MONITORING RIVER CHANNEL AND FLUME SURFACES WITH DIGITAL PHOTOGRAMMETRY

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ABSTRACT: This paper describes and illustrates a technique for high resolution monitoring of the surface morphology of water-worked sediments. The monitoring uses close-range digital photogrammetry. While photogrammetry is a long-established technique, more recent developments in digital photogrammetry allow application in fluvial research to be highly cost effective in both flume and natural river channel studies. Results are presented that involve two scales of laboratory flume: a smaller-scale application associated with sediment sorting processes in a straight channel; and a larger-scale application involving sediment transport and bed material feedbacks in a meandering channel subject to overbank flows. A preliminary assessment of data quality is undertaken with encouraging results. The precision of elevation estimates corresponds to the scale of the imagery acquired and hence may be controlled by design of the image acquisition process.

INTRODUCTION

It is increasingly recognized that quantification of the surface characteristics of riverbeds is critical to understanding both flow processes and sediment transport. Photogrammetry has a well-established history and is commonly used as a surface measurement tool in a wide variety of disciplines. In terms of hydraulic engineering, it has been used in studies of river bank erosion (e.g., Painter et al. 1974; Collins and Moon 1979; Barker et al. 1997; Pyle et al. 1997; Dixon et al. 1998), braiding processes in both the field (Lane et al. 1994, 1996; Lane 1998) and the flume (Stojic et al. 1998), and studies of surface roughness of exposed gravel bars in field environments (Butler et al. 1998). Until recently, the potential of photogrammetry has been restricted by hardware limitations. Digital-image analysis means that photogrammetry is an increasingly cost- and time-effective solution for three-dimensional measurement of surfaces, as it opens up the possibility of automating at least some parts of the data collection process and is more dependent upon access to relatively cheap software as opposed to expensive hardware. The aim of this paper is to illustrate that digital photogrammetry is a technique that has increasing potential for use by hydraulic engineers, particularly in flume studies. This paper does not address the methods involved in any detail, as a full description and evaluation of these is provided in a companion paper being published in a photogrammetric journal (Chandler et al. 2001). Rather, this paper focuses upon showing what sort of results a photogrammetric approach can achieve in two experimental flume studies of different spatial scales, both performed at Hydraulics Research (HR), Wallingford, U.K.

EXISTING SURFACE MONITORING METHODS FOR EXPERIMENTAL FLUME STUDIES

Central to both studies is the need to measure surface morphology under different experimental conditions (discharge, sediment supply, grain-size characteristics). Study 1 was based in a 60 m long, 2 m wide tilting flume, with a two stage channel and an active bed that was 0.6 m wide [Fig. 1(a)]. The study was concerned with determining the evolution of bed structure in response to various in- and out-of-bank flows and sediment supply rates, and involving experiments on the transport of graded sediment (Willetts et al. 1998). Surface monitoring was important to identify the temporal evolution of bed texture resulting from changes in response to flow and sediment supply rate change. The typical duration of any single experiment was three weeks. An area of 0.25 × 0.25 m in the center of the channel was measured using a laser sensor mounted upon a motorized positioning system, which locates the laser within an assumed horizontal plane. The distance to the bed is measured at a point, the sensor is displaced, and the cycle repeated until full coverage of the desired area is obtained. This system measures very precise distances between the sensor and the bed and has the ability to measure directly through shallow water. The narrowly defined laser beam allows well-defined digital elevation models (DEMs) to be generated, with a horizontal resolution of just 0.0005 m, such that bed particles are clearly identifiable within the height model. The main problem with this particular system is the speed of data acquisition; eight hours to acquire a DEM of the 0.25 × 0.25 m area. While this is not a problem in terms of identification of the evolution of surface texture, it proved to be more difficult to record the evolution of larger-scale morphological structures due to the small area covered (McEwan, personal communication, 2000). Thus, the application of digital photogrammetry to the tilting flume was done to investigate the extent to which it could provide information over a larger area and more frequently.

Test 2 was based in the Flood Channel Facility [Fig. 1(b)]. This study was concerned with the evolution of interactions between flow, sediment supply, and bedform development in a meandering channel with in-bank and out-of-bank flows and different floodplain characteristics (e.g., roughness, sinuosity, etc.). This also involved mixed grain-size sediment. In these experiments, that channel was run until equilibrium was reached, then the bed was frozen to allow flow measurements to be made. During this period, a touch sensitive, incremental, automated 2D bed profiling system was used to record the bed surface using a 10 mm diameter stainless steel rod, which was lowered onto the bed surface. This was used to record the morphology of cross sections with a 0.5 m spacing. Again, data acquisition rates are comparatively slow, with approximately five seconds required to measure each point within any given cross section. The aim of using digital photogrammetry in this situation was less to increase the speed of data capture, and more to increase the spatial density of surface information.

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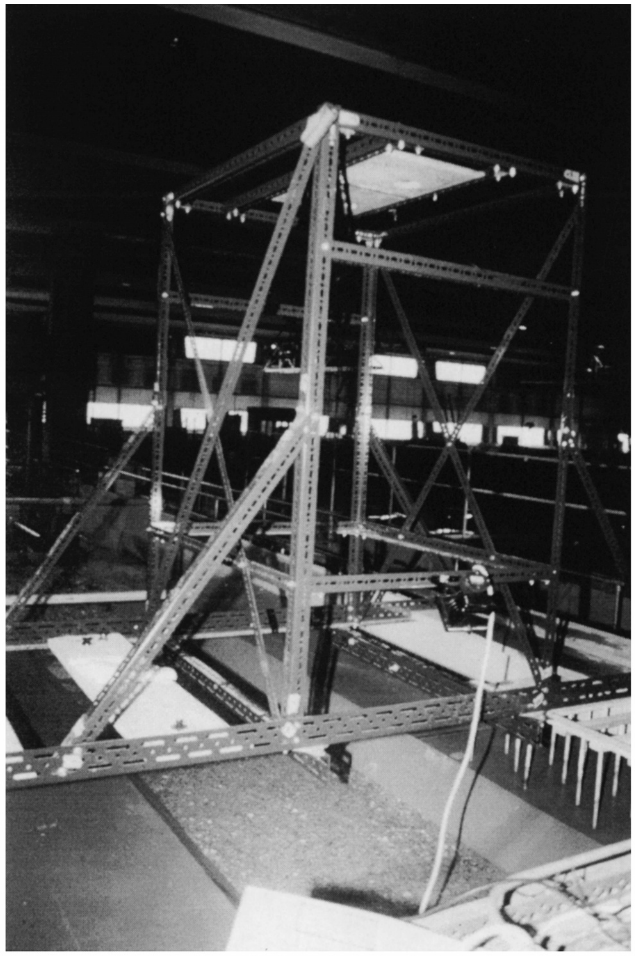
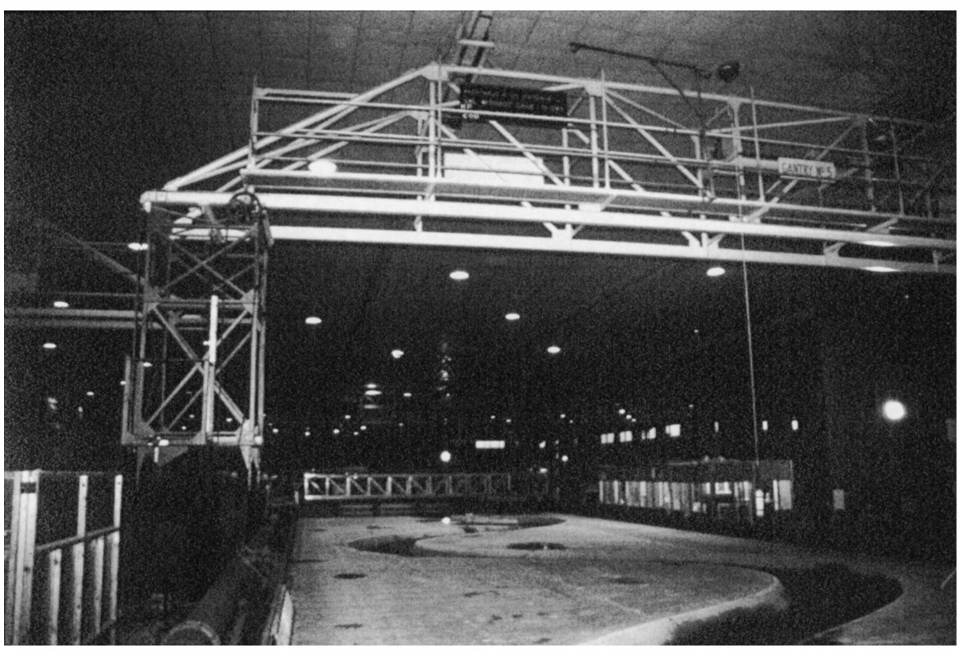


(a)



(b)

FIG. 1. Illustrations of: (a) Tilting Flume; (b) Flood Channel Facility Studies

CLOSE-RANGE DIGITAL PHOTOGRAMMETRY

Close-range digital photogrammetry is based upon automated analysis of digital imagery using the basic principle of the perspective projection (Albertz and Kreiling 1975; Slama 1980). The general projective transformation describes the relationship between the two mutually-associated coordinate systems:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = k\mathbf{M} \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix} \tag{1}$$

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where k is a scale factor, and **M** is a rotation matrix with elements $m_{11} \ldots m_{33}$.

In the ideal case (Albertz and Kreiling 1975; Slama 1980), it can be assumed that a straight line passes between a point on the surface of interest (in the object space with coordinates X, Y, Z), the perspective center of the imaging device (e.g., the camera lens with coordinates in the object space of X_o, Y_o, Z_o) and the image of that point on the recording medium (in the image space with coordinates x, y, z). The rays are transformed from the 3D object to the 2D-image plane and so the z coordinate of any imaged point is a constant value, equivalent to the focal length of the camera ($-c$). Therefore, expansion and rearrangement of (1) derives the well known collinearity equations (Ghosh 1988), which provide the foundation of photogrammetry:

$$x = \frac{-c[m_{11}(X - X_o) + m_{12}(Y - Y_o) + m_{13}(Z - Z_o)]}{[m_{31}(X - X_o) + m_{32}(Y - Y_o) + m_{33}(Z - Z_o)]} \tag{2a}$$

$$y = \frac{-c[m_{21}(X - X_o) + m_{22}(Y - Y_o) + m_{23}(Z - Z_o)]}{[m_{31}(X - X_o) + m_{32}(Y - Y_o) + m_{33}(Z - Z_o)]} \tag{2b}$$

The collinearity equations are used to generate the coordinates of new points, which normally involves two distinct procedures: a 3D intersection and spatial resection. Assume that two images of an object are acquired from two separate locations and assume initially that the positions (X_o, Y_o, X_o) and orientations (**M**) of these two images are known. For simplicity, assume also that the same camera is used to obtain both images with a stable focal length that is known. By measuring the photo-coordinates of a single point (x, y) visible on both images, (2) generates four equations with the three object space ordinates of the point (X, Y, Z) as unknowns. The collinearity equations can therefore be used to obtain this object coordinate and are analogous to a 3D-intersection procedure. This procedure can be repeated for any point visible on both images, thus generating a series of coordinates to represent any object or surface. However, the intersection process does require knowledge of **M** and (X_o, Y_o, Z_o) for each image, and, although it is possible to measure these parameters directly at the time of image acquisition, a more efficient procedure is available. If at least five points at known object locations are clearly visible, a spatial resection can be carried out to derive the positions and orientations of the images. Such points are known as photocontrol points and, by combining their measured photo-coordinates with their known object locations, it is possible to determine **M** and (X_o, Y_o, Z_o) for each image, again by using the collinearity equations. Implementation of the spatial resection and intersection using collinearity is the essence of analytical photogrammetry (Ghosh 1988).

In practice, these procedures are complicated by the fact that a perfect perspective projection is rarely achieved due to imperfect lenses, atmospheric refraction, etc. It is normally possible to correct for such systematic effects by modifying the image coordinates using various mathematical models before the collinearity equations are applied. If a specialized camera designed for photogrammetry is used, then a calibration certificate should be available and will provide all necessary information. If film is used to obtain imagery and then scanned using a low quality desktop scanner (Baltsavias 1994), a further system calibration is necessary. Photogrammetric or ''metric'' cameras are expensive, and it is increasingly common to use ''nonmetric'' cameras (e.g., professional 35 mm cameras). Camera calibration then becomes critical, particularly if accurate data are to be generated (Chandler et al. 2001).

Digital photogrammetry uses either manual measurement or automated stereo matching of the two digital images to identify conjugate points and, hence, extract elevation coordinates. Stereo matching has the advantage that it may significantly decrease data collection time, but it may result in a number of incorrect matches that necessitate careful checking and perhaps editing of any derived DEM. The work presented in this paper used the ERDAS Imagine OrthoMax package, which provides cheap access to area-based stereo matching (Schenk and Toth 1991) using the Vision International Matching Algorithm. This software also provides interactive editing using stereo vision.

A summary of the stages of a photogrammetric analysis is shown in Fig. 2. This emphasizes that the critical first step in any photogrammetric survey is project design, in which the desired precision of elevation and the required DEM density, in combination with various camera parameters, will be used to determine the necessary image scale and consequent coverage. The desired elevation precision (p) is related to the dimension of individual pixels in the object space or surface of interest (d_o), so that approximately: $p \approx d_o$. For vertical photography, the dimension of a pixel on the object is controlled by the scale of the photography (c/H, where c = focal length and H = camera flying height) and the physical size of the pixel in the image space (d_e). For a digital camera, d_e equates to the physical size of an individual sensor element, but for a film-based camera, d_e is equivalent to the optical resolution of the scanner. Thus, the expected precision of derived elevations is given by

$$p \approx d_o = \frac{d_e}{c/H} \tag{3}$$

To achieve a given precision, and given that c will be defined primarily by the type of lens available, it is possible to alter either d_e or H. Smaller values of d_e or H will increase the precision of the results obtained. In practice, the user has less control over d_e than H because the image space pixel dimension depends on the image source. It is a fixed parameter for a digital camera but if digital imagery is obtained by scanning

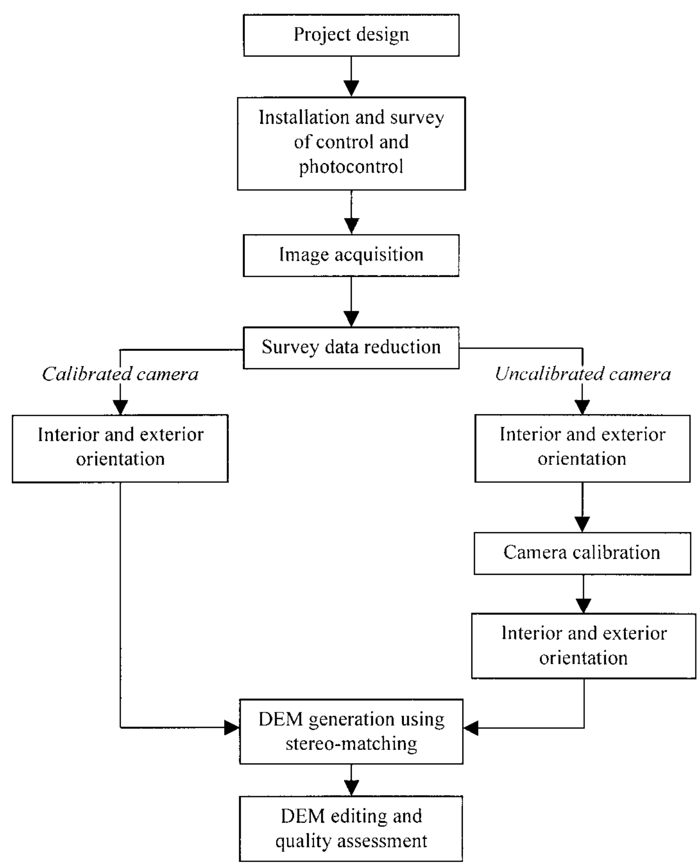

FIG. 2. Basic Stages in Data Collection Using Digital Photogrammetry

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film, this can be varied, possibly to a value as low as 12.5 μ. Reducing H can be used to increase precision, but this will also reduce the area of coverage. With a smaller area of coverage, progressively more image pairs will be needed to cover the measurement area. Effectively, the initial phase of project design involves determining the largest H, to maximize area of coverage, to achieve an acceptable p. An additional consideration is the density of the final extracted data. If stereo matching using area-based correlation is adopted, the smallest recommended DEM spacing possible is $5p$, as the matching procedures tend to use a 5×5 area-weighted template.

The two applications described here are categorized ''close-range'' (Atkinson 2000), because in both instances the camera to object distance is less than 300 m. A full consideration of the methods, issues, and results is provided in Chandler et al. (2001), particularly with respect to image-configuration, ground survey, camera calibration, and optimization of the image acquisition process (e.g., lighting). This paper only seeks to illustrate the potential of this monitoring technique. For both applications, imagery was acquired with a Kodak DCS460 digital camera as previous research had suggested that these had considerable potential for photogrammetry (Fraser and Shortis 1995; Peipe and Schneider 1995; Ganci and Shortis 1996; Fraser 1997; Shortis et al. 1998). A major advantage of digital cameras is that no photographic processing is required, and hence it is possible to check image quality immediately and reacquire if necessary. The DCS460 comprises a 35 mm camera body with a $3{,}060 \times 2{,}036$ CCD array. Each pixel has a dimension of 9 μm.

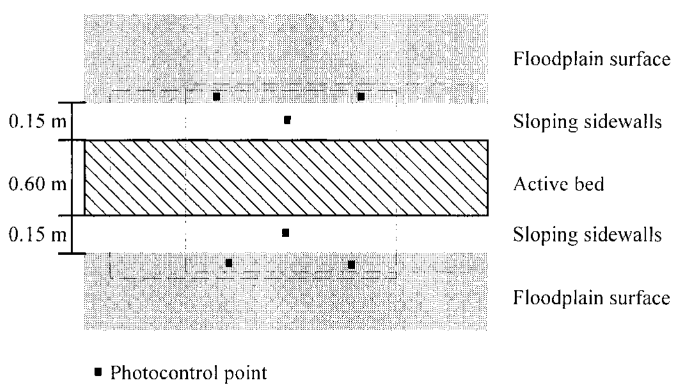

FIG. 3. Photogrammetric Design for Tilting Flume Application

APPLICATION 1: TILTING FLUME

Existing laser-based methods provide data at a 0.0005 m resolution and precision over a 0.25×0.25 m area. As the channel of the tilting flume was 1.0 m wide, and given that inserting photocontrol points in the active bed would have created unacceptable disturbance, photocontrol points had to be installed on the sloping channel sidewalls and on the floodplain surfaces (Fig. 3). These comprised cross-head screws drilled into the floodplain surface. Photocontrol point location dictated the scale of image acquisition; the camera had to be high enough above the flume for the ground coverage to contain all the photocontrol points, which resulted in a flying height of 2 m.

Given image space pixel dimensions (d_e) of 9 μm, as defined by the CCD array, and an approximate value of the focal length of 0.0287 m, this suggested an optimum vertical precision of 0.0006 m. The best possible spatial resolution is somewhat coarser than this, normally about five times the object space pixel size, or 0.003 m in this case. Thus, while constraints upon the design of this system meant that the spatial resolution was much lower than that provided by the laser profiling device, the advantage was a much larger spatial coverage: the full channel width (0.60 m).

Fig. 4(a) shows a DEM generated with a horizontal resolution of 3 mm. Comparison with the laser-profiler DEM [Fig. 2(b)] shows that both methods capture some components of the individual grain characteristics and, more importantly, the macroscale morphology associated with grain organization. McEwan (personal communication, 2000) had suspected that this sort of macromorphology might be present in his datasets, but was unable to be conclusive about this due to the small area of coverage of the laser profiler. Fig. 5 shows a comparison of the photogrammetrically acquired DEM with the laser-profiled DEM, the latter sampled onto the same grid as the former. Comparison of elevation differences gives a root mean square error of 0.0015 m. This is somewhat greater than the expected precision, and three times larger than the precision of the laser profiler. However, one of the particular difficulties of this application is the high relative relief of the rough gravel surface with respect to the flying height of the camera. The associated crevices are of importance for surface representation, but this can cause look-angle problems, with the two cameras seeing different views. Such ''dead-ground'' difficulties are well known among photogrammetrists, resulting in erroneous matches and poor height estimates, which are replaced by values interpolated from surrounding matched data. The

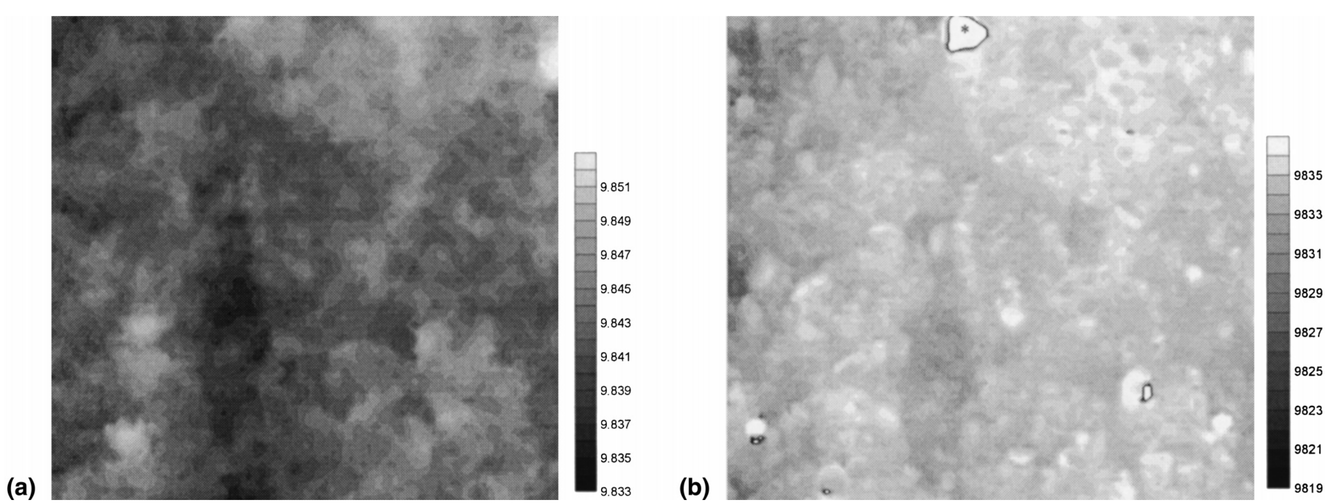

FIG. 4. Photogrammetrically Acquired DEMs of Tilting Flume, Showing Same 0.25×0.25 m Area, Obtained (a) Photogrammetrically and (b) Using Laser Profiler

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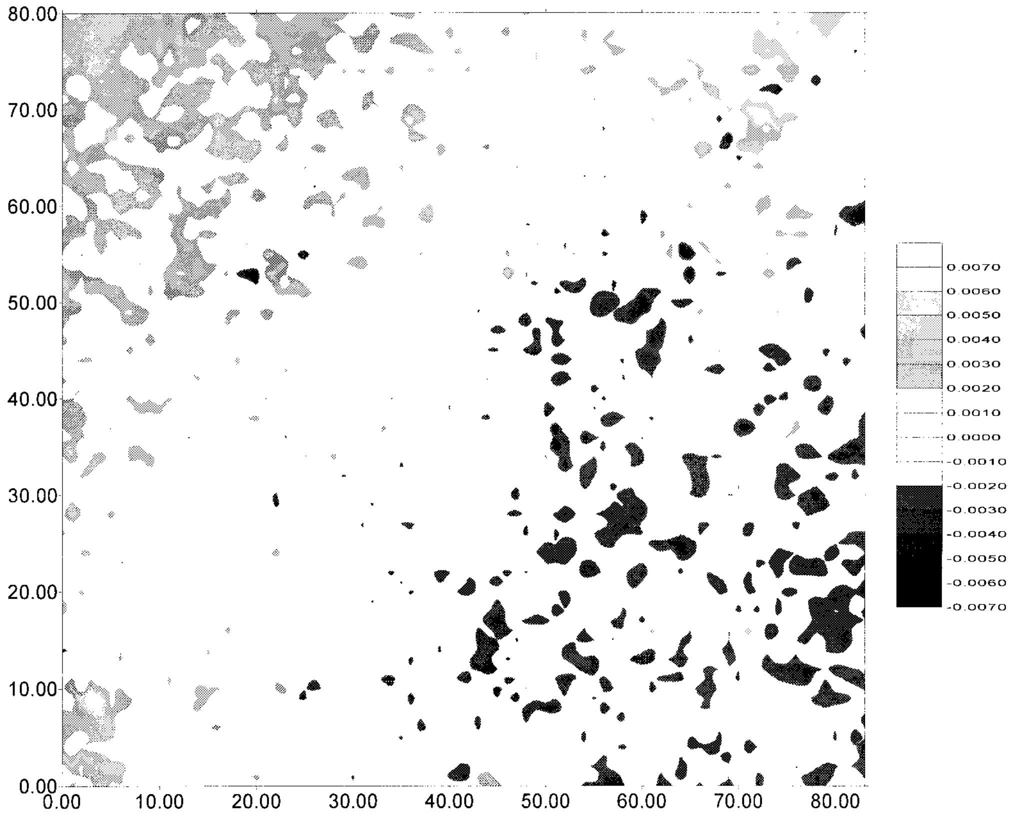

FIG. 5. Absolute Values of Elevation Difference between Photogrammetrically Acquired DEM and Laser Profiler DEM

relationship between match success and dead-ground was confirmed by analyzing a random sample of points, for which there was a significant association ($p < 0.05$) between match success and whether the pixel was on the edge of a clast or in the middle.

Thus, in comparing the laser profiler with the photogrammetrically acquired DEM, the higher resolution of the laser profiler means that it is able to "see" into crevices, thus providing a more detailed picture of the surface. However, the spatial extent of the laser profiler is limited to an area of just 0.25×0.25 m, as compared with full coverage of the width of the channel (0.6 m) to a length that is dictated by the number of image pairs acquired in the downstream direction. This demonstrates how the photogrammetry can provide complimentary, if different, information.

APPLICATION 2: FLOOD CHANNEL FACILITY

Existing methods used at the flood channel facility were based upon mechanical profiling, which provided cross sections sampled every 0.5 m with a spatial sampling density of 0.025 m. The sampling rod had a precision for vertical estimation of about 0.0005 m. However, given that the experiments involved were sand and gravel mixtures, and that the diameter of the sampling rod was 0.010 m, the latter defined the sampling resolution. The channel was 1.6 m wide, and the aim was to acquire DEMs for a full meander wavelength for each experiment being undertaken, with a spatial resolution as good as existing methods, but providing information on the whole area. Thus, photocontrol points were installed along the channel margins, both on the floodplain surface and where the channel sidewalls were sloping (Fig. 6). These comprised 0.05×0.04 m photogrammetric targets that were glued to the floodplain surface and sloping sidewalls using silicon sealant and were coordinated using a total station located over four permanent control points situated on the floodplain. Imagery was acquired from a gantry above the floodplain surface. Given image space pixel dimensions of 9 μm, as defined by the CCD array, and an approximate value of the focal length of 0.028 m, (3) suggested that a flying height of 5 m would produce a precision in the vertical of 0.0016 m and a best possible DEM sampling density of 0.008 m. Thus, while vertical precision was not as good as the profiler, the sampling resolution was slightly better, and there was a significant potential for increased sampling density. This flying height produced a ground coverage length of 4.8×3.2 m. Thus, five strips of either three or four images (Fig. 6) were used to provide sufficient coverage. There was some redundancy of coverage in this respect, which was useful for two reasons. The redundancy provided a check on the reliability of the data by ensuring that DEMs of the same area obtained from different image pairs produced the same results. In addition,

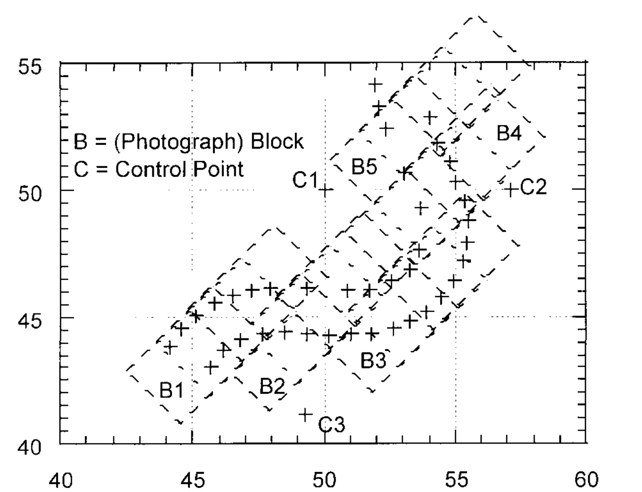

FIG. 6. Photogrammetric Design for Flood Channel Facility Application (Edges of Channel Marked by Photocontrol Crosses; Axis Units in Meters)

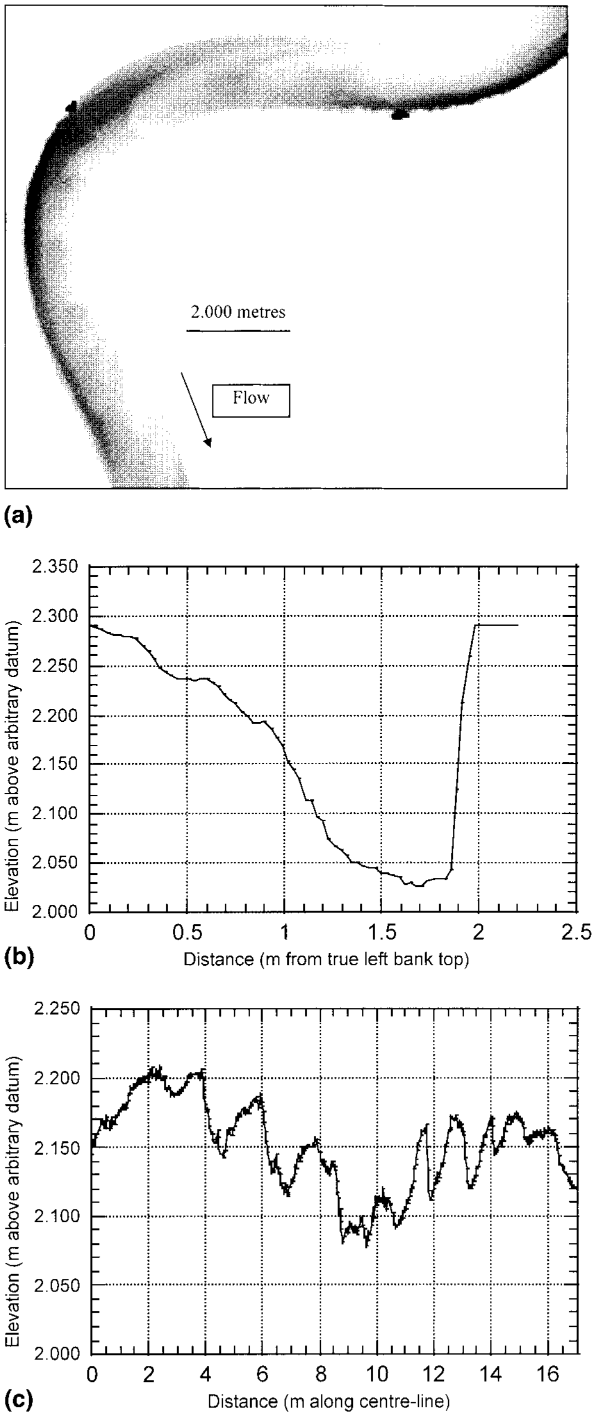

FIG. 7. Shaded Elevation Model of Photogrammetrically Acquired DEM of: (a) Section of Flood Channel Facility Study; (b) Sampled Cross Section; and (c) Long Section

DEM data collected from peripheral image areas could be avoided; this is desirable because uncertainties in lens calibration are greatest towards the edges of each image. Overall image acquisition took less than 1 hour.

DEMs were extracted from each image pair with a 0.008 m resolution and then merged to produce a single DEM. Fig. 7(a) shows a shaded surface portion of that DEM, Fig. 7(b) a sampled cross section across a bend apex, and Fig. 7(c) a sampled long section, taken down the channel centerline. These are especially encouraging, as they show not only bedform macromorphology, but also micromorphological features situated within this macromorphology. For instance, Fig. 7(c) shows the superposition of micromorphological bedform features on top of the bar-pool topography associated with each single meander. Fig. 8 shows a comparison of photogrammetrically acquired data sampled from the DEM with the corresponding data sampled from an independently profiled cross section. The correspondence is excellent, with a correlation of 0.993. The standard deviation of error is 0.0059 m, which is somewhat higher than that reported for the same facility using a sand-bed (0.0015 m). This may be due to: (1) the coarser grain size in this study, with a higher number of matching errors due to the introduction of a more significant relative relief problem, as in the tilting flume study; and (2) the effects of the sampling rod resolution, with grains of a similar magnitude to the probe diameter and hence some uncertainty in exactly where the profile sits on the bed. The error is well within the sampling resolution defined by the probe width.

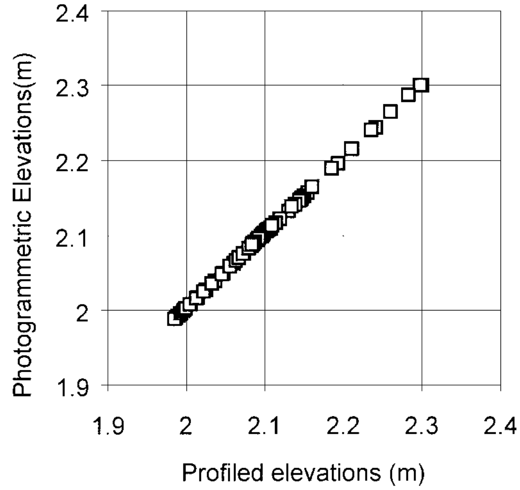

FIG. 8. Comparison Plot of Profile DEM Elevations and Photogrammetrically Sampled DEM Elevations for Flood Channel Facility

CONCLUSIONS

This paper demonstrates the potential that photogrammetry has for monitoring flume channel (particularly laboratory flumes) surfaces at two different spatial scales. The direct link between desired elevation precision and design of the data collection process [see (3)] provides a rapid means of establishing the required data quality. Assessment of the results does suggest that photogrammetry provides information that is of slightly lower quality to existing methods (e.g., laser or mechanical profiling). However, the increased spatial coverage and significant reduction in time spent collecting data is particularly advantageous for studying physical models of river channels in the laboratory. The method has been extended to the two media case, where the cameras are located above the water surface and refractive index corrections are required, and it has been used equally successfully in field applications (Butler et al. 1998; Chandler et al. 2000).

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