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Image analysis for measuring stratigraphy in sand-gravel laboratory experiments

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Abstract

Measurements of spatial and temporal changes in the grain size distribution are crucial to improving the modelling of sediment transport and associated grain size-selective processes. We present three complementary techniques to determine such variations in the grain size distribution in sand-gravel laboratory experiments, as well as the resulting stratigraphy: (1) particle colouring, (2) removal of sediment layers, and (3) image analysis. The resulting stratigraphy measurement method has been evaluated in two sets of experiments. In both sets three grain size fractions within the range of coarse sand to fine gravel were painted in different colours. Sediment layers are removed using a wet vacuum cleaner. Subsequently areal images are taken of the surface of each layer. The areal fraction content, i.e. the relative presence of each size fraction over the bed surface, is determined using a colour segmentation algorithm which provides the areal fraction content of a specific colour (i.e., grain size) covering the bed surface. Particle colouring is not only beneficial to this type of image analysis but also observing and understanding grain size-selective processes. The stratigraphy based on areal fractions is measured with sufficient accuracy. Other advantages of the proposed stratigraphy measurement technique are: (a) rapid collection and processing of a large amount of data, (b) very high spatial density of information on the grain size distribution (so far unequalled in other methods), (c) the lack of disturbances to the bed surface, (d) only minor disturbances to the substrate due to the removal of sediment layers, and (e) the possibility to return a sediment layer at its original elevation and continue the flume experiment. The areal fractions can be converted into volumetric fractions using a conversion model. The proposed empirical conversion model is based on a comparison between the photogrammetry results and dry sieve analysis.

1   Introduction

Spatial and temporal variations in the grain size distribution of the river bed surface are the outcome of grain size-selective processes and/or abrasion (e.g., Parker, 1991a, b). Having insight in such variations is crucial to understanding a river system and pre-
dicting the autonomous morphodynamic behaviour of a river system, as well as the morphodynamic effects of (future) human interventions. Spatial variations in the grain size distribution are usually indicated with the term sorting. An example of streamwise sorting is downstream fining, which is characterized by a decrease in mean grain size in streamwise direction. Downstream fining is usually attributed to abrasion and grain
size-selective transport (e.g., Parker, 1991a, b). An example of sorting in the vertical direction is armouring. Two types of armouring can be distinguished: a static armour layer and a mobile armour layer (e.g., Parker and Klingeman, 1982; Jain, 1990). A static armour forms at low shear stresses when the finer grains are mobile while the coarser ones are not, which under limited sediment supply conditions results in
a coarsening of the bed surface. This coarsening prevents the underlying finer sediment from being entrained by the flow. Instead a mobile armour develops at higher shear stresses at which also the coarser grains are transported and a coarse surface layer is then needed to enable the sediment supplied to a reach from upstream to be transported downstream. Dune sorting is another example of vertical sorting, and orig-
inates through (a) avalanching of grains down the bedform lee face which results in an upward fining pattern (e.g., Bagnold, 1941; Allen, 1965) and (b) selective or partial transport, which can result in the formation of a coarse layer underneath the migrating dunes consisting of the less mobile sediment (e.g., Zanke, 1976; Blom et al., 2003). Monitoring techniques that allow for rapid and non-destructive measurement of sort-
ing and the resulting stratigraphy are required to better understand and predict grain size-selective river processes and the river bed evolution. In this study we focus on the development of such a technique to measure the stratigraphy in sand-gravel laboratory experiments.

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Before moving to techniques measuring the stratigraphy, we first discuss measuring the grain size distribution of the bed surface. An overview of earlier methods to measure the grain size distribution of the bed surface such as sieving and grid sampling were presented by Kellerhals and Bray (1971) and wax sampling by Diplas and Sutherland

⁵ (1988). These procedures are commonly used to collect samples from a gravel bed surface. Wax sampling generally is limited to coarser mixtures because of the limited penetration of liquid wax in the pores for finer particles. In the case of grid sampling the grains lying below the grid points constitute the sample. Therefore application of the method is limited to collecting mostly coarse sediment. The major drawback of these

¹⁰ techniques is their time-consuming procedure for determining the grain size distribution due to the time required for taking the samples as well as for sieve analyses.

It is worth noticing that particularly in the case of determining the grain size distribution of the bed surface the results of the areal sampling techniques (e.g., wax or clay sampling, image analysis) are not equivalent to the outcomes of sieving. A conversion

¹⁵ model (e.g., Kellerhals and Bray, 1971; Diplas and Sutherland, 1988; Fraccarollo and Marion, 1995) is then needed to convert areal fraction contents into volume fraction contents.

In the last years image analysis techniques have emerged as a reliable, practical and non-destructive procedure (McEwan et al., 2000; Sime and Ferguson, 2003; Graham

²⁰ et al., 2005a, b, 2010). The first image processing techniques still required laborious work through manual measuring on the images, overlaying transparent grids on the image to count the grains (Adam, 1979) or manually digitizing large prints to delineate the particle edges (Ibbeken and Scheyler, 1986). The development of fully automated methods was obviously connected to the advancements in computer technology. The

²⁵ common automated procedures are based on detecting the edges of individual grains and determining the particle dimensions (McEwan et al., 2000; Sime and Ferguson, 2003; Graham et al., 2005a, b, 2010). Application of these techniques to an extensive variety of grain shapes, lithotypes, texture, and sizes still needs to be assessed (Graham et al., 2005a). The limiting accuracy for the finer particles is controlled by the

resolution of the image. Graham et al. (2010) remark that even when accounting for the improvement in the resolution of digital cameras, there will be constraints in the accurate identification of the edges of the smaller grains. A compromise between the minimum grain size that can be detected and the surface area covered by an image is

5 required.

The restriction to the minimum grain size that can be detected within a certain surface area covered by the image was avoided by combining the image analysis with particle colouring (Wilcock and McArdell, 1993, 1997; Wu and Yang, 2004). In their laboratory experiments the detection of the edges of the particles is replaced by the detection of

10 colour. This has enabled application of image analysis to smaller grain sizes: sands and fine gravels (Wilcock and McArdell, 1993, 1997; Wu and Yang, 2004). Wilcock and McArdell (1993, 1997) introduced the so-called Bed Of Many Colours (BOMC) to evaluate the grain size distribution of the bed surface. They placed a grid over the images and the colours of the grains positioned on the grid intersections were registered. Wu

15 and Yang (2004) modified the procedure of Wilcock and McArdell (1993, 1997) and counted the number of grains present inside the grid cells in images taken at different times to also allow for the detection of grain mobility. An improvement in image analysis combined with particle colouring was suggested by Heays et al. (2010a, b). Their approach consists of recognizing sediment colours by setting RGB colour thresholds

20 in order to detect a specific colour and the isolation of grain clusters based on their colour. No longer detecting individual grains allows to automatically and rapidly determine the areal fraction contents covered by each colour. Yet, the measurement of other parameters such as particle velocity (Wu and Yang, 2004; Heays et al., 2010a, b) still requires to analyse individual or small groups of particles.

25 A large variety of samplers and box cores is available to determine the stratigraphy of a deposit formed out of cohesive sediment, whereas measuring the stratigraphy of a non-cohesive deposit has always been a challenging task as the sediment sample drops from the box core unless the box is closed or the sample is fixed with some substance. The combination of using a box core with sieve analysis is a common method

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to obtain information about the vertical variation of the grain size distribution. Jonasson and Olausson (1966) proposed two devices with different closing mechanisms for sampling the uppermost layers of marine sediment. The method does not allow for undisturbed samples and the operation procedure together with the devices' large dimensions limit their use to field surveys. Blom et al. (2003) developed a box coring method to analyse the vertical sorting within a sand-gravel bed under laboratory conditions. The sampler is shaped as a rectangular box which is closed using a rectangular plate that is pushed obliquely into the sample. After it is closed, the box is removed from the bed. Some grains are pushed down when pushing the box into the bed and when pushing down the closing device.

In order to take samples out of non-cohesive sediment in a less disturbed way, many methods are based on pouring a liquid substance inside the pores and letting the sample solidify. In this manner the particles are attached to each other and to the sampling tool (i.e., box corer or probe pipe) creating a sample that can be lifted from the bed in one piece. Various fixing methods are used: wax coring (Sibanda et al., 2000); freezing samples by liquid nitrogen (Gomez, 1983; Pallara et al., 2006) or liquid carbon dioxide (Walkotten, 1976; Carling and Reader, 1981), and epoxy resin (Alexander et al., 2001). The resulting sample is then analysed melting the fixing substance (Walkotten, 1976; Gomez, 1983; Sibanda et al., 2000) or first cutting sections of the sample at various elevations (Carling and Reader, 1981) and sieving the sediment.

A final option to define the stratigraphy in laboratory experiments consists of removing separate layers from the deposit and subsequently analyse the grain size distribution through sieve analysis. This was realized by means of siphoning of sand layers by Ribberink (1987) or, for a coarser sand-gravel mixture, removing the sediment layers using a spatula by Kleinhans (2005).

The objective of this paper is to present a technique for measuring the stratigraphy of a deposit in laboratory sand-gravel experiments. The method combines three of the above techniques: (1) particle colouring, (2) removal of thin sediment layers, and (3) image analysis. The image analysis is based on the approach by Heays et al. (2010a,

b). The difference lies in the fact that (a) we extend the image analysis to analysing the grain size distribution of the substrate rather than only the bed surface, (b) we use another algorithm for colour detection, and (c) we work with the wider subset of colours of the Lab colour space. In Heays et al. (2010a, b) colour detection is based on
the isolation of a limited number of colours (equal to the number of grain sizes), with consequently the loss or nondetection of pixels (e.g., darker grains due to shadows). Instead our approach is based on colour segmentation and therefore assigns a colour to each pixel in the image.

2   The stratigraphy measurement technique

In this section we present the three steps in the new method to measure the stratigraphy of a coloured sand-gravel deposit: (1) particle colouring, (2) removal of thin sediment layers, and (3) image analysis. The deposit used to assess the applicability of the stratigraphy measurement technique is a Gilbert or foreset-dominated delta formed in laboratory experiments (Chavarrías et al., 2013). A Gilbert delta (Fig. 1) is formed where (a) a river flows into a deep basin such as a lake or an ocean, and (b) sediment deposition is dominated by avalanches over its steep slip face. Its stratigraphy consists of three parts (Gilbert, 1885): (a) a topset that forms as a result of deposition over the fluvial reach (b) a foreset that forms as a result of avalanches of grains (i.e. grain flows) over a steep lee face, and (c) a bottomset that forms due to fine sediment that deposits downstream from the foreset as a result of grain fall. The avalanches down the steep slope of the delta front typically result in an upward fining profile.

In a drained laboratory flume areal images of the Gilbert delta were taken from above at different elevations of its deposit to determine its stratigraphy. These elevations correspond to the top of layers of 1 cm thickness that were removed one by one using a wet vacuum cleaner. The grain size distribution of the surface of each sediment layer is analysed through image analysis. We compare the results of the image analysis to the results of sieve analysis to assess the image analysis method.

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2.1 Particle colouring

The sand-gravel deposit was composed of three well-sorted grain size fractions within the range of coarse sand to fine gravel. The grain size fractions were non-overlapping to facilitate the sieve analysis, which is required to evaluate the image analysis technique

5 (Fig. 2). The original sediment mixture is composed of a fine size fraction ($D_{50,1}$ = 1.05 mm), a medium size fraction ($D_{50,2}$ = 2.13 mm) and a coarse size fraction ($D_{50,3}$ = 4.32 mm). The grains were coloured with a common paint for walls using a concrete mixer. Each size fraction was coloured twice to obtain a resistant and bright colour and to fully coat the grains with paint. Sieve analysis was performed to determine the

10 grain size distribution of the painted sediment. Only little difference between the grain size distribution of the original and the painted grain size fractions is found (Fig. 2). The median grain sizes of the painted fractions are: $D_{50,1P}$ = 1.04 mm (fine fraction, blue), $D_{50,2P}$ = 2.19 mm (medium fraction, red) and $D_{50,3P}$ = 4.36 mm (coarse fraction, yellow).

15 ## 2.2 Removal of sediment layers

The water was drained from the flume once the experiment was stopped. The sampling procedure was started when the bed was dry. Two metal sheets with a thickness of 2 mm, a width of 0.39 m and a height of 0.30 m were driven along the edges of the sampling area into the delta deposit to support the sediment faces while thin sediment

20 layers in between the metal sheets were removed (Fig. 3).
A rigid plexiglas sampling grid was placed on the bed surface and was used to divide the reach into patches (Fig. 4). This subdivision of the reach was introduced to enable a comparison of a local grain size distribution determined through image analysis with the one determined through sieving. The plexiglas grid and the sieve analysis are only

25 required when assessing the image analysis procedure and to determine the method for converting areal fractions into volumetric ones. Please note that once the conversion method is clear, the sampling grid is no longer required and an entire thin sediment

layer can be removed at once without using the grid. A grid with a vertical grid size of 1 cm was indicated on the glass side walls of the flume as an aid to removing the 1 cm sediment layers. We took areal images of the deposit within each grid cell. After this a 1 cm sediment layer was removed from each grid cell and later sieved. Subsequently the camera position was lowered by 1 cm and the full procedure was repeated until reaching the initial bed profile. We excluded the grid cells of the reach bordering the metal sheets from the analysis as the sediment in that area may have been disturbed by driving the metal sheets into the bed.

The 1 cm sediment layers were removed using a wet vacuum cleaner (Fig. 5). The vacuum nozzle was placed at a certain distance from the surface of the deposit to extract the sediment. The sediment extracted from each grid cell was collected from the vacuum cleaner cylinder, and stored for sieve analysis. The cylinder was created with a filter net having a mesh smaller than the finest fraction. This was done to reduce the time consumed to collect the sediment inside the vacuum cleaner. If continuation of an experiment is required, the removed sediment patches can be placed back separately at the original elevations of the deposit after sampling.

2.3   Image analysis

The areal images taken during the experiments are processed with an image analysis algorithm that is written using Matlab. The code is based on colour segmentation and provides the areal fraction content of a surface area covered by a certain colour, i.e., a certain grain size (Fig. 6). The camera lens used, the Canon EF-S 18–55 mm IS f/3.5–5.6 wide-angle to mild telephoto, has very low geometric distortions. The barrel distortion is 3.35 % at a focal length of 18 mm, which means that at the applied focal length of 55 mm the barrel distortion is lower than this value. The pincushion distortion at a focal length of 55 mm is 0.389 %. For these reasons we decided not to correct the images for the geometric distortions.

A preparatory step in the procedure concerns cropping of the images and the detection of cluster centre values. Each cluster centre corresponds to a colour (i.e. grain

size) and indicates the mean values of its colour coordinates in colour space. In other words, if we have N grain size fractions, we define N cluster centres. These cluster centres are determined analysing a limited number of images (in our case 5 % of all images) using a Matlab demo script that was adapted by the authors. The colours are detected automatically using k-means clustering while imposing the number of colours. We consider images in which the presence of each colour is at least higher than 10 % to obtain suitable cluster centres thus allowing for a proper colour segmentation.

The procedure for the initial analysis of the chosen images using k-means clustering is summarized in the following steps:

1. image reading;

2. colour saturation (Zaman, 2011);

3. image conversion from RGB colour space to Lab colour space;

4. colour classification by k-means clustering to obtain the cluster centres;

5. taking the average of the cluster centres.

Below these steps are explained in more detail:

1. The RGB images chosen to determine the best cluster centres are loaded.

2. Colour saturation enhances the image colours and gives more uniformity to the different tones of the grains.

3. The RGB values of each pixel are converted into lab colour space values. In the Lab colour space each pixel includes a combination of three indices consisting of a luminosity value L and two chromaticity values a and b that delineate the colours.

4. The segmentation is based on k-means clustering. The function checks the colours by means of the a and b values of the image and it separates them into

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the different clusters comparing their indices. The cluster centre values consist of the mean a and b values for each cluster.

5. The cluster centre values of the selection of images are averaged using the k-means function to compute one mean centre value per cluster. Please note that in this case the k-means algorithm is applied to average the cluster centre values of the images instead of clustering the pixels of the images as done in point 4.

Subsequently, in all images the colours are segmented imposing the cluster centre values. This a priori setting of the cluster values leads to a much faster computation during the image analysis and most importantly to a more robust colour segmentation. More specifically, the colour segmentation based on forced cluster centres shows good results even for cases in which when one of the colours has an areal fraction smaller than 10 %, whereas k-means clustering results in an incorrect clustering of the colours under these conditions. The procedure for analysing all images using forced cluster centres is summarized in the following steps:

6. initialization of the cluster centre variables;

7. image reading;

8. colour saturation (Zaman, 2011);

9. image conversion from RGB colour space to Lab colour space;

10. calculation of the distances of a and b coordinates to the cluster centres;

11. colour segmentation defining the minimum distances;

12. calculation of areal fraction content covered by each colour.

Below these steps are explained in more detail:

6. The cluster centre values of the N colours, defined in the previous script using k-means clustering, are set up as input parameters.

7. The RGB images are loaded from the organized folders and read.

8. Colour saturation is performed to render the image colours uniform.

9. The RGB values of each pixel are converted into the Lab colour space values.

10. The chromaticity values a and b are used to classify the colours. The distances between the a and b coordinates and the cluster centres of the N colours (input parameters see item 6 above) are calculated for each pixel in the image (i.e. for each pixel there are N values for the distance to each cluster centre).

11. Among the N distances calculated a minimum distance is identified. The value of the minimum distance determines in which cluster (i.e. to which colour) every pixel is allocated (Fig. 7).

12. The pixels within each cluster are counted and the areal fraction covered by each colour in the image is computed.

The image analysis algorithm assigns a cluster to 100 % of the pixels of the image. In Heays et al. (2010a, b) colour detection is based on the isolation of each colour, with the consecutive loss or non-detection of some pixels due to shadows in the image or particles with a darker colour. For these reasons their maximum surface detection reached of the images is 91 %. Moreover, rather than working in the RGB colour space like Heays et al. (2010a, b), we work in the wider subset of colours of the Lab colour space which includes all perceivable colours. Our algorithm considers the two-dimensional space composed of the two chromaticity values a and b. Using the Lab colour space instead of the three-dimensional RGB colour space results in a shorter computational time for the algorithm.

The image analysis procedure presented here was applied to measure the stratigraphy of a coloured sand-gravel deposit. Figure 8 shows a schematic of the method concept. Images of the deposit are taken at various elevations and each image is processed with the above described algorithm in order to obtain the areal fraction content

covered by each colour (i.e. grain size). Before discussing the results of applying the method to the Gilbert delta (Sect. 4), the stratigraphy measurement technique will be assessed in the next section.

3   Assessment of the stratygraphy measurement technique

The stratigraphy measurement technique has been assessed in two sets of experiments conducted at the Environmental Fluid Mechanics Laboratory of Delft University of Technology. The image analysis technique was optimized and tested in an image analysis experiment (Fig. 9). As mentioned in Sect. 2, the stratigraphy measurement technique was applied to a Gilbert delta progradation experiment.

3.1   Image analysis experiment

The image analysis experiment was performed to determine the best settings to take the images and to develop, optimize, and test the image processing algorithm. Once the best settings (e.g. lights, camera settings) were chosen, images were taken of the same area of the bed for different water depths. The experiment was realized in a rectangular pool in which a wooden box of 2 m length, 1.04 m width, and 0.60 m height was placed. The box was divided into 12 compartments with vertical wooden panels and filled with sediment (Fig. 9). One compartment was left empty to place the water pump for varying the water depth in the pool. The experimental set-up was designed to test also other measurement techniques and patches 1–3 and 5–9 were used for testing the image analysis procedure.

We used the same three well-sorted non-overlapping grain size fractions as described in Sect. 2.1. For some patches we used the finest fraction in its natural colour to evaluate if the image analysis can be applied to unpainted fines. This would avoid painting and potential stickiness of large quantities of relatively fine sediment.

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The compartments used to test the image analysis were filled with different mixtures, i.e. different volume fraction contents of the three grain size fractions and by different colour combinations (Fig. 9). The colour combinations are: (A) blue for the fine size fraction, red for the medium size fraction, and yellow for the coarse size fraction (patches 1, 3, 5), and (B) natural colour for the fine size fraction, red for the medium size fraction, and blue for the coarse size fraction (patches 2, 6). In the remaining compartments a single size fraction was present on the surface, i.e. one colour (patches 7–9). It is important to note that in the compartments filled with sediment mixtures (patches 1–3, 5, 6) it was not possible to exactly reproduce the foreseen areal fraction content of each size fraction on the bed surface. In particular, the finer grains on average deposit at lower elevations due to kinetic sieving while pouring the sediment.

The camera used in the experiment was a Canon EOS 550D, an 18.0 megapixel digital single-lens reflex camera with a CMOS sensor. It has a maximum resolution of 5184 × 3456 and 3 : 2 aspect ratio. Images were stored in colour JPEG format and taken in Live View mode. The camera was used with the Canon EF-S 18–55 mm IS f/3.5–5.6 wide-angle to mild telephoto zoom lens. Tests were carried out to assess the camera lens and the proper camera height. The distance between the camera and the bed surface was set to 50 cm. The focal length for the camera lens was 55 mm. All pictures were taken with the Auto Exposure Program (PAE) and without flash and the lens was used with the Image Stabilizer function (IS), which automatically corrects for vibrations of the photo camera.

In order to apply this technique to submerged beds, a plexiglas plate was placed on the water surface to reduce reflection and refraction caused by water surface fluctuations (Wu and Yang, 2004). We used four flood lights to illuminate the bed surface. The lights were switched on at least 20 min before taking the pictures to provide a steady illumination and to avoid reflections on the plexiglas plate from the different sources of light in the laboratory. In this way there was as little influence as possible from (naturally varying) natural light from outside.

In the image analysis experiment the area of the bed surface covered by the pictures was about 18 cm by 12 cm and the pixel resolution was 0.03 mm. The upper limit of the tested pixel resolution was 0.1 mm (pixel dimension). For this resolution we still obtain a correct segmentation of colours in the image processing. With the camera settings for this maximum pixel resolution we can cover a bed surface area of about 60 cm by 40 cm in one image. A higher camera resolution would enable covering even bigger bed surface areas.

Mixtures composed of a blue fine fraction appeared to be segmented more accurately than the ones in which the fines were of a natural colour. The remaining part of this paper considers the colour combination blue (fine), red (medium), and yellow (coarse).

The camera was mounted on a carriage that was controlled by an operator and a computer to move the camera over the pool. The camera coordinates were registered to be able to reposition the camera at the same location to take pictures for different water depths. In this way we obtained images of equal surface areas for water depths equal to 0.0 m, 0.1 m, 0.2 m, and 0.3 m. The water depth was increased by inserting a hose in the space between the wooden box wall and the swimming pool wall in order to have negligible flow velocities to not disturb the bed surface. The water depth appeared to not significantly affect the resulting grain size distribution (Fig. 10). Yet, images for the submerged cases show somewhat better results compared to the unsubmerged case, since in the presence of water the colours were more saturated.

Certain images taken of an unsubmerged bed present some white pixels in the segmented image for the colour blue, which are caused by reflections due to water drops (Fig. 11). For this reason it is advised to wait for the sediment to dry when taking pictures of an unsubmerged bed surface, which can require a few hours.

3.2 Accuracy of the stratigraphy measurement

The sources of errors in the stratigraphy measurement technique are due to a combination of inaccuracies in the: (1) particle colouring, (2) removal of thin sediment layers, and (3) image analysis.

An error that occurs in particle colouring is an imperfect or thin coating of the paint over the grains showing the original colour of the sediment. As explained before, we have tried to reduce this effect by colouring the grains twice. Another issue is due to the potential stickiness of grains which can be almost completely avoided by shaking and mixing the sediment several times while the paint is drying. The medium size fraction consisted of some flat grains which appeared to be difficult to separate during the shaking procedure (Fig. 2). An important aspect for the colour segmentation is the choice of the combination of the colours. For a proper colour segmentation it is essential to choose colours that are as different as possible. This means as distant as possible in the applied colour space. Also the original colour of the sediment play a role and can cause the resulting colour of the painted grains to be slightly different from the paint colour.

The inaccuracies in the removal of the sediment layers are mostly related to using the wet vacuum cleaner. The effect of the wet vacuum cleaner and the removal process of grains did not appear to be grain size selective, which seems to be due to compaction of the sediment. A source of error in the sediment removal is the precision in removing layers of 1 cm thickness. A vertical grid was attached to the side walls of the flume to aid the estimation of the layer thickness. Based on our observations the inaccuracy in thickness of the sediment layers was between 1 to 2 mm. The imprecision is caused by an oblique view of the grid due to the position of the operator or the distortion due to the glass of the side walls. Another reason for inaccuracy in the layer thickness is due to varying the elevation of the mouth of the wet vacuum cleaner above the bed surface. Please note that these errors in the thickness do not have a cumulative effect while removing more and more sediment layers.

The sources of inaccuracies intrinsic in image analysis techniques have been recognized since the earliest methods were presented (Kellerhals and Bray, 1971; Adams, 1979; Ibbeken and Schleyer, 1986) and later examined in depth in more recent studies (McEwan et al., 2000; Sime and Ferguson, 2003; Graham et al., 2005a, b, 2010). The
⁵ main bias is related to the fact that the geometry of three-dimensional grains is estimated by a two-dimensional image (Sime and Ferguson, 2003). Graham et al. (2005b) referred to this error as the spatial distortion given by the lens projecting a three-dimensional object into a two-dimensional image. The errors described in the work of Graham et al. (2005b) are related to the image analysis technique and to the arrange-
¹⁰ ment of the grains. In the case of image analysis based on particle edge detection the errors are related to the capability to detect and measure the sediment particles (Graham et al., 2005b). These errors are encountered for instance in: (a) the detection of edges of a single grain, (b) the distinction between voids and parts of grains in the shadow, and (c) the estimation of the grain axes dimensions. With respect to the errors
¹⁵ related to the arrangement of the exposed grains, Graham et al. (2010) distinguished the following three causes of errors: partial burying of grains, overlapping of grains (imbrication), and grains appearing smaller when viewed from an angle (foreshortening). This generally results in the underestimation of the correct diameter of individual grains (Graham et al., 2010).
²⁰ The image analysis method proposed here is accompanied by errors mostly related to colour segmentation. Verifying the proficiency of the image processing in the colour segmentation is not straightforward. First, the size of the finest grain size fraction used in our experiment prevents the use of validation methods as "paint and pick" or the manual digitation used in other studies to verify the results of the image analysis (e.g.,
²⁵ Graham et al., 2005b; Sime and Ferguson, 2003). Secondly, in the image analysis experiment it was difficult to reproduce the foreseen grain size distribution on the bed surface as, due to kinematic sieving, in the deposition process the fines tend to find lower elevations than the coarser ones.

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As such, we have created an image with an imposed grain size distribution and analyse the results of the colour segmentation. The image combines the images of three areas of equal pixel size, each with a uniform grain size (colour). Each image was taken of a compartment filled with only one grain size fraction. This means that the imposed areal fraction content equals 0.333 for each colour. The results after repeating the colour segmentation on several images show average areal fractions of 0.346 for the colour blue, 0.315 for the colour red, and 0.339 for the colour yellow (Fig. 12).

The error originates from an incorrect colour segmentation for shadow-rich grains. These pixels are then incorrectly clustered with a darker colour. For example, when zooming in on the images we noticed that few red particles that suffer from shadows due to partial burial underneath other grains are recognized as blue in the colour segmentation (Fig. 13).

A final source of errors is observed when the grains show a bright colour tone due to light reflections or in some cases by a defect coating of the paint showing the original often lighter colour of the sediment. Despite these errors sources the maximum error in the image analysis has appeared to be only 0.02 (2 %) of the measured segmented area. This can be considered to be a relatively high level of accuracy in determining the grain size distribution of the bed surface. Overall, the stratigraphy measurement method, despite the sum of errors in particle colouring, sediment removal, and image analysis, results in a significantly smaller error in measuring the stratigraphy of a deposit than a box corer.

4 Stratigraphy measurement

In this section we describe the application of the stratigraphy measurement technique to two Gilbert delta experiments. The stratigraphy within the deposit measured through image analysis is compared to the one found through sieve analysis. We present an empirical conversion model that converts the areal fraction contents found through image analysis into volumetric fraction contents.

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4.1 The Gilbert delta experiment

Laboratory experiments on the progradation of a Gilbert or foreset-dominated delta (Chavarrías et al., 2013) are used to assess the applicability of the stratigraphy measurements. In this paper we consider only the data related to Experiments 1 and 2 (called E1 and E2) which are conducted with a constant base level. In the experiments the sediment transported over the brinkpoint was too coarse to form a bottomset and deposited over the foreset through avalanches (grain flows). The tests were conducted with the same three sediment fractions as used in the image analysis experiment with the colour combination blue (fine), red (medium), and yellow (coarse) also see Fig. 2. The flume length was 14 m, the flume height 0.45 m, and the flume width 0.40 m. At the upstream end of the flume the water discharge ($13 \, \mathrm{L \, s^{-1}}$) was maintained constant. The downstream water level was maintained constant and created a flow depth over the brinkpoint equal to 0.06 m, resulting in a flow velocity of $0.54 \, \mathrm{m \, s^{-1}}$ over the brinkpoint. The sediment was fed at a constant rate of 280 g/min using a feeder, which was located at 2.5 m upstream from the initial delta brinkpoint. The volume fraction content in the sediment mixture fed to the flume as well as the one constituting the initial bed were 0.50 (fine fraction), 0.35 (medium fraction) and 0.15 (coarse fraction). After the formation of the delta deposits (with a length between 1.5 m and 2.0 m), the experiment was stopped and the water was carefully drained from the flume.

4.2 The Gilbert delta stratigraphy

The deposits of the Gilbert deltas were analysed following the stratigraphy measurement technique described in Sect. 2.2, and using the plexiglas sampling grid to compare the results of the image analysis to the ones from sieve analysis. In this analysis two parts of the deposits are considered: one location at the centre of the flume and one location at the side, close to the flume walls. The two grid cells, and therefore the image, cover an area of about 24 cm by 18 cm (centre) and 24 cm by 11 cm (side). The height of the delta deposit (i.e., the distance from the top of the topset to the

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foreset base) was about 18 cm in Experiment E1 and therefore consisted of 18 sediment layers. The height of the delta deposit in Experiment E2 was about 16 cm, with consequently 16 layers.

In Fig. 14 the results on areal fraction contents based on the image analysis are indicated at the elevation corresponding to the top of a specific sediment layer. The volume fraction contents resulting from sieve analysis are represented by bars covering some vertical distance, as the data represent the volume fractions of each grain size within an entire layer. Before we consider the differences between the results of the two methods, we can see that the trends of the areal fraction contents determined through image analysis and the volumetric fractions due to sieve analysis are similar. A topset is present within the vertical range of 17 and 18 cm from the foreset base. The topset appears to be coarser than the material below. The upper layer of the topset is characterized by a mobile armour layer (e.g. Fig. 14c). Below the topset we find the foreset, which is the main part of the delta deposit. It is characterized by a fining upward profile (Fig. 14a).

Let us now consider the differences between both methods. Please note how the mobile armour layer, i.e., the top layer of the topset, is more clearly identified in the image analysis. This is due to the fact that in the upper sediment layer analysed in the sieve analysis sediment from the mobile armour layer is mixed with fine sediment just underneath. This is the reason for the top sample resulting from sieve analysis to be finer than the top image. Except for this top layer, we find that the areal fraction content of fines derived by image analysis is somewhat larger than the corresponding volume fraction content based on sieve analysis. For the medium and coarse fractions we find the opposite trend. The larger areal fraction contents of fines in the image analysis can be due to: (a) the colour segmentation in the image analysis sometimes incorrectly attributing buried and so darker red grains to the blue (fine) fraction, (b) the loss of some fines during the sampling procedure using the wet vacuum cleaner, and so in the sieve analysis, (c) the image analysis representing a more discrete elevation than the sieve analysis which represents a sediment layer, and (d) the particle arrangement, such as

the orientation and/or partial burial of the grains of the medium and coarse fractions. Similar errors, due to the particle arrangement, have been encountered by previous authors using image analysis (Sect. 3.2). The sediment arrangement influences the relative areal presence of the particles on the bed surface, which affects the number
5 of pixels of a certain colour in an image. It is likely that the medium and coarse grains are covered by several fine particles, so reducing their areal fraction content when compared to the volume fraction content resulting from sieve analysis.

4.3 Conversion from areal to volumetric fraction

The proposed technique has appeared to be a powerful tool to determine areal fraction
10 contents within a deposit. We develop an empirical model to convert these areal fractions resulting from image analysis into volumetric fractions as for modelling purposes we sometimes need information on volume rather than areal fraction contents.

In general, the results of the areal sampling techniques (e.g., wax or clay sampling, image analysis) are not equivalent to the outcomes of sieving. The only procedure
15 that leads to a grain size distribution that is directly comparable to the results of sieve analysis is the grid by number technique (Kellerhals and Bray, 1971). The grid by number technique consists of collecting the particles below the nodes of a grid and counting the number of grains in the various size classes. The frequency of each size class is expressed as the percentage by number compared to the total number of particles.
20 The method used to sample the particles in the grid by number is therefore equivalent to the resulting grain size distribution (i.e., frequency by number). For the other areal sampling techniques (e.g., wax or clay sampling), the sampling methods are not equivalent to sieve analysis. Each sample has its own bias, which often not only depends on the method used for sampling and for the analysis, but also on the grain size
25 distribution of the deposit. Kellerhals and Bray (1971) were the first to provide a conversion model valid for a wide series of methods. They suggested an idealized cube to model the arrangement of mixed size particles without pores. Diplas and Sutherland (1988) modified the model to account for porosity. Fraccarollo and Marion (1995)

present a conversion model that takes into account the irregular shape and random arrangement of the bed material. Application of the model of Fraccarollo and Marion (1995) therefore is, unlike the cube model of Kellerhals and Bray (1971) and the modified version of Diplas and Sutherland (1988), not restricted to a fixed amount of grain size fractions, certain particle sizes and shapes.

The conversion model is derived using the data from the Gilbert delta Experiments E1 and E2. From both datasets we first remove the data related to the mobile armour layer that is located on top of the topset. This is because the result of the sieve and image analyses are different due to the presence of the mobile armour layer and the thicker sample analysed in the sieve analysis. The areal fraction contents resulting from image analysis are linearly interpolated between vertical elevations to provide data on the areal fractions at the same elevations as the values of the volumetric fraction contents. We now apply the following empirical conversion model to the above described dataset to determine the volume fraction content of each grain size fraction, F_{Vi}, from the areal fraction content resulting from image analysis, F_{Ai}:

$$F_{Vi} = \frac{F_{Ai}\left(1 + k\left(\phi_i - \phi_{Am}\right)\right)}{\sum\limits_{i=1}^{n} F_{Ai}\left(1 + k\left(\phi_i - \phi_{Am}\right)\right)} \tag{1}$$

where i denotes the number of grain sizes fractions ($i = 3$), F_{Vi} is the volume fraction content of size fraction i in a sediment layer, F_{Ai} is the areal fraction content of size fraction i in the same sediment layer, k is an empirical constant, ϕ_i is the arithmetic grain size of size fraction i, ϕ_{Am} is the arithmetic mean grain size based on areal fraction contents, d_i is the grain size of size fraction i, and d_{ref} is the reference grain

size ($d_{\text{ref}} = 1$ mm). The values for ϕ_i and ϕ_{Am} are determined from:

$$\phi_i = -\log_2 \left(\frac{d_i}{d_{\text{ref}}} \right) \tag{2}$$

$$\phi_{\text{Am}} = \sum_{i=1}^{n} F_{\text{A}i} \phi_i \tag{3}$$

5 The optimal value for the empirical constant k is found by computing the minimum mean absolute difference, E_{m}, between the volume fraction content predicted using Eq. (1) and the measured volume fraction content determined from sieve analysis:

$$E_{\text{m}} = \frac{1}{M} \sum_{m=1}^{M} \frac{1}{N} \sum_{i=1}^{N} |F_{\text{V}i} - F_{\text{S}i}| \tag{4}$$

where M denotes the number of samples, N the number of grain sizes fractions, $F_{\text{V}i}$ is
10 the volume fraction content of size fraction i in a sediment layer predicted with Eq. (1), and $F_{\text{S}i}$ is the volume fraction content of size fraction i in a sediment layer measured through sieve analysis. Computing the mean absolute difference for all 64 sediment layers for the fine and medium fraction, we obtain a minimum value for k equal to −0.30 (see Fig. 15).

15 Figure 16 shows the results of the conversion model for the near-wall sample of Experiment E2. We now compare: (1) the predicted volume fraction contents using Eq. (1) and (2) the volume fraction contents measured through sieve analysis, (3) the areal fraction contents determined through image analysis. Observing these three profiles we notice that the conversion model reduces the overestimation of the fine fraction
20 and the underestimation of the medium and coarse fractions. After converting the results of the image analysis into the corresponding volume fraction contents we plot the variation of these volume fractions over the vertical (Fig. 17). We recognize a topset deposit over the elevation range between 15 to 16 cm from the foreset base. The topset is

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somewhat coarser than the sediment below which belongs to the foreset deposit. The resulting foreset deposit is characterized by upward fining as a result of the avalanching process.

Figure 18 shows an example of the result of stratigraphy measurement method proposed in this manuscript (Chavarrías et al., 2013). The graph shows the stratigraphy of the delta in which the colours represent the mean grain size in an area within the deposit equal to $0.40\,\text{m} \times 0.06\,\text{m}$ (lateral vs. streamwise distance) at every 1 cm over the vertical. Figure 18 demonstrates the strength of the developed stratigraphy measurement method as it results in an unknown spatial density of information on the grain size distribution.

5 Conclusions

In this paper we present a new technique to measure the entire stratigraphy of a sand-gravel deposit in a laboratory experiment, which is a combination of particle colouring, removal of sediment layers, and image analysis. Colour segmentation of areal images of a bed surface covered by coloured particles is combined with a non-destructive and flexible method to remove sediment layers using a wet vacuum cleaner.

A clear advantage of the technique is its high spatial resolution of the resulting data on the grain size distribution, which is unequalled in other methods. Other methods generally provide information on the grain size distribution in a limited number of locations.

We observed small inaccuracies in the sediment removal technique which are mainly attributable to imprecisions in the exact thickness of a sediment layer. Despite this, the presented stratigraphy measurement method creates less disturbances than a box core. Disturbances caused by driving a box core into the bed, such as compressing sediment layers and/or displacing grains to lower elevations, are here completely avoided.

Using the proposed technique a large amount of data is quickly collected, time consuming sieve analyses are avoided, and the data is quickly processed using an automatic and fast script that requires only very limited action from the user. The image analysis processing is based on colour segmentation within the Lab colour space which results in an improved colour detection of the entire pixels of the image. The results of this new method have accurate outcomes. A new empirical conversion model to convert areal fraction contents derived by image analysis into volume fraction contents has been developed.

The image analysis method was successfully used to determine the grain size distribution of a submerged bed surface, while creating no disturbances to the bed surface. Measurement of the grain size distribution of the bed surface during a running laboratory experiment, at flows with transported sediment, is currently being tested by the author. When it is important to continue a flume experiment after sampling, this technique offers the possibility to place back the sediment of each layer at its original elevation directly after sampling.

The particle colouring by itself appeared to be of large help in the interpretation of grain size-selective processes.

Overall, the stratigraphy measurement method, despite the sum of errors in particle colouring, sediment removal, and image analysis, results in a significantly smaller error in measuring the stratigraphy of a deposit than a box core.

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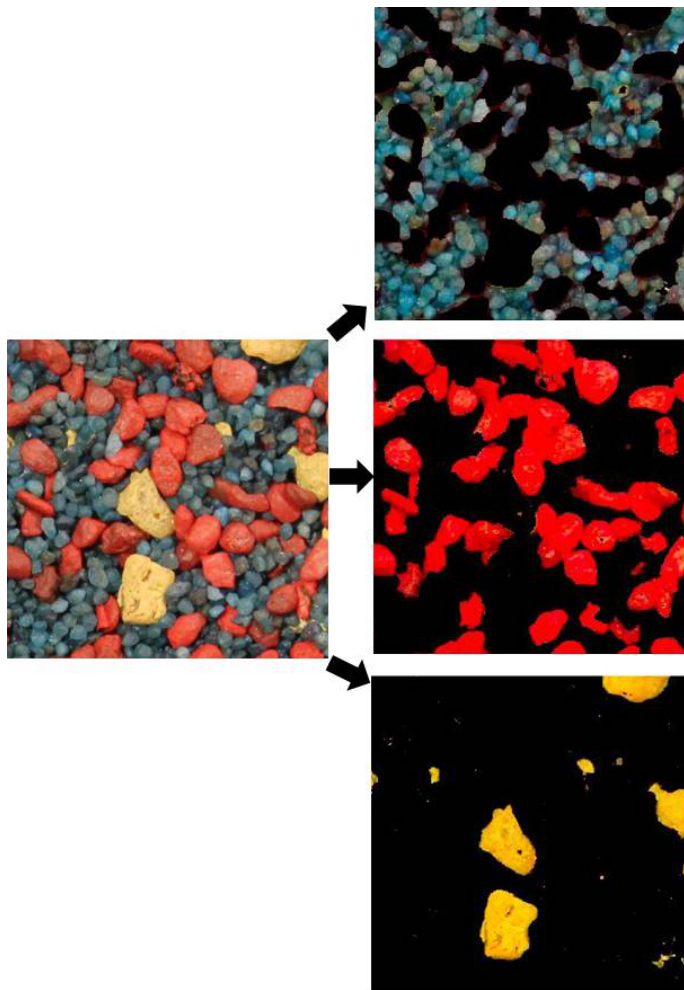Printer-friendly Version

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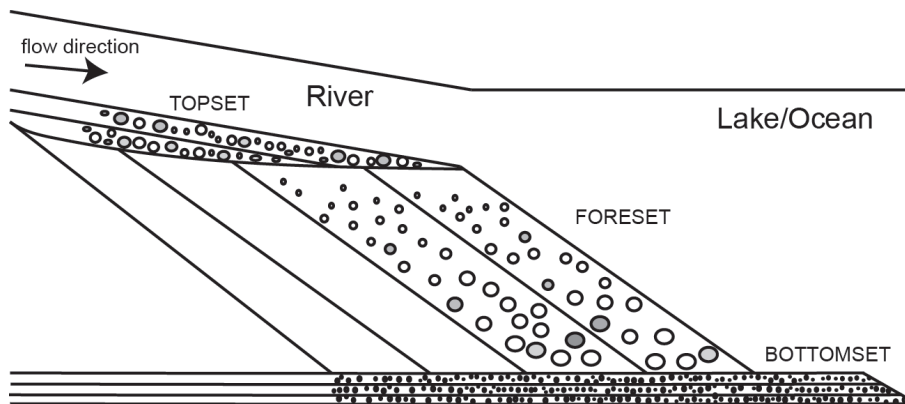
Fig. 1. Schematic of a Gilbert-type delta (after Gilbert, 1890).
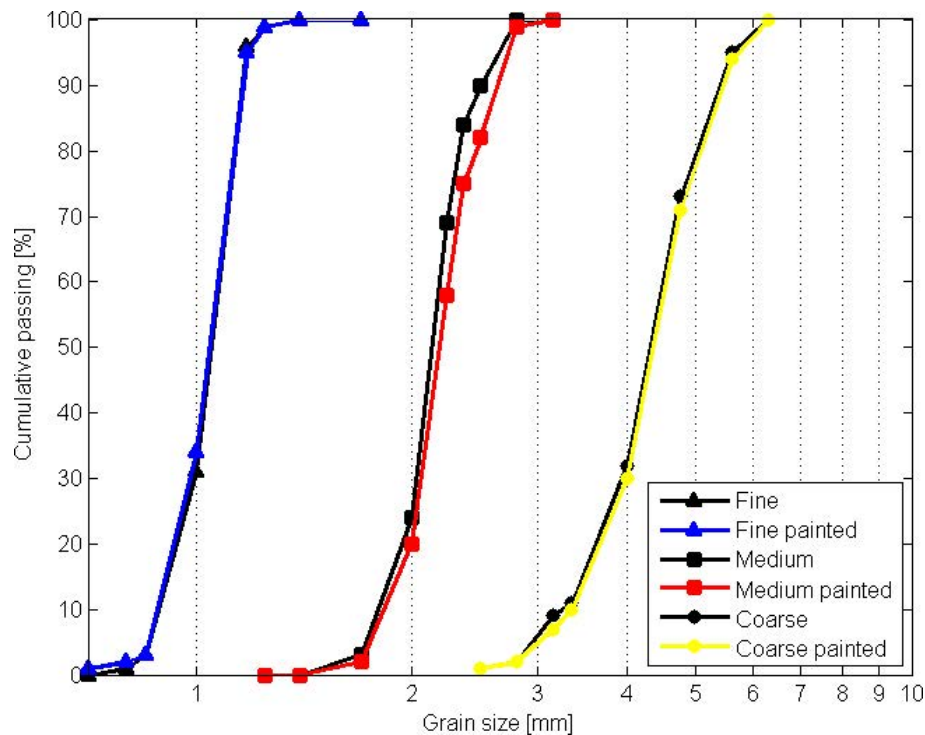
Fig. 2. Grain size distribution of the original sediment (black lines) and the coloured sediment (blue, red and yellow lines).

Fig. 3. Experimental set-up. Side view of the delta progradation experiment during the removal of sediment layers and sampling for sieving purposes.

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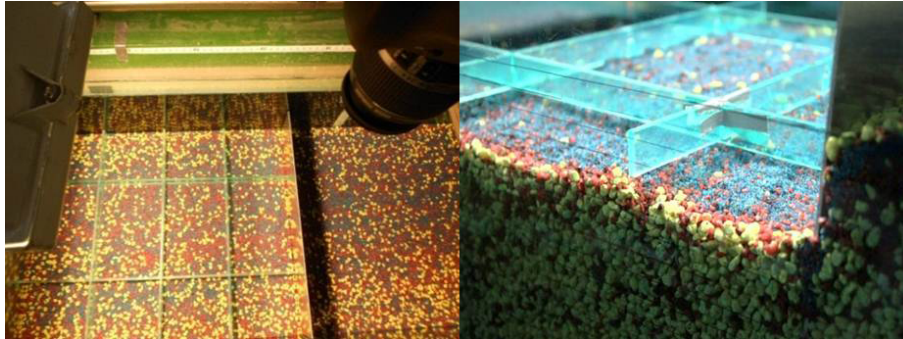
Fig. 4. Set-up for image analysis and sampling: top view of the sampling area with the sampling grid placed on the bed surface and the metal sheets inserted into the bed. The plexiglas grid and sampling per grid cell is only needed for the assessment phase of the image analysis method. Once the conversion method is clear, the sampling grid is no longer required and an entire thin sediment layer can be removed at once without using the grid.
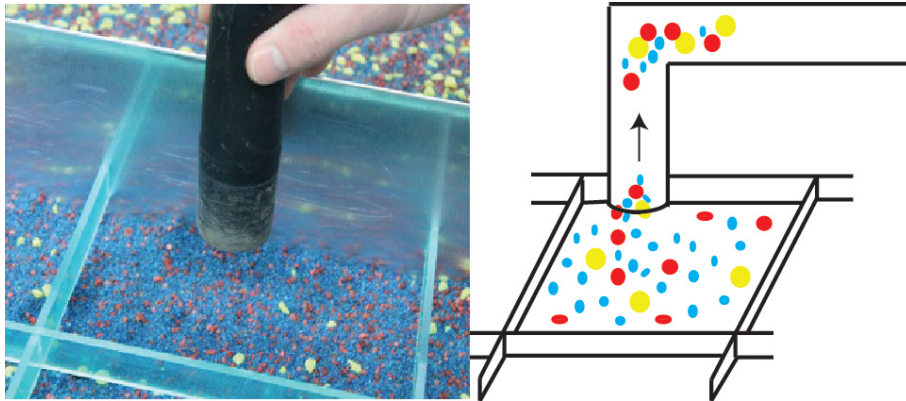
Fig. 5. Nozzle of vacuum cleaner close to the bed surface removing the 1 cm sediment layers.

Fig. 6. Colour segmentation for the three grain size fractions.

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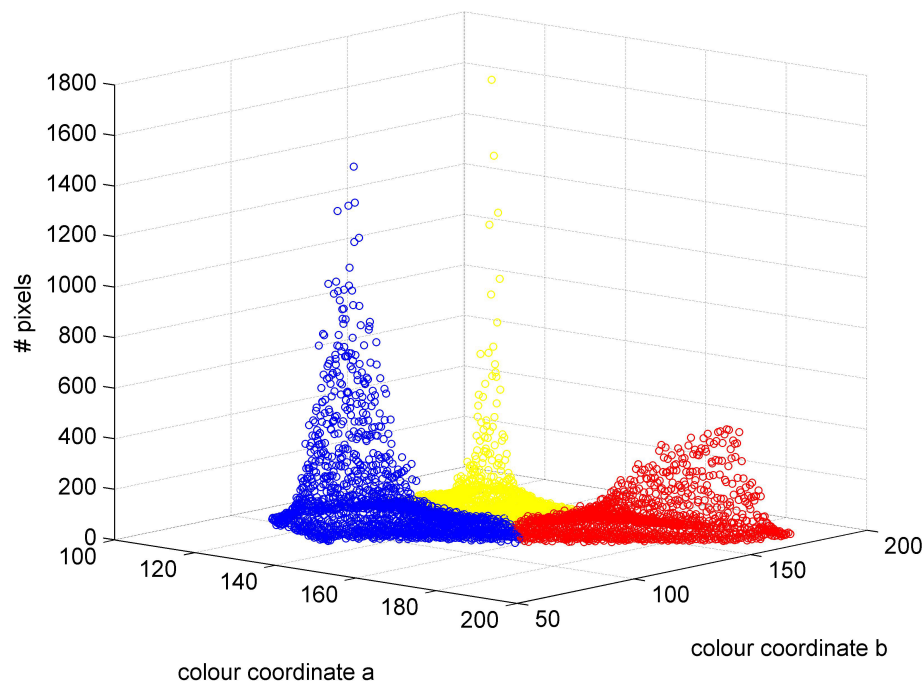
Fig. 7. Three-dimensional view of the *a* and *b* domain. Example for one image. Clusters segmented in the three colours blue, red and yellow. The position of each dot in the *a* and *b* plane is related to the colour and its vertical position indicates the number of all pixels with the same colour coordinates.
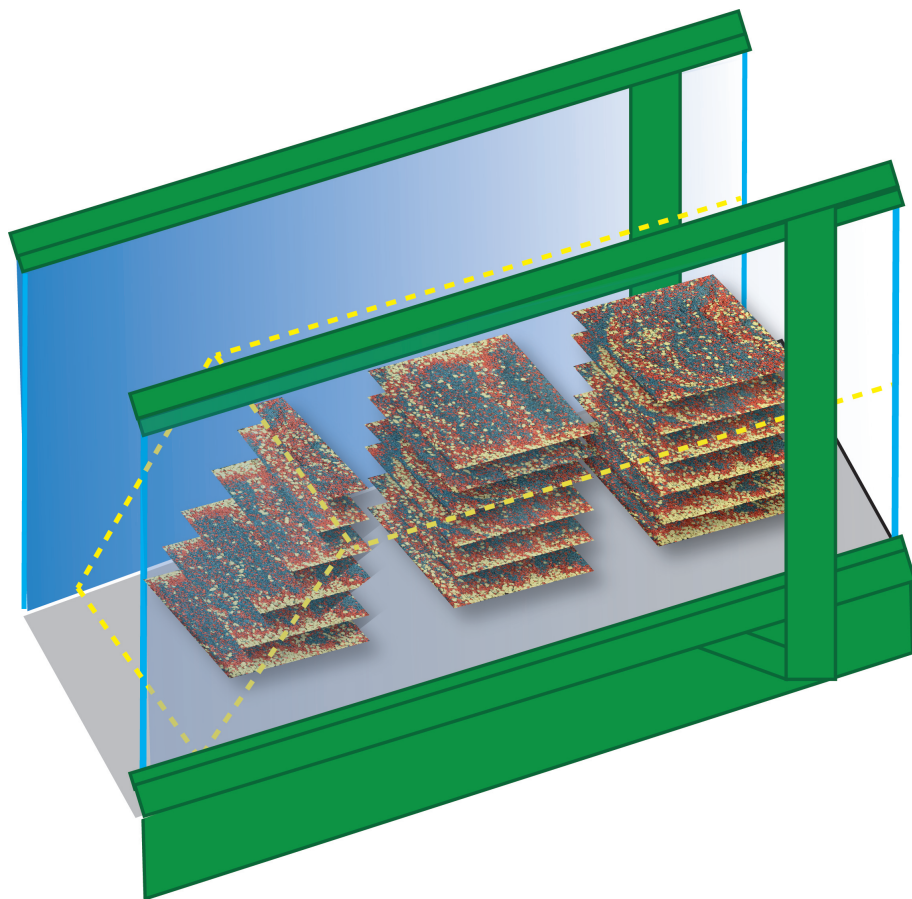
Fig. 8. Application of the image analysis technique to stratigraphy measurements. Schematic of stratigraphy of a deposit evaluated with image analysis.
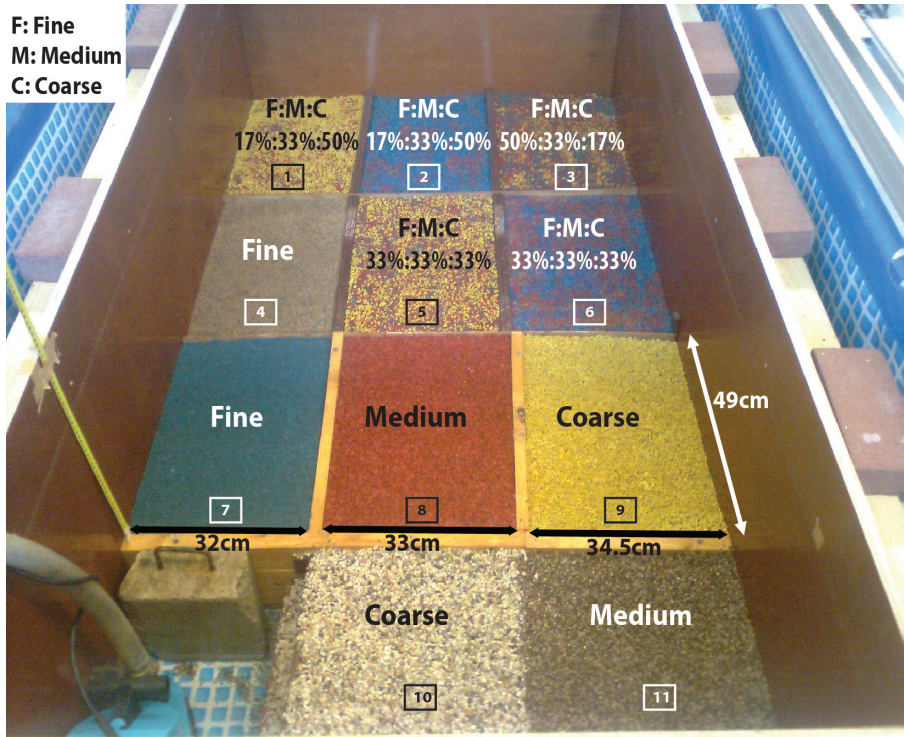
Fig. 9. Settings of the image analysis experiment. Grain size distribution within the compartments, compartment geometry and numbers.
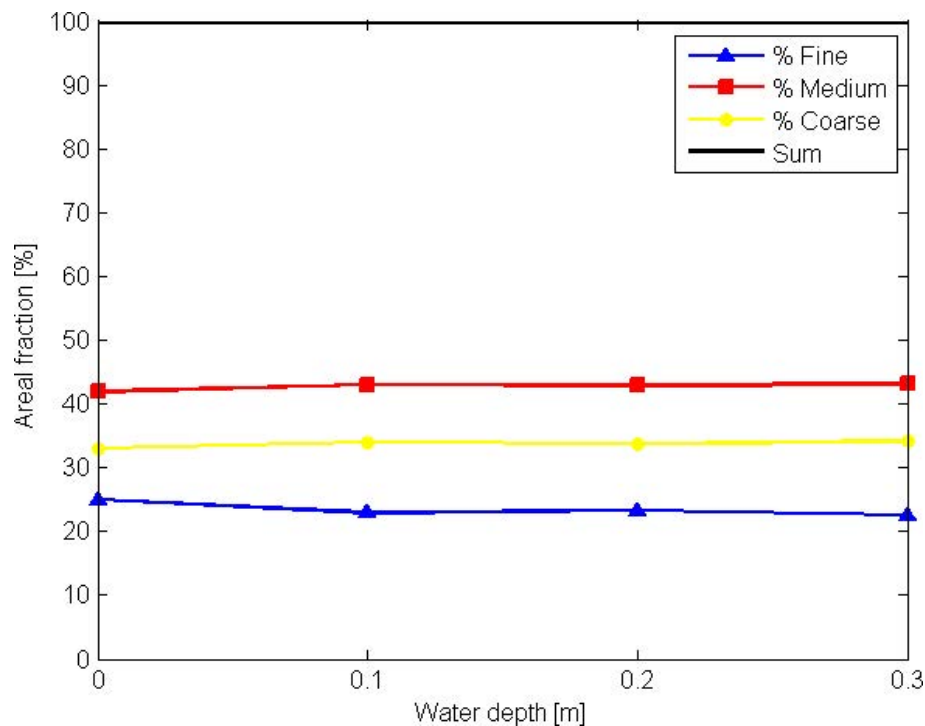
Fig. 10. Example of the effect of water depth on the areal fraction in patch 5. The data represent the areal fraction of the three size fractions for different water depths obtained through processing of images covering the same surface area.

Original pictures
Segmented pictures (blue)

Pictures of
unsubmerged
wet bed

Pictures of
submerged
bed
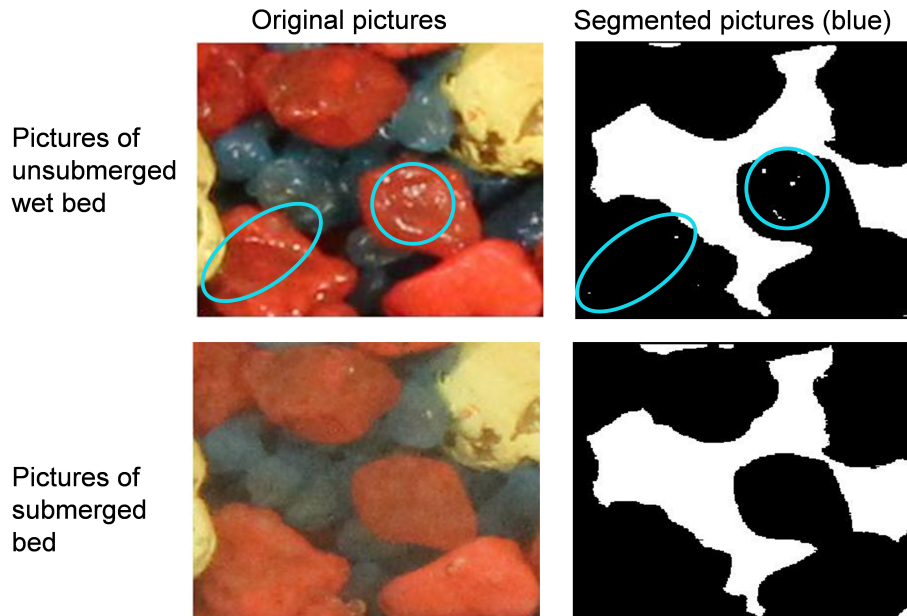
Fig. 11. Origin of white pixels in images of an unsubmerged bed. Left: original images. Right: binary image of the segmented image for the colour blue. At the top: images for an unsubmerged bed. At the bottom: images for a submerged bed. The extra white pixels in the unsubmerged pictures, indicated with blue circles, are due to reflections of water drops.

Results from image analysis

Image with imposed areal fraction
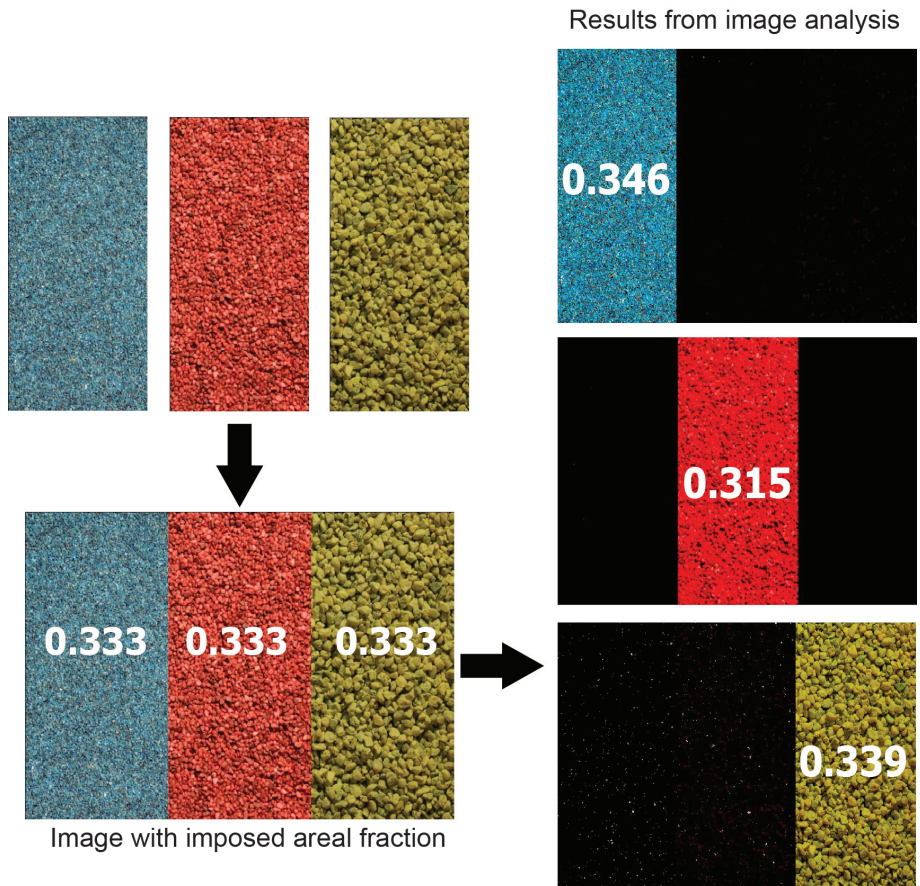
Fig. 12. Accuracy test. Left: image with imposed areal fraction content created by combining 3 images of uniform sediment of the same pixel area. Right: segmented images and mean areal fraction contents resulting from the image processing.
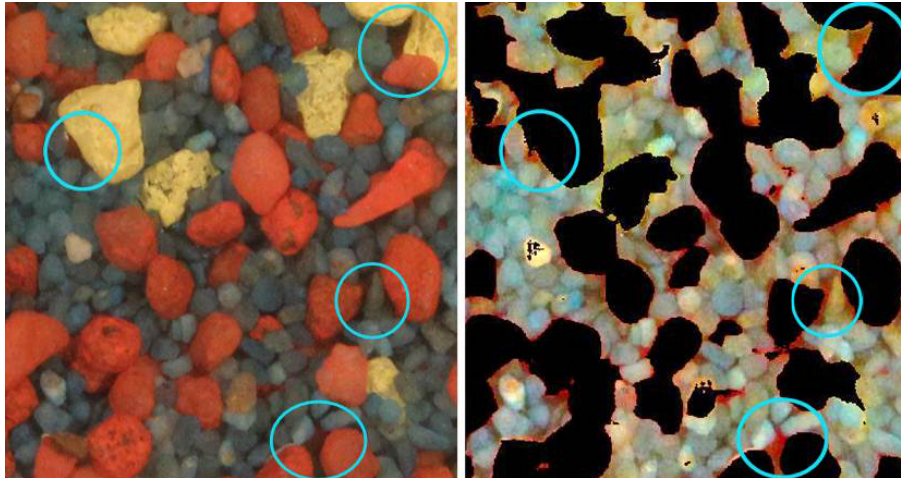
Fig. 13. Example of partially buried and therefore shadow-rich red grains, indicated with blue circles, recognized as blue in the colour segmentation. Left: original image of a submerged bed surface. Right: corresponding segmented image for the blue colour. Please note that the blue colour in the segmented image was lightened to better illustrate the incorrect segmentation of some red grains.
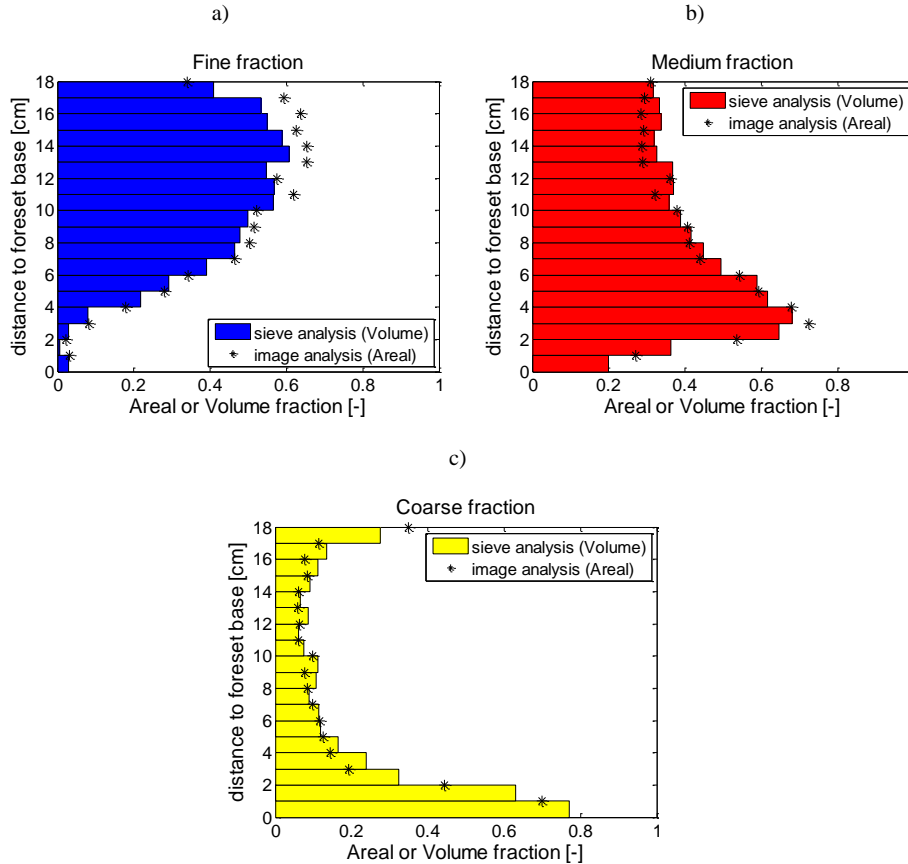
Fig. 14. Vertical profiles of (1) the measured volumetric fraction contents measured through sieve analysis and (2) the areal fraction contents determined through image analysis for each grain size fraction: **(a)** fine, **(b)** medium, and **(c)** coarse for Experiment E1, Centre sample.
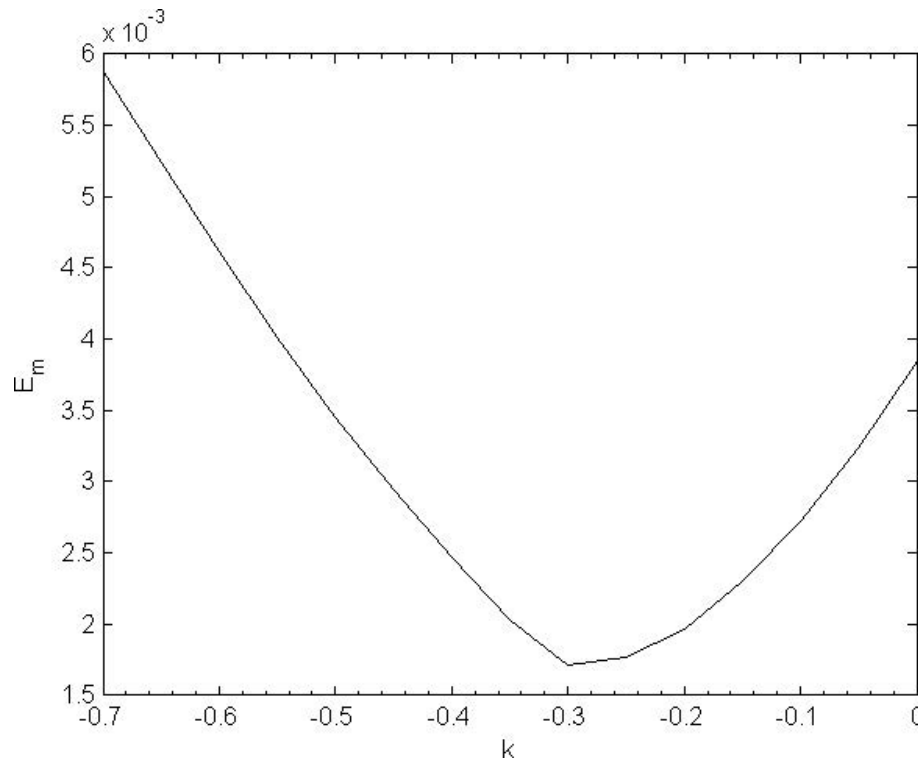
Fig. 15. Mean absolute difference between the volume fraction content predicted using Eq. (1) and the measured volume fraction content determined by sieve analysis to find the value for k that corresponds to the minimum difference ($k = -0.30$).
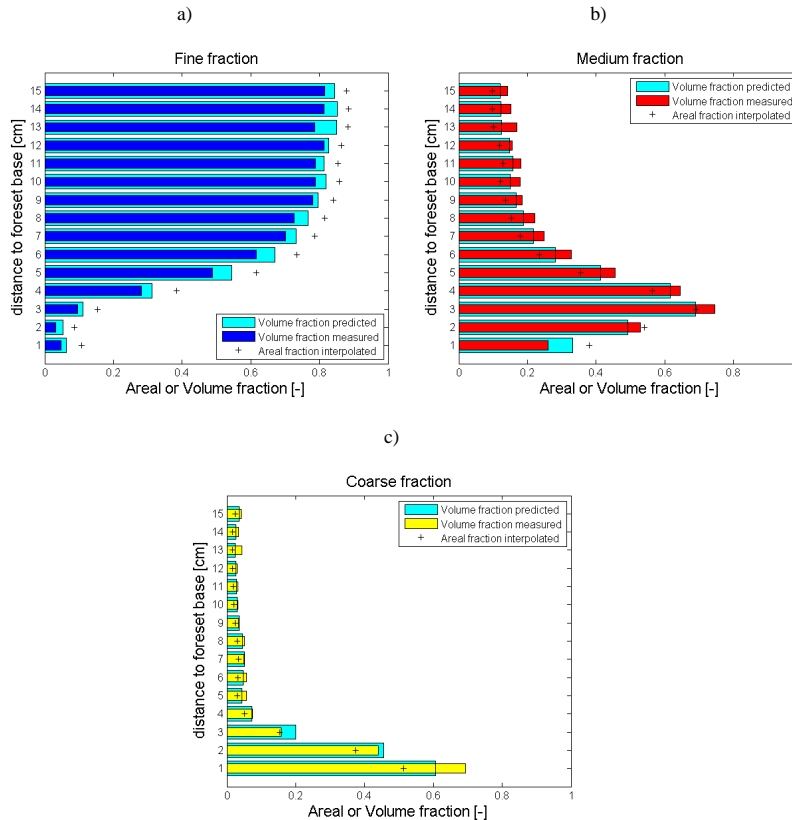
Fig. 16. Vertical profiles of (1) the predicted volume fraction contents using Eq. (1), (2) the measured volume fraction contents measured through sieve analysis, (3) the areal fraction contents through image analysis for each grain size fraction: **(a)** fine, **(b)** medium, and **(c)** coarse for Experiment 2, Side sample. Note the areal fractions have been linearly interpolated. The crosses are now located at the elevation corresponding to the middle of the layer.
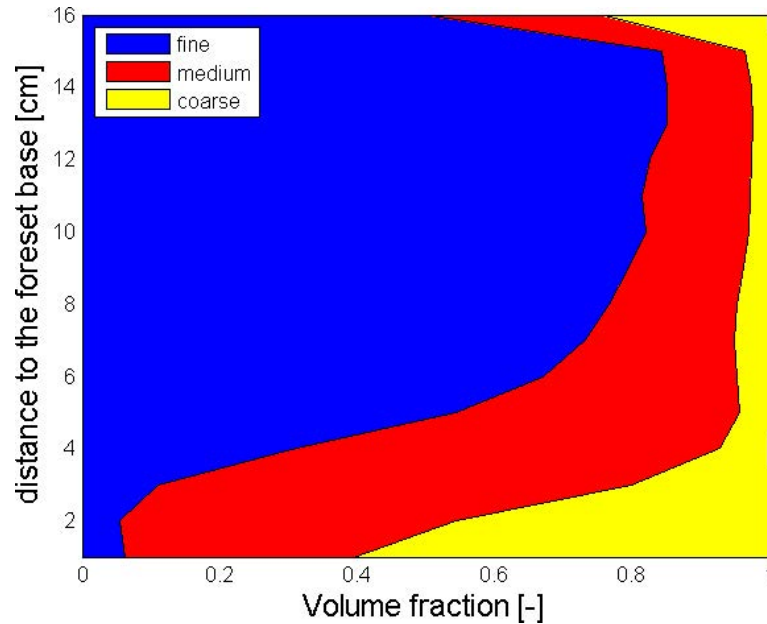
Fig. 17. Vertical profile of the predicted volume fraction contents for Experiment 2 (side sample).
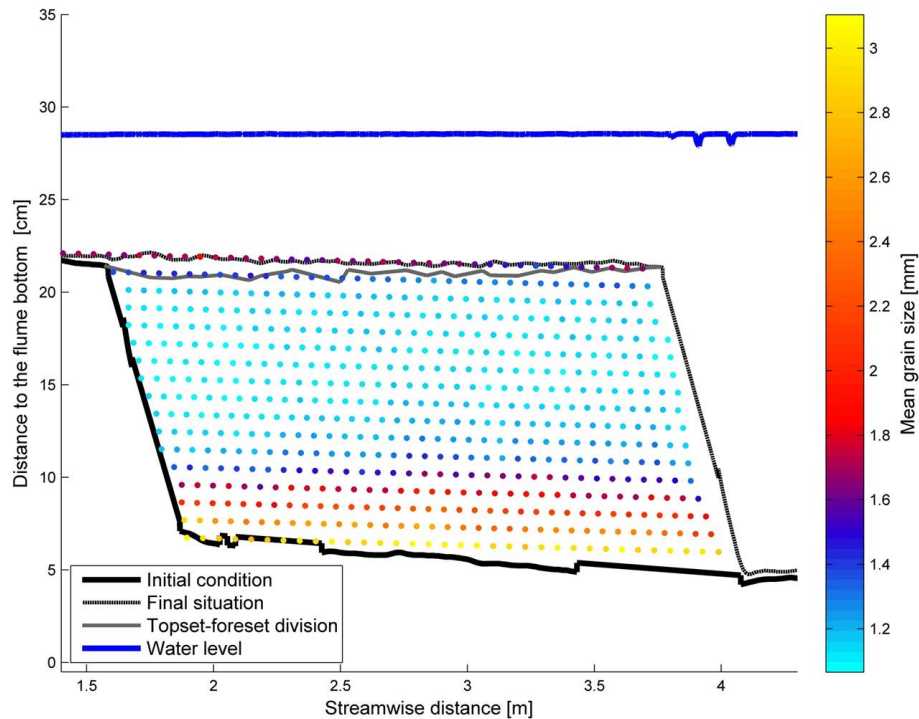
Fig. 18. Stratigraphy within a Gilbert delta deposit measured using the stratigraphy measurement technique proposed in this paper.