74237	67709	74233	67698	74224	67689	74216	67685	74215
6a00140	**140**	67696	74333	67688	74321	67673	74313	67662	74300	67652	74295	67642	74289	67634	74280	67629	74277
6a00142	**142**	67626	74420	67610	74413	67598	74396	67587	74387	67576	74380	67568	74374	67559	74367	67557	74361
6a00144	**144**	67583	74468	67467	74460	67552	74448	67542	74439	67530	74430	67522	74425	67512	74419	67505	74419
6a00146	**146**	67523	74533	67510	74521	67500	74509	67487	74499	67477	74493	67471	74485	67463	74479	67457	74472
6a00148	**148**	67456	74604	67443	74596	67430	74586	67417	74574	67409	74568	67400	74564	67393	74555	67390	74548
6a00151	**151**	67359	74713	67343	74703	67333	74696	67323	74682	67314	74674	67364	74669	67297	74662	67293	74658
6a00155	**155**	67224	74858	67209	74854	67199	74843	67189	74834	67181	74626	67172	74817	67161	74809	67158	74809
6a00158	**158**	67132	74969	67115	74955	67105	74949	67093	74937	67084	74929	67077	74922	67067	74913	67064	74911
6a00161	**161**	67023	75085	67008	75076	66997	75065	66989	75057	66976	75048	66969	75041	66956	75032	66954	75027
6a00164	**164**	66932	75182	66920	75169	66910	75156	66901	75147	66890	75138	66886	75131	66876	75125	66871	75118
6a00166	**166**	66860	75247	66853	75237	66843	75230	66832	75218	66824	75212	66817	75203	66805	75196	66802	75190
6a00169	**169**	66763	75360	66749	75350	66736	75341	66729	75332	66717	75323	66710	75316	66702	75308	66697	75303
6a00172	**172**	66660	75464	66646	75453	66634	75440	66627	75434	66618	75426	66609	75420	66602	75408	66596	75406

APPENDIX 2: SEDIMETRICS® DIGITAL GRAVELOMETER™ IMAGE COLLECTION CHECKLIST

Sedimetrics® Digital Gravelometer^{tm}: Image collection checklist

This checklist may be printed and used as guide when collecting images in the field.

Sampling area:

- There must be four markers in each image defining the corners of a rectangular sampling area of known dimensions
- Make the shape of the sampling area rectangular to reflect the aspect ratio of your image (usually 4:3)
- The sampling area should be small enough that the diameter of the smallest grain of interest is more than 23 pixels in the image

Composing the photograph:

- Nothing other than sediment and the control markers should appear in the image (no frame etc)
- All grains that intersect the boundary of the sampling area must be entirely contained within the image (i.e. ensure that the photograph is bigger than the sampling area)
- Avoid using a very wide angle lens setting – raise the camera height instead
- Ideally the ground surface should be dry (dampness in the interstices is fine)

Lighting:

- The sampling area must be shaded from direct sunlight
- The flash should be set to 'always on'
- If possible, use a camera-mounted external flash to increase the overhead lighting intensity
- Try to ensure even illumination – this is easier if the camera is held higher

Camera settings:

- Set the camera pixel resolution to maximum and store the images as JPEG using the minimum compression supported
- All other parameters should be left at their default values (other than the flash)

Taking the photograph:

- The camera may be held in the hand
- Try to take the photograph as vertically as possible

Treatment of the images:

- After downloading the images from the camera, don't modify them in any other software – this may degrade their quality and result in loss of metadata

APPENDIX 3: SUMMARY OF ACCEPTED AND REJECTED IMAGES

The table below indicates – for each profile and morphological position – which images were accepted and rejected at the visual inspection stage of image processing. Five images were collected at most sampling positions (a few positions had 4 or 6 photographs). Rejected images are indicated by a 'x' and accepted images by a number. For example, '123x5' indicates that image 4 was rejected and images 1, 2, 3 and 5 accepted. A total of 948 images were collected, of which 62 were rejected (6.5%).

Profile	Position							
	a	b	c	d	e	f	g	h
109							xxxxx	xxxxx
110						12345	12345	12345
113						12345	12345	12345
115					12345	12345	12345	12345
117					12345	xx3x5	x2345	123456
119					x234	12345	123	1x3xx
121		12345	12345	12345	12x45	12345	12345	12345
124		12345	123456	12345	12345	12345	12345	12345
125		12345	12345	12345	12345	12345	12345	12x45
127		12345	12345	12345	12345	12345	12345	12345
129		12345	12345	12345	12345	1x345	12345	12345
131	12345	12345	12345	12345	12345	12345	12345	12345
133	12345	12345	12345	12345	12345	12x45	1x34	12345
136	12345	12345	12345	12345	12345	12345	12345	12345
138	12345	12345	12345	12345	12345	12345	12345	12x45
140	12345	x234	12345	1x345	12345	12345	12345	12345
142	12345	12345	12345	1234x	12345	12345	x2345	12345
144	12345	12345	12345	1234	12345	12345	12345	12345
146	1x345	12345	12345	12345	1x345	1x34x	12345	12345
148	12345	1234x	1234x	12345	1234x	1x345	123456	12x45
151	12345	12345	12345	1234	12345	1234	12345	x23x5
155	12345	12345	1234	12345	12x45	12345	12345	12345
158	123456	12345	12345	12345	12345	12345	12345	12345
161	12345	x2345	12345	12x45	12345	12345	123456	1234x
164	12345	123x5	12345	12345	12345	12345	xx34	1xx45
166	12345	1234x	1x34	12345	12345	12345	x234	123x5
169	12345	12345	1x345	12345	12345	1x345	12xx5	12345
172	12345	123x5	12345	12345	12345	12345	x23xx	12xx5

APPENDIX 4: 'WOLMAN' AND CALIBRATED PHOTOGRAPHIC PERCENTILES FOR POSITION F

Profile	'Wolman' percentiles			Calibrated photographic percentiles			Error in calibrated percentiles		
	ψ_{16}	ψ_{50}	ψ_{84}	ψ_{16}	ψ_{50}	ψ_{84}	ψ_{16}	ψ_{50}	ψ_{84}
110	5.26	5.58	5.90	5.34	5.61	5.91	0.08	0.03	0.01
113	5.11	5.33	5.58	5.08	5.31	5.57	-0.04	-0.01	-0.01
115	5.06	5.25	5.44	4.89	5.16	5.40	-0.17	-0.09	-0.04
117	4.95	5.18	5.39	4.89	5.14	5.35	-0.06	-0.05	-0.04
119	4.81	5.13	5.39	4.80	5.06	5.29	-0.01	-0.07	-0.11
121	4.79	5.10	5.36	4.75	4.97	5.19	-0.04	-0.13	-0.16
124	4.70	5.01	5.32	4.75	4.97	5.26	0.05	-0.04	-0.07
125	4.63	4.87	5.19	4.71	4.90	5.13	0.08	0.02	-0.07
127	4.60	4.79	5.02	4.65	4.90	5.09	0.06	0.11	0.06
129	4.61	4.82	5.08	4.69	4.91	5.07	0.08	0.09	-0.01
131	4.60	4.79	5.02	4.62	4.86	5.11	0.02	0.07	0.09
133	4.59	4.77	4.98	4.62	4.84	5.07	0.03	0.08	0.09
136	4.58	4.75	4.93	4.62	4.84	5.07	0.03	0.10	0.13
138	4.59	4.76	4.97	4.58	4.78	4.99	-0.01	0.02	0.02
140	4.58	4.75	4.94	4.53	4.72	4.90	-0.06	-0.03	-0.04
142	4.58	4.76	4.96	4.60	4.82	5.03	0.02	0.06	0.08
144	4.57	4.73	4.91	4.56	4.79	5.11	-0.01	0.06	0.20
146	4.58	4.74	4.92	4.51	4.78	4.99	-0.07	0.04	0.07
148	4.58	4.74	4.92	4.49	4.68	4.98	-0.09	-0.06	0.06
151	4.56	4.73	4.91	4.47	4.69	4.90	-0.09	-0.03	-0.02
155	4.52	4.70	4.90	4.45	4.63	4.86	-0.07	-0.07	-0.03
158	4.50	4.69	4.89	4.43	4.62	4.81	-0.06	-0.07	-0.08
161	4.44	4.65	4.86	4.45	4.59	4.78	0.01	-0.06	-0.08
164	4.45	4.66	4.88	4.47	4.64	4.83	0.02	-0.02	-0.04
166	4.39	4.62	4.85	4.47	4.63	4.83	0.08	0.01	-0.02
169	4.32	4.58	4.84	4.45	4.63	4.89	0.13	0.05	0.05
172	4.34	4.59	4.84	4.43	4.58	4.78	0.10	-0.01	-0.06

APPENDICES PROVIDED ELECTRONICALLY

Appendix 5: Digital Gravelometer reports for each sample

Appendix 6: Digital version of all images and Digital Gravelometer project files

Appendix 7: Excel data file