ADVANCES IN MICROTOPOGRAPHY MEASUREMENT OF GRAVEL BED SURFACE STRUCTURE IN THE FIELD

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Field characterization of gravel-bed surface structure is important for studies on flow resistance, sediment transport and in-stream habitats. The following study presents technical developments that make obtaining high-resolution digital elevation models (DEMs) from gravel beds in the field more efficient and effective. Using close-range digital photogrammetry (CRDP), only two consumer-grade digital cameras, a mounting system and a laptop are needed to start collecting data. Unlike previous photogrammetric approaches, calibration was performed in the laboratory prior to moving to the field. The calibration validity was assessed on site using a simple chequerboard. Final DEM quality was assessed with a light-weight ground-truth object to guarantee reliable information can be extracted from the measured microtopography.

1   INTRODUCTION

The surface texture and structure of gravel-bed rivers exert significant control on flow hydraulics, sediment transport and distribution of in-stream habitats [1]. In response to the flow acting on the bed, when of sufficient strength, the bed coarsens and develops peculiar grain arrangements (e.g., cluster bedforms, imbrication, which are typical of the armor layer). As such, the texture and structure of gravel beds can be indicative of the flow and transport processes that have formed (water-worked) the surface [1]. Field observations on surface texture and structure, and their stability over mobilizing flow events, have traditionally been obtained through photographic evidences and sediment size analysis [2].

With progress in remote sensing and computer performance, fluvial topography can now be measured at high spatial resolution and represented as a 2.5D digital elevation model (DEM), revealing the complex grain arrangements at the surface. Sophisticated analyses of bed microtopography provide the researcher with an array of information on surface structure and bed roughness, which supplement typical information on bed material size. Using DEMs, it is possible to measure particle imbrication, orientation, packing and exposure, as well as the geometry of small-scale sedimentary structures, and to infer the surface-forming flow direction [1].

Field application of topography remote sensing at the grain scale, using either close-range digital photogrammetry (CRDP) or terrestrial laser scanning (TLS), is currently hindered by the tedious workflow challenges one needs to overcome to obtain high-accuracy DEMs and reliable information from the measured microtopography. Repeating scans, in addition to applying erroneous points filtering techniques, is currently the best option to reduce errors and improve accuracy for TLS applications, with the measuring precision otherwise being dependent on the used instrument and software [3]. Compared with applying TLS in the field, a well-developed CRDP system has the advantage of being easily deployed due to its reduced cost, its small size and weight, its optional power supply and the possibility of very-quick data acquisition. However, the challenge with CRDP is the development of a stable workflow from image acquisition to surface structure data. For this reason, the majority of previously published grain-scale gravel-bed DEMs were obtained using commercial software packages. This required setting up control points on the riverbed, surveyed with an independent measuring device for bundle adjustment and subsequent DEM reconstruction. Recent progress was made in the laboratory, where the use of non-proprietary digital photogrammetry (i.e. using off-the-shelf calibration and stereo matching computer programs) allows optimizing the workflow to the tasks ahead, which when done appropriately can result in sub-millimeter accurate gravel-bed DEMs [4, 5] – a development that is yet to be tested in a natural river environment.

2 METHODOLOGY OVERVIEW

This research mapped fluvial microtopography using non-proprietary CRDP, following the method presented in Bertin et al. [5], on three exposed and vegetation-free gravel bars in the Whakatiwai river, NZ (**Figure 1A**). Gravel bars were labeled bar #1 to #3, with numbers increasing upstream. Within each bar, a small area of exposed gravel (~0.5 m^2), termed "patch", was chosen at the bar head close to the water edge for consistency, also ensuring the surfaces studied are regularly flooded. The following presents how CRDP was deployed to collect DEMs, and how those DEMs were assessed to ensure reliable findings. The analysis of the DEMs, and a comparison of the texture and structure characteristics of the three gravel bars investigated, is presented elsewhere.

2.1 CRDP deployment and DEM collection

Imagery data was collected from the three patches in August 2014, during a period of low flow, using two consumer-grade digital cameras in stereo (Nikon D5100s with Nikkor 20 mm lenses, separated by a 250 mm baseline, **Figure 1B**). Necessary camera calibration [5] was performed in the laboratory prior to transporting the setup to the field. The aperture was set to f/20, ensuring a large depth of field, and focus was set at a distance of 0.8 m, based on the expected field requirements. After calibration, care was taken to ensure that the cameras' arrangement was not disturbed, and subsequent testing in the field was undertaken (see *Section 2.2*). Whilst in the field, we attempted to orientate the mounting bar parallel to the surface-forming flow direction, determined by eye from channel shape (**Figure 1B**). Stereo photographs of the exposed patches were recorded vertically from a height of ~0.8 m, resulting in point data spacing ~0.2 mm and a theoretical depth resolution ~0.6 mm. Cameras were remotely controlled from a laptop and operated in manual mode, with the possibility to vary the shutter speed to have well-illuminated and contrasted photographs necessary for successful stereo matching [5].

From the imagery data, the surface texture and grain orientation were determined for each gravel bar using BASEGRAIN® [6], and DEMs were created from which we measured various indices known to represent surface structure and roughness. DEMs were interpolated onto grids with 1 mm spacing, first by interpolating onto 0.25 mm grids to minimize the loss of topographic information, then resampling onto the final grids to expedite calculations with minimal surface smoothing (mean unsigned error, MUE ~0.025 mm). Before resampling onto a 1 mm grid, outliers were identified using the mean elevation difference parameter [3], and replaced in the DEMs using bi-cubic spline interpolation. The MUE between original and filtered DEMs accounted for less than 0.01 mm. Therefore, filtering was considered optional and its application was not stringent. DEMs were finally detrended (using bi-linear surfaces fitted by least-squares) to remove the combined effect of local bed slope and setup misalignment, and normalized to have a mean bed level corresponding to a zero elevation.
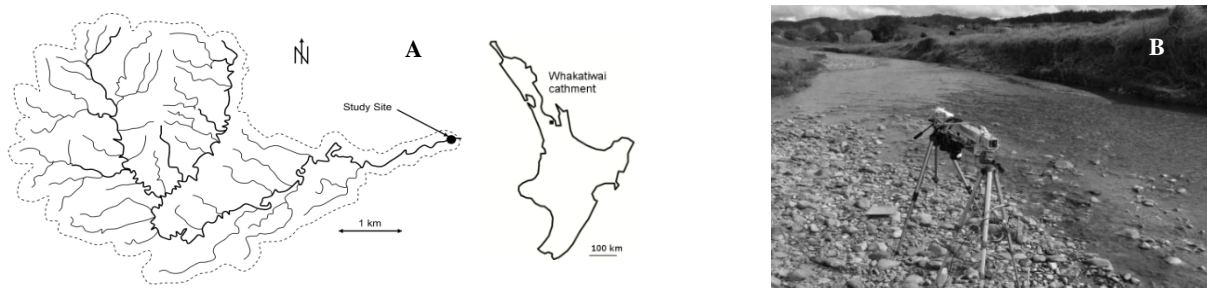

Figure 1. Whakatiwai catchment in the North Island of New Zealand, A) site location; and B) image of CRDP deployment on bar #2, looking upstream. Note the alignment of the setup with the apparent flow direction.

2.2 CRDP validation and DEM accuracy

After transport of the setup to the field, a small chequerboard, covering the common field of view (CfoV), was used to evaluate the laboratory calibration. The stereo photographs were rectified [5] using the calibration data obtained in the laboratory, and the rectification error, which is the absolute scanline difference between corresponding pixels, was measured for every square's corners in all rectified stereo photographs of the chequerboard (i.e. at about 200 locations throughout the measurement area). The mean, standard deviation, and

maximum rectification error were computed, and compared with values obtained before moving to the field. Final DEM quality was assessed with a 3D-printed gravel bed of known dimensions, as per the method of [4].

3   RESULTS

3.1   Grain-scale DEMs and ortho images

CRDP naturally produced 2D (i.e. ortho-images, after image distortion is removed) and 2.5D (i.e. DEMs, where one planimetric location is associated with a single elevation) maps of the surfaces studied. Field experiments using TLS generally also require imagery data to be collected, whether it is for documenting and/or for grain size analysis. CRDP has the advantage that both the DEMs and the ortho-images are automatically referenced within the same coordinate system (**Figure 2**), which eliminates the need to align the two.
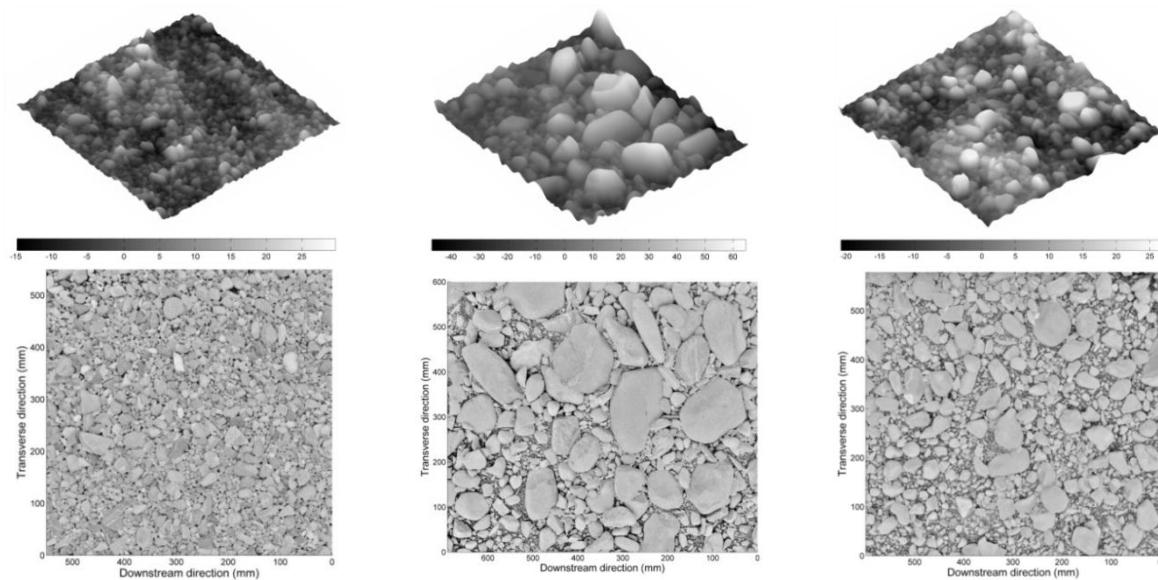
Figure 2. Final DEMs and ortho-images from the Whakatiwai patches (bar #1 to #3 from left to right). Elevation is represented as gradient of greys and is in millimeters. Flow direction is from right to left.

3.2   Data quality assessment

After calibration, the rectification error was represented by a mean of 0.09 pixel, a standard deviation of 0.08 pixel and a maximum of 0.37 pixel, ensuring minimal systematic stereo matching error, as the latter is performed along lines of 1 pixel width [5]. After moving the CRDP setup to the field (simply placed flat in the boot of a car, surrounded by soft material to protect the equipment and hinder any movement), the rectification error increased (mean = 0.29 pixel, standard deviation = 0.23 pixel and maximum = 0.91 pixel), certainly caused by the transport (and shaking that occurred) in the car. Despite the increased rectification error, which naturally will affect stereo-matching performance, the rectification error remained below 1 pixel throughout the imaging area, the threshold above which stereo matching errors become inevitable [5].

The 3D-printed gravel-bed model used for in-situ DEM quality assessment is presented in **Figure 3A**. **Figure 3C** shows the DEM of difference (DoD), obtained by differentiating the measured DEM of the 3D-printed model (**Figure 3B**) with the truth DEM, after alignment of the two. Visually, large errors (> 10 mm) are rare and are limited to the grains' edges and the surface troughs. It is well known that both CRDP and TLS have difficulties measuring occluded areas [3, 5]. Generally, the consequences are a reduction in pore depth and DEM properties such as the bed-elevation standard deviation, σ_Z. Quantitatively, most of the measured DEM points (98%) were within ± 3 mm from the truth data, 82% were within ± 1 mm, and 58% were within ± 0.5 mm. σ_Z measured from the DEM was 99.8% of the truth value, hence verifying the reliable measurement of surface roughness. A MUE of 0.67 mm between measured and truth values was estimated from the DoD, with a SDE of 1.16 mm and a maximum unsigned error of 17.1 mm. Using a measuring distance of 640 mm and a 250 mm baseline between the cameras, improved DEM accuracy was achieved in the laboratory (MUE = 0.43 mm, SDE = 0.62 mm and maximum unsigned error of 8.16 mm, [4]). The reduction in field DEM quality is essentially the

result of the increased camera-to-object distance and the increased rectification error due to transport. However, this evaluation shows that CRDP can measure exposed fluvial surfaces in the field with sub-millimetre resolution and vertical accuracy (based on MUE), and guarantees reliable grain roughness information.
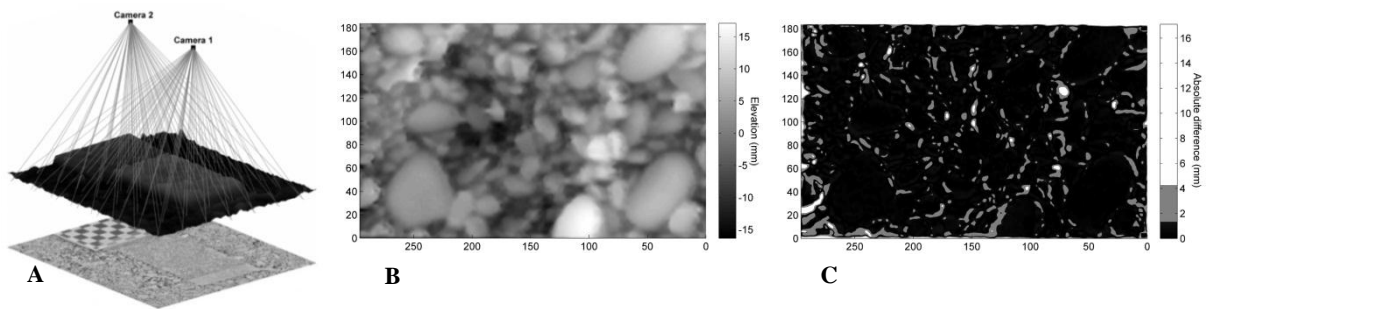

Figure 3. A) On-site evaluation of CRDP performance using a 3D-printed gravel-bed model (296 × 184 mm, D_{50} = 13 mm); B) measured DEM of the 3D-printed model; and C) DoD between measured and truth data (0.25 mm sampling distance).

4   DISCUSSION AND CONCLUSION

CRDP can be efficiently deployed in the field to collect high-resolution and high-accuracy DEMs from exposed gravel bars. The only resources needed are two digital cameras, a mounting system, and a laptop. Compared to other photogrammetric approaches, the necessary calibration was undertaken in the laboratory, prior to moving to the field. This removed the need to dispose control points, distributed on each measured surface, and required to be independently surveyed. Using a simple chequerboard confirmed that the calibration was still valid after moving the setup to the field. The possibility to adjust the camera settings (e.g., the shutter speed) and to post-process images [5] benefitted the collection of DEMs without being impacted by variable lighting conditions, which challenge applications of TLS and range imaging. A light-weight (~1.5 Kg) 3D-printed model, resembling a water-worked gravel bed, was used on site as a ground-truth object to assess the accurate measurement of elevation data. In this work, DEMs were collected at a 1 mm sampling distance, although it is worthwhile to note that data can be re-processed at 0.2 mm sampling distance, the pixel size at the riverbed's plane, with a measured accuracy of 0.67 mm (based on MUE), which guarantees reliable grain roughness properties from the DEMs.

Continuous progress in topography remote sensing is important to extend our fluvial knowledge, for example by allowing the study of flow-channel processes at different scales, in both space and time. Future work will concentrate on applying the developed methodology to the survey of larger areas and submerged topographies, ultimately to develop a technique customized for use by fluvial geomorphologists in the field.

5   ACKNOWLEDGEMENTS

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