DEM QUALITY ASSESSMENT WITH A 3D PRINTED GRAVEL BED APPLIED TO STEREOPHOTOGRAMMETRY

S. BERTIN (sber081@aucklanduni.ac.nz)

H. FRIEDRICH (h.friedrich@auckland.ac.nz),

P. DELMAS (p.delmas@auckland.ac.nz)

E. CHAN (ycha171@aucklanduni.ac.nz)

G. GIMEL'FARB (g.gimelfarb@auckland.ac.nz)

The University of Auckland, New Zealand

Abstract

Using stereophotogrammetry to obtain digital elevation models (DEMs) for surface topography analysis is becoming popular in hydraulic research, especially for coarse gravel beds. This paper assesses the DEM quality by using a realistic 3D printed gravel-bed model, with known elevations every 0.25 mm, as ground truth. Two Nikon D5100 cameras and non-proprietary photogrammetric software for camera calibration and DEM reconstruction are used for the study. A measured DEM is compared point by point with the ground truth and displays a very high measurement accuracy. The 3D printing of ground truths facilitates fast and versatile evaluation of both the DEM quality and the sensitivity of its errors to changes in surface topography and collection parameters. It has the potential to streamline evaluations of calibration and image quality, as well as error filtering strategies. Ultimately, 3D printed models will help in exploring stereomatching error reductions in occluded regions and defining the most suitable strategy for gravel-bed DEM collection, both in air and through water.

KEYWORDS: DEM accuracy, close range digital photogrammetry, gravel bed, 3D printing, ground truth

INTRODUCTION

THERE IS A GROWING DEMAND for high-resolution topographic data in hydraulic experiments, especially over natural water-worked gravel beds. Fine-scale representations of gravel beds with digital elevation models (DEMs) are becoming more and more

important for characterising the range of structures associated with water-worked surfaces (Butler et al., 2001; Qin et al., 2012), and the links between microtopography and interfacial hydraulics (Rice et al., 2014).

Digital stereophotogrammetry is capable of obtaining dense topographic data, in both the laboratory and the field, and over dry and submerged riverbeds (Bertin et al., 2012; Butler et al., 1998; 2002; Carbonneau et al., 2003; Chandler et al., 2001; 2003) with lower cost, greater versatility and higher speed of data acquisition, than alternative surveying techniques. However, as with all these methods, small-magnitude errors are likely to propagate and significantly affect the quality of both the resulting DEM and extracted topographic parameters (Lane et al., 2005), especially with low relief surfaces (Hodge et al., 2009).

To ensure that recorded topographic models suit experimental requirements, it is important to evaluate the overall performance of the recording environment. To do so, the performance of the device and of the chosen methodological approach is represented in terms of DEM quality and can be characterised by a global measure of error (Lane et al., 2005).

Errors should also be investigated at each stage of the recording process, in order to define a means of data collection improvement (Lane et al., 2005; Rieke-Zapp et al., 2009). This is a particular concern for digital stereo-photogrammetric automated DEM generation, as errors can arise from various parts of the process (Bertin et al., 2012; Carbonneau et al., 2003; Lane et al., 2000).

RELATED WORK ON THE QUALITY OF TOPOGRAPHIC DATA

The topographic data quality in engineering surveying is described in terms of accuracy, precision and reliability (Butler et al., 1998; Carbonneau et al., 2003; Cooper and Cross, 1988; Hodge et al., 2009; Lane et al., 2000). The *accuracy* is the most commonly employed descriptor (Lane et al., 2005) related to systematic errors in a DEM and generally represented by the mean error (ME) between observed metrics and true values. According to Cooper and Cross (1988), the inaccuracies occur in the measurements due to an incorrect functional model, such as an inadequate lens distortion model in stereo photogrammetry. The measurement *precision* refers to inconsistencies (random errors) between repeated measurements under the same conditions. Such errors cannot be eliminated by refining the functional model or applying corrections (Cooper and Cross, 1988). Most importantly, global precision is traditionally computed using the standard deviation of the errors (SDE). The root mean square error (RMSE) is normally obtained through independent checks on the measured data (Brasington and Smart, 2003; Butler et al., 2002; Carbonneau et al., 2003; Lane et al., 2000; Lane et al., 2003) and will quantify random and systematic errors into a single measure of data quality (Butler et al., 1998; Chandler et al., 2003; Lane et al., 2005). The RMSE is frequently labelled the 'accuracy' and assumes that the method of determining the independent checks is superior to the method under consideration (photogrammetry in this instance). Gross errors or blunders, which arise from an incorrect measuring process or malfunctioning equipment, determine the *internal reliability* of the DEM. This descriptor is assessed by comparing semi-independent metrics, such as DEMs obtained using different baselines (Butler et al., 1998), or extracted from different imagery (Brasington and Smart, 2003), or obtained through water and in air (Butler et al., 2002; Smith et al., 2012). The *external reliability*

is quantified by comparing a topographic parameter of interest, calculated from the DEM, with a theoretical reference. Such external parameters can be slopes of the measured surface for large-scale DEMs (Lane et al., 2000), or scaling properties of small-scale surfaces (Carbonneau et al., 2003). Whilst tests of the external reliability can be beneficial in investigating effects of changing DEM collection parameters, when accuracy statistics are insensitive, the difficulty resides in defining the reference values for the parameters of interest (Lane et al., 2000).

In practice, the topographic data quality is quantified in both the laboratory and field by comparing metrics contained in a DEM for a small number of check points (generally, less than 1% of all the DEM points), directly over the measured surface. Total stations or alternative measuring devices are usually employed to locate and register the check points within the DEM. Limitations of this approach are positioning errors, low density and arbitrary distributions of the check points. Reliability of the data quality measured with this approach cannot be ascertained, especially over rough surfaces, possibly leading to wrong conclusions about the DEM quality (Bouratsis et al., 2013; Brasington and Smart, 2003; Butler et al., 1998; 2002; Carbonneau et al., 2003; Chandler et al., 2003; Gooch et al., 1999; Lane, 2000; Lane et al., 2000; Rieke-Zapp et al., 2009; Smith et al., 2012).

To improve the check-point density, Chandler et al., (2001) measured a rough flume-bed surface with both stereophotogrammetry and laser scanning and compared point-by-point 5589 homogeneously distributed elevations. However, the laser-scanned and photogrammetric data were obtained using different datums, and whilst data alignment was said to be problematic (Lane, 2000), a detailed procedure was not presented. Additionally, whilst laser scanning over rough surfaces is very accurate in theory, it is not error-free in practice (Hodge et al., 2009). Therefore, each assessment calls for both DEM reconstruction and error editing.

The measurement of objects of known size is another traditional approach to evaluate the quality of topographic surveys (Bouratsis et al., 2013; Hodge et al., 2009; Pollyea and Fairley, 2012). Wang et al. (2009) used a realistic 3D seafloor model of known elevations to evaluate laser-scanning and photogrammetric capabilities in measuring seabed roughness. The seafloor model built with a computer-assisted milling machine achieved a 1 mm sampling distance between the check points and 0.1 mm vertical accuracy. However, whilst the model mimicked the seafloor topography, its all-white surface had unnatural appearance and lacked texture, resulting in adverse photogrammetric measuring conditions. Additionally, Wang et al. (2009) had to align check points with the observations, which hindered point-by-point comparisons and computation of accuracy. Instead, external reliability measures were evaluated, with the advantage that a reference value for an external parameter (roughness spectrum) could be calculated from the known elevations of the seafloor model.

Whilst the above studies made significant progress on the DEM quality evaluation, additional work is still needed to ensure that derived data-quality measures are sufficient to evaluate a DEM collection strategy and allow for optimising the recording process. At present, DEM evaluation strategy recommendations are twofold: confidence in check points, their density and uniform distribution over the surface; and correct alignment of measured and true values. The evaluation also needs to be improved for use in different environments.

PAPER OVERVIEW

In this work a novel methodology for assessing DEM quality was developed and applied to laboratory gravel-bed DEMs collected with digital stereo photogrammetry. Initially, a 3D printed model of known dimensions was produced, based on the experimental stereo-photogrammetric pre-measuring of spatial topography and the visual appearance of a water-worked gravel bed. The dense and uniformly-distributed grid of check points from the 3D printed gravel-bed model acted as ground truth for assessing the subsequent stereo-photogrammetric measurements. Adaptive surface de-trending and search means were implemented to align the measured and ground-truth data, thus enabling reliable point-by-point comparisons. The 3D printed model was then assessed as to its ability to reveal variations in DEM collection parameters, based on the parametric 'DEM sampling distance', and how representative the derived accuracy statistics were.

METHODOLOGY

Measurement Environment and General DEM Collection Process

The DEM acquisition environment and the photogrammetric workflow (Table I) are identical to the earlier work by Bertin and Friedrich (2014) on monitoring gravel beds at the grain scale. A purpose-built hydraulic flume (19 m long, 0.5 m wide and 0.5 m deep, with a slope set to 0.5%) has been used for the measurements. A one metre long, full-width sediment recess 14 m downstream from the inlet was used to prepare the water-worked gravel bed. The evolving gravel-bed topography was recorded through air after the flume was drained.

A gantry-mounting system, sliding on a rail, allows the cameras to be rigidly attached horizontally above the test section. The stereo photogrammetric setup comprises two Nikon D5100 cameras with 16.2 Mpixel complementary metal oxide semiconductor (CMOS) sensors (4928 x 3264 pixels) and Nikkor 20 mm fixed-focus lenses. The baseline between the two cameras, and the setup 'flying' height, are adjustable within the ranges 200 to 400 mm, and 400 to 1000 mm, respectively. To minimise the effects of gravel protruding and shadowing the surroundings, the two cameras are mounted in a canonical vertical photogrammetric configuration, assuming parallel optical axes directed vertically toward the centreline of the flume.

The lighting consists of two pairs of 1 m long neon lights (58W with carbon dioxide), placed horizontally on each side of the flume, one light above the other. White Plexiglas sheets at the transparent flume sidewalls diffuse the lighting, creating a more homogenous illumination. The gravel-bed test section is thus illuminated by a 'cool daylight' colour. Two additional neon lights, which hang above the flume, are used during the acquisition of the calibration images. In order not to cast shadows on the surface, these latter lights are turned off for image acquisition of the gravel bed.

The general DEM collection process is presented in Table I and explained in detail below.

TABLE I. The workflow used for collecting, processing and assessing photogrammetric data.
RSEV is the repeat stereomatching error value.

(1) The design of the stereo setup is the first step in a photogrammetric project. It constrains the theoretical accuracy achievable by the setup, and is thus critical to the success of the measurements (Lane et al., 2001; Lane, 2000). A MATLAB® routine, where the standard central perspective projection equations (pinhole camera model) are implemented, forms a systematic approach to determine the optimum camera-to-object distance (the distance resulting in the best measurement resolution), which complies with the experimental requirements of the measurement window size. Since DEM errors increase near the edges (Butler et al., 2002), a margin around the desired measurement window is commonly accounted for in the design and removed from the DEM during analysis.

(2) During image acquisition, each camera is connected to a computer, allowing remote control and live view with Nikon Control Pro 2® software. This helps to manually focus on the object to be measured and to mechanically align the cameras. After these steps, it is necessary to ensure no modification is made to the physical setup for the duration of the experiment. Adequate selection of the camera settings is important, as the crucial element to a successful close-range photogrammetric process is attaining ‘good photographs’ (Matthews, 2008), where the term ‘good’ refers to pictures that have uniform exposure with high-contrast sharp images. Since the lighting environment will constrain the potential camera settings, it is important that both the lighting environment and the exposure settings are optimised in common as an interdependent pair. To obtain the best quality photographs, the cameras are operated in manual mode. With the Nikkor 20 mm lenses, a combination of an aperture of f/8 (sometimes increased to f/10 or f/11) with a generic sensitivity value such as ISO 200, ensures a good depth of field, a reduced chance of vignetting and sharpness across the image. Once the aperture and ISO are set, these settings must remain constant throughout the acquisition of all images. The shutter speed can be changed to adapt to different lighting conditions.

(3) The camera and setup calibration is performed using the camera calibration toolbox for MATLAB®, developed by Bouguet (2010). This technique relies on the

calibration method of Zhang (1999), whereby calibration parameters (both intrinsic and extrinsic) are computed from a series of photographs of a planar chequerboard in different orientations. Radial distortion (up to the fourth order) and tangential distortion are also modelled during the calibration. Using the calibration results, all stereo pairs obtained with the setup in the calibrated configuration can be rectified to epipolar geometry, where corresponding pixels are on a same scan-line. Image rectification (Fusiello et al., 2000) is included in the calibration toolbox. It should be noted that the toolbox transforms images to greyscale equivalents during rectification, but the code can easily be modified to obtain rectified images in red/green/blue (RGB) format.

(4) Stereomatching is performed on the rectified RGB images using the symmetric dynamic programming stereo (SDPS) algorithm (Gimel'farb, 2002), providing both the grey-coded depth maps and ortho-images for a reconstructed DEM. The SDPS matches corresponding points by minimising pixel mismatches along each scan line in the stereo pairs. Compared with previous photogrammetric applications in hydraulic experiments (Bouratsis et al., 2013; Brasington and Smart, 2003; Butler et al., 1998; 2001; 2002; Carbonneau et al., 2003; Chandler et al., 2001; 2003; Gooch et al., 1999; Lane, 2000; Lane et al., 2000; 2003; 2005), the SDPS matching is not 'area-based'. Hence, the DEM smoothing will be less, and the sampling distance can be chosen, if necessary, as small as the pixel size at the object's distance. The SDPS search for the corresponding pixels is bounded by a disparity search range, calculated during the design by predetermining the surface elevation ranges. Post-processing by median filtering, a common practice in photogrammetric surveys (Carbonneau et al., 2003), is applied to eliminate blunders in the depth maps. Using the default filter width of 3 pixels and height of 11 pixels, each given pixel elevation is replaced by the median value over a 3 x 11 neighbourhood around the corresponding pixel position in the input image. In terms of the matching precision, the SDPS is able to distinguish disparity layers up to one pixel, which will give the theoretical depth resolution achievable by the setup after the pixel size is determined in the object space (see Table III).

From the depth maps and the calibration results, point cloud text files, containing the 3D object coordinates of each pixel in the depth maps, are extracted. The points in these clouds are not regularly spaced, because they pertain to different disparity levels. Using the function 'gridfit' in MATLAB®, the point clouds are interpolated (using the default triangle interpolation) into regular grids, with adjustable spacing, and represented as 2.5D DEMs with normalised elevations.

Preparation of a Realistic 3D Printed Gravel-Bed Model

Grain sizes are frequently quoted as D_i , which is the grain size at which the specified percentage i of the grains are finer (so $D_{50} = 10$ mm means 50% of the grains are smaller than 10 mm). To ensure that the 3D printed model mimics the topography of gravel beds simulated in hydraulic laboratory experiments, a standard sediment mixture, with a median size of the intermediate axis $D_{50} = 7.3$ mm, a minimum size of 0.7 mm, a maximum size of 65 mm and a geometric standard deviation of the grain size distribution, calculated as $\sqrt{D_{84}/D_{16}} = 2.98$, was used to create a screeded gravel bed in the hydraulic flume. The sediment was water-worked with a flow rate of 60 l/s and a constant water depth of 200 mm, until no sediment movement was observed. The water-worked surface presented evidence of armouring, with a general coarsening of the

sediment. The grain size distribution was re-estimated using an orthophotograph of the surface and the image-based method developed by Detert and Weitbrecht (2012), called BASEGRAIN®. It was found to have a D_{50} of 13 mm, and $\sqrt{D_{84}/D_{16}} = 3.25$.

Digital stereophotogrammetry was chosen for data collection, as it was the available technique to allow the best compromise between measurement resolution and theoretical depth accuracy (Bertin and Friedrich, 2014). For obtaining the ground truth, two Nikon D90 cameras with Nikkor 18-105 mm lenses were experimentally set up with a baseline of 300 mm and a camera 'flying' height of 575 mm. The resulting pixel size on the gravel-bed surface was 0.18mm, the overlap was 60% and the theoretical depth resolution was 0.35 mm.

Limitations due to the 3D printer restrained the size of the ground truth to 296 mm and 184 mm along the flow and transverse directions, respectively. However, surfaces of this size and smaller have been shown to be suitable for characterising grain-scale surface properties of laboratory gravel beds (Marion et al., 2003; Ockelford and Haynes, 2013). Photogrammetric data were interpolated on a regular grid with a 0.25 mm sampling distance, generating 873 345 points of known elevations (Table II). To facilitate the assessment of future data using the 3D printed model, 5 mm squares at the four corners were made flat, and elevations were normalised to have a mean value of zero and stored in the *ground truth elevation matrix* (of data size 1185 x 737). Additionally, before sending it to the 3D printer, the DEM was rendered as a hollow object by replicating the surface 5 mm below the original and connecting the two with prolonged edges. The 3D DEM (Fig. 1) was finally transformed in a stereo lithography (.stl) file and sent to the 3D printer.

A ProJet® 3500 HDPlus from 3DSYSTEMS, available at The University of Auckland, was employed for the manufacturing. 3D printing is an additive process, where successive layers of material, VisiJet® Crystal (described as a transparent plastic), are laid down in different shapes. The gravel-bed model was built in approximately 15 hours, with a manufacturer's specified accuracy range of 0.033 to 0.066 mm. After manufacturing, the model was left to dry. During the drying process, the edges of the model experienced a minimal upwards curvature due to thermal contraction of the material. The model was therefore mounted onto a flat Perspex plate, ensuring a planar 3D datum.

TABLE II. Characteristics of the realistic 3D gravel-bed model (ground truth).

Size (mm)	296 x 184
Sampling distance (mm)	0.25
Number of points with known elevation	873 345
Standard deviation of surface elevation (mm)	5.5
Surface elevation span (mm)	32.6

FIG.1. DEM of a representative patch of gravel bed, of size 296 x 184 mm, and 0.25 mm sampling distance, selected for 3D printing.

Preliminary tests showed that stereomatching of images of the 3D printed model does not perform well because of the transparency of the material and weak texture, in other words the lack of contrast and patterns on the surface (Fig. 2(a)). The surface was subsequently finished (Fig. 2(b)), maximising the chance of correctly matched pixels. This was an important step to allow the investigation of the joint effect of topography and DEM collection strategy on the DEM quality, with minimal influence from surface-dependent stereo correspondence problems. Similarly, images of natural gravel beds contain fine texture for successful stereomatching (Bertin et al. 2012; Butler et al. 1998).

Surface finishing was achieved by painting the model in matt black to make the object opaque. Very fine sand ($D_{50} < 0.2$ mm) was spread on the freshly painted surface so that, due to the contact with the paint, a single layer of sand attached to the surface. Theoretically, the addition of this real texture altered the initial topography contained in the ground truth elevation matrix. However, the impact on the assessment of measured data was neglected as: (i) the addition of sand can be approximated by a uniform shift in bed elevation, which is suppressed when the measured DEM is vertically aligned with the ground truth DEM; and (ii) the sand layer thickness is smaller than the minimum depth measurable by the photogrammetric setup developed for the laboratory experiments (Table III).

(a)

(b)

FIG. 2. Photographs of the 3D gravel bed: (a) the raw model; (b) the rendered model.

EXPERIMENTS

Implementation of the Measurement Technique

This section reports on the particular photogrammetric setup that was evaluated with the 3D printed gravel bed. The setup was designed to comply with a desired measurement window of size 450 mm in the flow direction and 400 mm transversely. The baseline between the cameras was set experimentally as close as possible to 250 mm. This was confirmed after stereo calibration by a numerically estimated 3D distance between the two cameras of 250.3 mm. A 50 mm margin around the measurement window was accounted for and cropped before analysis. Table III summarises the resulting measurement specifications. JPEG (1:4) fine format was selected for the image recording. An aperture of f/10 and sensitivity of ISO 200, combined with a 1/15 s exposure time, allowed good contrast and dynamic range, while manual focusing ensured sharp images.

Data acquisition consisted in obtaining:

- (i) 30 stereo pairs of a calibration chequerboard covering the whole cameras' common field of view (CFoV) and at distances close to the camera-to-object distance;
- (ii) 10 additional calibration stereo pairs to evaluate the rectification error after calibration;
- (iii) five stereo pairs of a gravel bed; and
- (iv) five stereo pairs of the 3D printed model.

The number of images used for each case is independent of that employed in the other cases. For the camera and setup calibration, it has been shown that it is essential to have numerous check points (Carbonneau et al., 2003). Further tests, specific to the calibration method employed, revealed that the calibration error reaches a minimum with 20 or more calibration images. The rectification error was spatially determined over the whole CFoV by using 10 additional calibration images. Finally, five stereo pair images of the measured surfaces (3D printed model and gravel bed) allowed an investigation into the effect of different imagery on stereomatching results (see the section 'Assessment of Stereomatching Reliability' for information on the images). In addition, restricting the number of images to five allowed for a time-efficient process to collapse the individually-extracted DEMs into one, with the aim of reducing stereo correspondence gross errors.

TABLE III. Summary of the photogrammetric setup designed for the test. All values were theoretically determined using the design equations and the rounded camera-to-object distance. Actual values may deviate because of the difficulty, in practice, to accurately set the cameras' 'flying' height and baseline.

Rounded camera-to-object distance (mm)	636
CFoV (mm)	500 x 498
Baseline (mm)	250
Range of disparity for 50 mm elevation span (pixels)	1580 to 1710
Overlap (%)	67
Sampling distance (mm) / resolution (pixel/mm ²)	0.15 / 43
Theoretical vertical accuracy or minimum measurable depth (mm)	0.39
Number of pixels in the 450 x 400 mm measurement window	≈7 800 000

Variation of DEM Sampling Distance

The visual aspect and quality of a DEM is strongly impacted by the sampling distance with which the DEM is represented (Lane et al., 2000). Too coarse a point

spacing results in a loss of topographic information. At the same time, grid size directly influences the size of numerical dataset that needs to be handled. A point spacing which is too fine will slow down the calculations. Although, the stereo-photogrammetric system allowed sampling distances as small as 0.15 mm (Table III), the default value for grid spacing was set to 0.25 mm, which is the same sampling distance used for the 3D printed model. The sensitivity of the DEM quality to changes in the collection parameters was evaluated by re-collecting the DEMs using different values for the parameter (sampling distance of 0.5, 0.75, 1, 1.5 and 3 mm).

Quantitative Assessment of DEM Quality Using the 3D Printed Gravel Bed

For assessing the measurement quality, the measured DEM of the 3D printed gravel bed needed to be aligned with the ground truth DEM. Data alignment had to be performed separately to the DEM reconstruction process, since no means was used to register measured DEMs within a common coordinate system with the ground truth. The data was aligned as follows:

- (i) the 3D printed model was placed horizontally in the hydraulic flume at the location where the gravel bed is normally recorded, with its long axis parallel to the cameras' baseline horizontal axis;
- (ii) horizontal alignment is performed with a search algorithm to find the region where the 3D printed model is represented in the measured DEM; and
- (iii) vertical alignment makes use of surface de-trending algorithms to remove any tilt between the measured and ground truth DEMs.

In cases where the sampling distance of the measured DEM is not 0.25 mm, elevations are interpolated onto a 0.25 mm grid to allow comparison with all check points contained in the 3D printed model. Finally, measured DEMs of the 3D printed model are quantitatively assessed after point-by-point elevation comparison with the ground truth DEM, providing measures of DEM quality.

Any vertical misalignment of the cameras, with the baseline not set parallel to the mean surface of the 3D printed model and/or when the cameras' optical axes are not perpendicular to it, results in systematic comparison errors. This translates to a DEM of difference (DoD) between the measured and ground-truth elevation maps that exhibits a linear trend when the cameras are tilting along one (nominally) horizontal axis and a bilinear trend when they are tilting along both axes (Fig. 3(a)). The trend corresponding to the deviation from the correct position is estimated by fitting a bilinear surface to the DoD in a least squares method (Fig. 3(b)). This surface is then removed from the measured DEM to perform the vertical alignment. The scale in Fig. 3(b) indicates that the vertical misalignment is responsible for systematic elevation discrepancies of up to several millimetres. It is thus fundamental to remove the misalignment before a realistic assessment of the measured DEM can be undertaken.

The reliability of the vertical alignment process was assessed by comparing the trends extracted from DEMs collected using a 0.25 mm (Fig. 3) with another employing a 3 mm sampling distance. The latter is the coarsest grid used in this study and thus it was expected that differences between the two trends would be maximised for this case. The vertical alignment was reliable, as even for the coarsest grid the mean unsigned (absolute) difference between the two estimated trends was 24 μm , the standard deviation was 29 μm and the maximum unsigned difference was 88 μm .

FIG. 3. (a) DoD before vertical alignment of the measured DEM collected with a 0.25 mm sampling distance with the ground truth DEM. (b) Fitted bilinear trend representing the vertical misalignment of the stereo setup. Elevations are displayed as gradient of greys; values are in millimetres.

Another trend was observed in the DoDs, after alignment and differentiation of the measured DEMs with the ground-truth DEM (Fig. 4). The trend is comparable to the material thermal contraction which caused the curvature observed during the drying process for the 3D printed model. The deviation of the final 3D printed model from its initial topography was measured with high precision by fitting a biquadratic surface to the DoDs using least squares. The magnitude of the deviation was found to be consistent throughout the various usages of the 3D printed model, exhibiting a mean absolute difference between two estimated trends (obtained using different setup geometry) of 0.02 mm, a standard deviation of 0.03 mm and a maximum unsigned difference of 0.24 mm, suggesting that the curvature originated during manufacturing and remained constant afterwards. The shape (Fig. 4(a)), inherent to the 3D printed model, was obtained by averaging two estimated trends and was incorporated in the ground-truth elevation matrix. The ground-truth DEM now represented the actual 3D printed model.

To confirm that the curvature trend observed in the DoDs did not originate from the measurements, but was indeed inherent to the 3D printed model, a stereo pair of the flat calibration chequerboard was matched with the SDPS. After alignment of the chequerboard's surface with the cameras' image plane using bi-linear de-trending, a range of elevations of 0.4 mm (which is exactly the theoretical accuracy of the setup and about 15% of the range of elevations found in Fig. 4) characterised the chequerboard surface and no clear trend was observed.

FIG. 4. (a) DEM of difference (DoD) before removal of the manufacturing-induced trend. (b) Fitted manufacturing-induced curvature that could not be eliminated by fixing the 3D printed model to a flat Perspex plate. Elevations are displayed as gradient of greys and values are in millimetre.

Assessment of Stereomatching Reliability

Quantitative evaluation and comparison of matching errors in DEMs of the 3D printed model and DEMs of the gravel bed was performed using the five DEMs that were collected for each case. It is important to note that the gravel-bed surface differs from the 3D printed model, although they share some common properties (the same sediment mixture and the same armouring process). The motivation of this test was to examine whether the 3D printed model is suitable as a real gravel bed substitute in terms of stereomatching.

The five DEMs were the result of matching stereo pairs taken continuously (Fig. 5), and rectified with the same calibration results. Matching performance between stereo pairs will thus only differ because of differences in the images themselves. Fig. 5 (b) reveals that image data acquired with a 2 s interval timer differ, although variations are small (the standard deviation in overall pixel intensity (averaged over a given image) between the five images was of the order of 0.01). However, intensity variations between repeat photographs at some pixel locations are larger than one, and influenced the stereomatching. Pixel intensity is defined as the maximum tonal value between the red, green and blue channels, expressed on an 8-bit (0-255) scale. The neon lights were identified as the cause of these differences, as they consist of periodic light stripes. Because the left-hand images are different (compared with the right-hand images), the similarity in intensity (area-based) between the left and the right images may change between stereo pairs (Table IV).

The five DEMs were differentiated one by one to provide a measure of the repeat stereomatching error value (RSEV) over the investigated surface. This procedure is similar to the use of the 'repeat scan error value' by Hodge et al. (2009). Here, RSEV is a matrix, the same size as the measured data, containing the mean absolute height discrepancies at the grid nodes between all repeated measurements. In the case of five repeated measurements, this leads to 10 independent comparisons (Fig. 5). The RSEV was calculated as:

$$\text{RSEV}(x,y) = \frac{\sum_{i=1}^5 \sum_{j=1}^5 |z_i(x,y) - z_j(x,y)|}{10}, \forall (i,j) \in [1,5], \text{ with } i \neq j$$

where $z_i(x,y)$ is the elevation at grid node with coordinates (x,y) in scan or stereomatch i . Both the mean RSEV (after averaging the height differences over the grid) and the maximum RSEV were calculated over the 3D printed model and the gravel bed for various DEM sampling distances (from 0.25 to 3 mm), providing an estimate of stereomatching reliability over the two surfaces.

FIG. 5. Example of photographs (left), and image histograms (middle) in the red, green and blue channels, for the five left-hand images, reduced to the zones of interest shown in the photographs of (top) the 3D printed model and (bottom) the gravel bed. The enlargements on the right show the small differences between images.

TABLE IV. Area-based differences in pixel intensity between the two images forming a stereo pair, for the five stereopairs taken in a row, with evaluation limited to the zones of interest shown in Fig. 5.

Difference in the mean pixel intensity		Difference in the median pixel intensity	
3D printed model	Gravel bed	3D printed model	Gravel bed
0.45	0.80	0	0
0.44	0.79	1	0
0.45	0.77	0	0
0.44	0.79	1	0
0.45	0.80	1	0

RESULTS

Qualitative Evaluation of DEM Generation Using Default Sampling Distance

Fig. 6 presents DEMs obtained from recorded data of the 3D printed model and gravel bed, collected with a 0.25 mm sampling distance. The associated probability density functions (PDFs) of surface elevations are shown. Visually, both DEMs correctly represent the surface investigated. However, the enriched texture and greater colour range in images of the gravel bed are thought to contribute to a ‘sharper’ graphical representation of the gravel-bed DEM.

Fig. 6 also shows that the recorded surface of the 3D printed model has a larger range of elevations with a narrower distribution around the zero-mean than the measured surface of the ‘real’ gravel bed. This infers that the effect of water-working was stronger on the surface replicated by 3D printing, which agrees well with the visual observation of coarser exposed particles and thus deeper troughs between particles, compared to the ‘real’ gravel bed.

3D printed model

Gravel bed

FIG.6. 2.5D DEMs collected with 0.25 mm sampling distance of (top) the 3D printed model and (bottom) the gravel bed. Elevations are in millimetres, and are represented with a gradient of greys. On the right are the associated PDFs of the DEM elevations.

Quantitative Assessment of DEM Quality

Fig. 7 shows the DoD (absolute differences are represented for clarity) obtained from the differentiation of the measured DEM (top left), after horizontal and vertical alignment, with the ground-truth DEM (top right), over the full dimensions of the 3D printed model. Visually, the two DEMs do not display obvious differences and analysis of the DoD is required. The DoD shows that surface errors are located at the grains' edges and gaps between grains. This observation relates well with findings obtained by Chandler et al. (2001), where stereomatching outliers were found near deep crevices between grains at the surface of a gravel bed. The reason is that occluded regions in the imagery, where pixels are replaced by values interpolated from neighbouring data, based on the assumption of a continuous surface, are smoothed in the DEMs and introduce surface errors.

Measurement

Ground truth

FIG.7. Top left: measured DEM of the 3D printed model collected with a 0.25 mm sampling distance, horizontally and vertically aligned with the ground truth. Top right: ground-truth DEM. Bottom: DoD over the full dimensions of the 3D printed model. The same colour representation, with elevations in millimetres, is used to represent both the measured and the ground-truth DEMs.

Table V shows statistics on the surface error, obtained from the comparison of the elevations contained in the DEM collected with default parameters with the ground truth elevations, over all check points ($n=873\,345$). There is little systematic error in the measured surface, witnessed by a mean error (ME) which is close to zero. In this study, computations of the mean height discrepancies between the measurements and ground truth confirm that the vertical alignment was correctly performed. In the case of DEMs registered with an external coordinate system, such as by using total stations, evaluation of the mean error can provide information on the presence of systematic shifts in the recorded elevations (Butler et al., 1998; 2002; Carbonneau et al., 2003; Lane et al., 2000).

The evaluation of the average surface error, represented by a mean unsigned, or absolute, error (MUE) of 0.43 mm, is needed to characterise the DEM accuracy. The global surface precision is characterised by a standard deviation of 0.62 mm ($\approx 5\%$ of surface D_{50}). Most DEM points (90%) are within ± 1 mm of check points, and 0.5% of DEM points exhibit errors above 3 mm (Fig. 7, bottom).

TABLE V. Quantitative assessment of the DEM collected with 0.25 mm sampling distance.

ME (mm)	0.04
MUE (mm)	0.43
SDE (mm)	0.62
Maximum absolute error (mm)	8.16
DEM points within ± 0.5 mm of check points (%)	71.4
DEM points within ± 1 mm of check points (%)	90.6
DEM points within ± 3 mm of check points (%)	99.5

The quality of the ‘default’ DEM is encouraging, as the actual accuracy of the measurements, represented by a MUE of 0.43 mm, is not severely degraded compared with the theoretical vertical accuracy of 0.39 mm, and is constrained by the image resolution. Fig. 7 confirms again that the loss in accuracy is associated with occlusions in the imagery, suggesting that the process steps undertaken to reconstruct the DEM were correctly executed, with minimal error propagation.

The quality of the DEM obtained in this study improves on previous photogrammetric measurements of gravel beds. However, any comparison is rather ambiguous, since the success rate of a photogrammetric survey essentially depends on the photogrammetric design and on the surface investigated, which differ between studies. In Carbonneau et al. (2003), mean errors from -1.5 to +3.6 mm, with surface precisions (SDE) ranging from 2.1 mm to 8.5 mm, were associated with the measurement of a dry natural gravel bed in the field, with a camera-to-object distance of 1.1 m. The surveyed surfaces were made of larger grains, with a D_{50} ranging from 18 mm to 61 mm, compared with a D_{50} of 13 mm in the present study. In the laboratory, a RMSE of 1.7 mm was obtained with a camera ‘flying’ height of 2 m by Chandler et al. (2001).

Effect of DEM Grid Size on DEM Quality

Fig. 8 presents the probability density functions of surface error for various grid spacings. No difference is visible when the sampling distance is increased from 0.25 mm to 0.5 mm. Above 0.5 mm, there is a consistent increase in the vertical error with increasing sampling distance (Fig. 8). Thus, increasing DEM grid size significantly affects the DEM quality.

Fig. 9 shows the effect of DEM grid spacing on statistical quality measures of the DEMs obtained from a single stereo pair and DEMs obtained from averaging five stereo pairs. It can be seen that the surface errors do not vary with DEM averaging. Fig. 9 agrees well with Fig. 8 in that changing the sampling distance from 0.25 mm to 0.5 mm does not vary the DEM quality. When the sampling distance is increased beyond 0.5 mm, the DEM quality is reduced. In addition, the flattening of the graphs, with decreasing grid spacing, suggests that no improvement will result from reducing the sampling distance below 0.25 mm. This cannot be verified since check points for this study are sampled every 0.25 mm, and a denser grid of check points is needed to confirm this statement.

There is a direct correlation between the different statistical parameters and DEM grid size. A very small change is quantified when grid size is increased from 0.25 mm to 0.5 mm, with an improvement or deterioration of the parameters of less than 1%. An average deterioration of 9% is associated with an increase of the grid size from 0.25 mm to 0.75 mm (the deterioration is 10.6% in the MUE and 7.7% for the percentage of DEM

points within ± 0.5 mm of the reference ground truth elevations).The deterioration is, on average, 34%, 102% and 308% (with a standard deviation between parameters of 4.3%, 13.4% and 33.8%), when the grid size is increased to 1 mm, 1.5 mm and 3 mm, respectively.

FIG.8. PDFs of vertical error for different grid spacing. Surface error is normally distributed, resulting in mean error close to zero. The PDFs for 0.25 and 0.5 mm grid spacings are virtually indistinguishable.

FIG.9. Effects of DEM grid spacing and averaging DEMs collected from different imagery on statistical measures of DEM quality. *Single* refers to a single DEM whereas *average* corresponds to the gridded elevations of the five DEMs averaged to produce one DEM.

Internal Reliability of Stereomatching

Fig. 10 presents the mean and maximum repeat stereomatching error values (RSEVs) for the DEMs of both the 3D printed model and the gravel bed, relating to different sampling distances. Overall, similar trends are observed, with reduced RSEVs for increased grid size. This is caused by smoothing DEM matching errors, due to more point cloud data being used for interpolating elevations at grid nodes.

FIG.10. Mean (left) and maximum (right) repeat stereomatching error value (RSEV) computed with 10 independent DEM comparisons for the 3D printed model and the gravel bed.

Figs. 10 and 11 and Table VI confirm that stereomatching is more consistent for data of the 3D printed model, compared to data of the gravel bed, with a mean RSEV reduced by 35%. Similarly, the maximum RSEV is larger for the gravel bed (4.59 mm) than for the 3D printed model (2.57 mm).

Finishing the surface of the 3D printed model maximised stereomatching performance, which is exemplified by a mean RSEV of 0.09 mm. However, the assessment of gravel-bed DEM quality using the 3D printed model results in accuracy statistics that may be understated (which means that DEM quality of a natural gravel bed is to be revised downwards), since errors due to stereomatching are globally lower in the DEMs of the 3D printed model.

TABLE VI. Summary of RSEV for DEMs of 3D printed model and gravel bed collected with a 0.25 mm sampling distance.

	3D printed model	Grave l bed
Mean (mm)	0.09	0.14
Maximum (mm)	2.57	4.59
DEM points with RSEV ≤ 0.5-mm (%)	96.1	89.08
DEM points with RSEV ≤ 2-mm (%)	>99.99	99.93
DEM points with RSEV > 2-mm (%)	<0.01	0.07

The ratio of the mean RSEV (0.09 mm) to the MUE (0.43 mm) is approximately 1:5 for the DEMs of the 3D printed model. This confirms the observations made in previous studies (Butler et al., 1998), which suggested that image quality is an essential parameter in determining the success of photogrammetric surveys. However, image quality is often reduced by the texture contained in the imagery. Results of the present study, however, where DEMs are collected from different images of similar quality, suggest that intensity

similarity between the two images forming a stereopair, on which stereo correspondence establishment relies, does affect DEM quality.

Whilst RSEVs cannot be ignored, especially at small sampling distances, averaging several DEMs collected from different imagery to mitigate stereomatching gross errors, proved to be of negligible interest in terms of measurement quality (Fig. 9). As an alternative, a filter, which removes and interpolates points in the average DEM, when RSEVs greater than 1 mm are detected, was tested on the DEM collected with default parameters. No significant change was observed. This is explained by the fact that stereomatching errors are essentially located in occluded regions of the DEM (Fig. 11), where elevations are already interpolated during stereomatching. Hence, a means to mitigate stereomatching errors in occluded regions of the DEMs has yet to be found, although the potential of multi-view stereo (MVS) methods might be investigated in this context.

3D printed model

Gravel bed

FIG. 11. Representation of the RSEV, which is the absolute difference between DEM points collected using different imagery, averaged over all ten independent comparisons (five repeat DEMs), for (top) the 3D printed model and (bottom) the gravel bed. The sampling distance is 0.25 mm.

605

DISCUSSION

606 Methods for assessing DEM quality, using independent check points, can easily
 607 result in misleading statistics, when the net of check points employed for the assessment
 608 is of low density and/or of poor repartition (Lane, 2000). Moreover, accuracy statistics
 609 might be insensitive to changes in DEM collection parameters. Another potential issue
 610 relates to the confidence with which check points are estimated and registered within the
 611 DEM. When measuring devices, such as total stations and laser scanners, are employed,
 612 errors can propagate so that the actual survey precision of check points is decreased and
 613 is generally not known.

614 The use of a 3D printed model to assess DEM quality improves greatly on previous
 615 approaches, which have been characterised by the need for an additional instrument to
 616 locate and register check points within the DEM. Furthermore, previously the preparation
 617 of ground truth data has been repeated for each assessment and has required DEM
 618 reconstruction and error editing, which is time consuming. This has been replaced, in the
 619 current method, by the preparation of a reliable and practical 3D printed model. Thus,
 620 future studies are not restricted by the common characteristics of check point measuring
 621 devices, such as bulkiness and long recording times, which not only limits field
 622 applications, but also the ability to record underwater check points. In future, a 3D
 623 printed model provides a dense and accurate set of check data, where resolution is only
 624 limited by the 3D printer capabilities. In this study, the 3D printer would have allowed
 625 check points to be spaced with distances as small as 0.07 mm. This is beyond what is
 626 achievable with the measurement techniques currently used in hydraulic applications.
 627 Producing and handling such high-resolution data would still be difficult at present. In
 628 addition, the depth accuracy with which the 3D model was printed, between 0.033 and
 629 0.066 mm and with no error slip, ensured increased confidence in check point location.
 630 The size of the 3D printed model, 296 x 184 mm, which is the maximum size that the 3D
 631 printer available for the study allowed, might not be suitable for all applications. DEM
 632 quality assessment solutions over larger measurement windows are either: (i) to move the
 633 ground truth to determine the spatial distribution of DEM errors; or (ii) to produce several
 634 ground-truth models that can be merged. However, the relatively small size of the model
 635 allows it to be used easily at various locations in future, for both laboratory and field
 636 setups.

637 The main uncertainties in the assessment using a 3D printed model result from the
 638 alignment procedure necessary to superpose the measurements with the ground truth.
 639 These uncertainties were present when metrics obtained with stereo photogrammetry
 640 were compared with laser-scanned data (Chandler et al., 2001; Lane, 2000). In the
 641 present study, the alignment was performed using search and surface de-trending
 642 algorithms. The reliability of the procedure was assessed semi-independently by
 643 comparing the setup vertical misalignment trends with different sampling distances. This
 644 demonstrated that the alignment procedure is able to align data with great precision,
 645 characterised in Table V by a mean error of 0.04 mm.

646 The present work also highlights the challenges that larger rigid 3D printed models
 647 might face, due to the material's thermal contraction. There is limited information
 648 available on preparation that ensures minimal thermal contraction during the printing and
 649 drying phase. The observed deformation is largely dependent on the 3D printer and
 650 material used, and care needs to be taken to design a suitable model. In this study, the

small warping effect the 3D print endured was corrected by mounting it on a flat and rigid Perspex sheet. The remaining trend of deformation was recorded by the setup, and was confirmed by multiple recordings and corrected during post-processing.

The inherent difficulty related to the use of a 3D printed model to assess surface error is the need to produce a realistic model of the surface to survey, since a global measure of error can be unreliable if it is based upon test sites that have little resemblance with the site of interest (Lane et al., 2005; Wang et al., 2009). Topography has an essential impact on measurement quality, especially with photogrammetric surveys, with occluded regions accounting for most of the errors detected on the surface (Chandler et al., 2001). A realistic topography was acquired by measuring a patch of gravel bed, representative of simulated riverbeds in laboratory flumes. However, because the ground truth was acquired with imagery, the interstices between particles are not always represented accurately. A technique which allows vertical recording, such as laser scanning, if available, may theoretically improve the details at the interstices between particles of the ground truth. To obtain a natural look for the transparent 3D printer material, the gravel-bed model was painted and sand was spread on the wet paint to ensure reliable stereomatching on images of the 3D printed model (mean and maximum RSEV of 0.09 mm and 2.57 mm, respectively). The difference in stereomatching performance between images of the 3D printed model and those of a laboratory gravel bed was quantified in terms of the repeat stereomatching error value (RSEV). This is proposed as an internal reliability test, addressing the stereomatching procedure. Larger RSEVs were obtained over the gravel bed (characterised by a 35% increase in mean RSEV), suggesting that stereomatching performs better, globally, over images of the 3D printed model. Hence, it is expected that DEM quality evaluated using the 3D printed gravel-bed model overestimates the DEM quality of natural gravel beds. For the 3D printed gravel-bed model, a ratio of 1 to 5 was obtained between the mean RSEV and the MUE. Assuming this ratio is valid for DEMs of natural gravel beds, this corresponds to an increase in the MUE from 0.43 mm for the 3D printed model to 0.7 mm for the natural gravel bed.

CONCLUSIONS

A 3D printed gravel-bed model was produced and subsequently used to evaluate the overall performance of a stereophotogrammetric setup developed for hydraulic experiments. The versatility and ease of use of the assessment method make it suitable to a large range of research areas, where small-scale and accurate topographic models are needed. The key advantages over traditional DEM evaluation methods can be summarised as follows:

- (i) High density and uniform repartition of check points, which makes the DEM assessment more realistic and allows for a better quantification of errors due to changes in the DEM collection parameters, and as such allows optimisations to be performed on the photogrammetric workflow.
- (ii) Strong (and measurable) confidence in check point locations and registration with the measured DEM.
- (iii) Easier implementation of the assessment routine in a DEM acquisition campaign, with significant improvements in time and efficiency, and a larger range of situations where the assessment can be performed.

The results in this paper will be useful for setting up the optimum strategy for gravel-bed DEM collection, both in air and through water. Experiments have confirmed that the grid spacing should be chosen with care, in order to ensure correct surface representation. In particular, a sampling distance larger than 0.5 mm resulted in a significant loss of geometric information and degraded the DEM quality. Furthermore, it has been shown that the ground truth needs to be representative of the surface under consideration, in order to obtain the most realistic assessment. 3D printing is suitable, and at present the most advanced method, for obtaining realistic ground truth for known surfaces, although printed models can be affected by the material's thermal contraction. The acquisition of ground truth with imagery affects the surface details at interstices between particles.

The assessment of using off-the-shelf processing and consumer-grade digital cameras for a stereophotogrammetric setup showed that high accuracy and precision, in terms of sub-millimetre MUE and SDE, can be obtained with the presented default DEM collection parameters. Finally, this research confirmed the common expectation that most of the errors are caused by occluded regions in the imagery, a recurring stereophotogrammetric measurement problem on rough surfaces. This suggests that new means for capturing occlusion, beyond traditional uniform surface smoothing, must be envisaged and the potential of employing multi-view stereo (MVS) methods to assist in this regard may be worthy of investigation. The ultimate goal is to obtain measurements with local vertical accuracy as close as possible to the optimal accuracy allowable by the setup.

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Résumé

Zusammenfassung