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TECHNICAL COMMUNICATION

A CASTING PROCEDURE FOR REPRODUCING COARSE-GRAINED SEDIMENTARY SURFACES

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ABSTRACT

In the field, the measurement of near-bed hydraulics remains problematic. Greater precision is possible in the laboratory, but, in the case of gravels, it is difficult to create a water-worked channel-bed that is realistic enough to replicate faithfully the conditions found in nature. In this paper, a technique to reproduce coarse-grained sedimentary fabrics of large areal extent is described. It involves moulding natural river-bed surfaces from which facsimiles are cast. Remarkably realistic casts with dimensions of 1 m by 2 m have been produced and their quality assessed using spatial data derived using automated digital photogrammetry. The casts reproduce the prototype surfaces with errors at millimetre scale (0·5 per cent of the microrelief). The technique has facilitated the introduction of sedimentary surfaces that incorporate natural, complex structures of grains up to cobble size into experimental channels where detailed studies of near-bed hydraulics can be carried out. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: artificial river bed, gravel-bed river, near-bed hydraulics, digital elevation model

INTRODUCTION

The microtopography of coarse-grained sedimentary surfaces is affected by syn- and post-depositional processes that arrange particles in a non-random fashion, imparting fabric and structure to the river bed or beach face. The role of such fabric in moderating fluid and particle fluxes is difficult to examine *in situ* with any reasonable degree of experimental control. This paper describes a casting procedure that reproduces accurately coarse-grained sedimentary surfaces of large spatial extent. To date, we have used the procedure to cast natural river-bed surfaces in order to study near-bed hydraulics and macroinvertebrate behaviour in a large flume. However, it could be deployed with equal success to replicate other sedimentary settings and, therefore, it has wide applicability.

Documenting flow structures in gravel-bed rivers has great importance for solving a number of environmental issues. In fluvial geomorphology, the structure of near-bed turbulent flow has been linked to the dynamics of sediment transport and to the development of bedforms through complex feedback relations (see numerous articles in Clifford *et al.* (1993) and Ashworth *et al.* (1996)). Evaluating these relations is crucial to gaining a better understanding of fluvial dynamics at various scales, from that of the individual grain to that of the channel bar. In freshwater ecology, the dynamics and behaviours of animals inhabiting the substrate are closely associated

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with near-bed flow structures and bed topography (Hart *et al.*, 1996; Fonseca and Hart, 2001). Our understanding of these diverse behaviours is poor and improvement is clearly needed in order to appreciate better many of the ecological processes that characterize the benthic system, such as habitat use, dispersal, resource acquisition, competition and predation (Hart and Finelli, 1999).

Quantifying the near-bed flow structure of natural gravel-bed rivers at millimetric and centimetric scales remains difficult. Studies of turbulent flow above gravel beds and other rough surfaces have involved both field- and laboratory-based experiments. These two approaches are complementary. However, each has its own advantages and drawbacks. Work in the field is impeded by the need for a complex instrumental set-up and is often weather-dependent. Most importantly, an inability to control the flow makes it difficult to replicate experiments. It can also encourage the adoption of pragmatic but suboptimal experimental procedures. So, for example, in attempting to determine a complex velocity field in as short a lapse of time as would allow a claim that flow conditions had been steady and uniform, the sampling period at individual locations might be shorter than would be desirable in order to capture the velocity spectrum associated with turbulence; or the spatial sampling resolution might be insufficiently high in order to depict a complex near-bed flow structure. In addition, making measurements of near-bed velocity when conditions are significant for sediment transport or for evasive action by benthic organisms, i.e. when a river is in spate, still constitutes a real challenge. Laboratory experiments have the advantage of providing control over a range of flow conditions and, to a certain extent, over sediment transport dynamics. It is also possible to 'fix' sediment so that a series of measurements can be taken in the vicinity of protruding bedforms without these changing during the sampling period. For example, Benson *et al.* (2001) recently described a technique to stabilize bedforms that develop in sand. Unfortunately, it is not suitable for coarser sediments. However, the use of laboratory flow channels has its own limitations. So, for example, channel and water pump capacities rarely allow flows that can move large clasts and thus replicate the complex bedforms, fabrics and structures that characterize natural gravel-bed rivers.

Researchers have responded to these problems in various ways. In order to assess the effect of boundary roughness on the flow, some have deployed regular configurations of square-edged blocks (Nowell and Church, 1979; Robert *et al.*, 1992) or laid down natural gravels on the bed of experimental channels (Kirkbride, 1993; Lawless and Robert, 2001). Others have attempted to reconstruct natural bed surfaces from pebbles, the original locations of which have been mapped by careful numbering in the field before removal to the laboratory (Young, 1992). To observe the effect of isolated obstacles on the flow, researchers have used hemispheres glued on to smooth beds (Acarlar and Smith, 1987; Shamloo *et al.*, 2000), pebble clusters preserved in the field and imported to the laboratory (Buffin-Bélanger, 2001) and artificially imbricated pebbles (Lawless and Robert, 2001). These experimental configurations have been of great value in highlighting the effects of surface roughness on near-bed flow, but each lacks the true complexity of a natural gravel substrate or is insufficiently extensive, so that the upstream boundary condition which affects the flow field at the site of interest is almost certainly not reproduced in a way that mimics the natural river bed. Similarly, the manufacture of realistic substrates that are suitable for making meaningful observations of animal behaviour in flumes has proved elusive (Lancaster and Mole, 1999).

Here, we report on a casting technique that reproduces the intricacy of an exposed water-lain gravel surface and transport it intact to the controlled environment of an experimental channel. This technique has allowed us to implement experiments that would be impossible to carry out in the field.

THE CASTING TECHNIQUE

The casting technique used involves classical sculpting, where a mould of the prototype – the bed surface – is made and the mould is then used to make facsimiles. The method is straightforward in principle. In practice, however, difficulties lie in finding the right moulding and casting materials to replicate a gravel-bed surface. Table I gives the materials that were found to be satisfactory and the average quantity of each used per unit area. We have used the technique successfully for surfaces with dimensions of 1 m × 2 m. It could easily be used for smaller areas and could even be deployed over larger areas, although the logistics of transport may set an upper limit. It should be noted that the technique can be applied only to exposed gravels and cannot be deployed where the surface is submerged.

Table I. Moulding and casting materials

Material	UK supplier	Average quantity (kg) used to reproduce a surface of 1 m^2
Mould		
Polyvinyl chloride (Gelflex™)	Tiranti	14
Polyurethane Foam Resin	K&C Moulding	7
Cast		
Epoxy resin – Araldite® 2011	Buck and Hickman	0·5
Polyurethane resin GM-725-1	Denaco	25
Pur 5 (resin hardener)	Denaco	5
Medium size dry sand		5–10

Moulding

A type of polyvinyl chloride, commercially known as Gelflex™, can be used for moulding different types of host material, including cement, stone, wood, metal, and plaster. Gelflex™ retains the very fine detail present in the object and is self-lubricating, which means that it does not adhere to the surface of the form being moulded. Gelflex™ has numerous advantages for use in the field. Among these are that it is easy to use (its melting point is not too high), it is virtually inert and it is relatively safe if simple precautions are taken. Also, once a cast is made from the mould, the Gelflex™ can be melted and reused to create another mould if required.

In the field, for our purpose of deriving a 2 m^2 mould of the river bed, two pots (each of 13 l) were mounted on a double-burner butane gas stove and used to melt approximately 25 kg of Gelflex™ in less than 90 minutes. The liquidizing of Gelflex™ requires constant stirring to avoid burning because the melting and carbonization points are only 10 °C apart (160 °C and 170 °C, respectively). Inhaling the fumes should be avoided and there is an obvious danger of scalding if the liquid comes into contact with skin. As with the other materials used, full safety details are available from the respective manufacturers.

Once melted, the liquidized Gelflex™ was gently poured over the selected, dry, bed surface, around which a metal retaining frame had been loosely placed (Figure 1a). The Gelflex™ must be poured quickly because its viscosity increases rapidly as it cools. To ensure that the mould consists of a single piece of Gelflex™, care should also be taken to cover the whole surface in a single application. With ambient air temperatures of around 10 °C or less – typical of British weather – application should be carried out within 5 minutes. To ensure that a layer of at least 5 mm covers the whole surface, particularly protruding pebbles and cobbles, the liquid can be spread manually using spatulae. However, care must be taken to ensure that the underlying gravel is not disturbed and that the hot Gelflex™ is not splashed onto nearby colleagues. The liquidized Gelflex™ flows into depressions on the surface and penetrates any interstices greater than 3 mm in diameter. Therefore, the amount of Gelflex™ required is dependent on the porosity of the surface layer. To avoid excessive penetration of the surface, the Gelflex™ can be allowed to cool until the viscosity increases. The temperature of the bed surface also affects the cooling of the Gelflex™ and hence its ability to penetrate smaller interstices. This may need to be taken into account, depending on the aims of the study.

It is essential to create a rigid mould on top of the flexible Gelflex™ before removing both as a whole from the bed. This second mould becomes a convenient base during the casting operation. Because of its low density and its fast curing time, expanding foam was used for this second layer. From experience, we recommend a polyurethane foam resin that cures quickly (within minutes) and has considerable strength on setting. The foam is generated by combining two liquids, a resin and a catalyst. Once mixed, the liquid can be poured onto the Gelflex™ mould (Figure 1b). The foaming reaction works best when air temperatures are comparatively high (20–25 °C). However, although there is some reduction in expansion, it has been used successfully at lower temperatures. Safety precautions are simplified because the work is carried out in the field where ventilation is usually good. Notwithstanding this, inhaling the vapours should be avoided and steps should be taken to prevent skin contact with the liquid foam. In order to cover 2 m^2, we have used 15 kg of foam at an ambient air

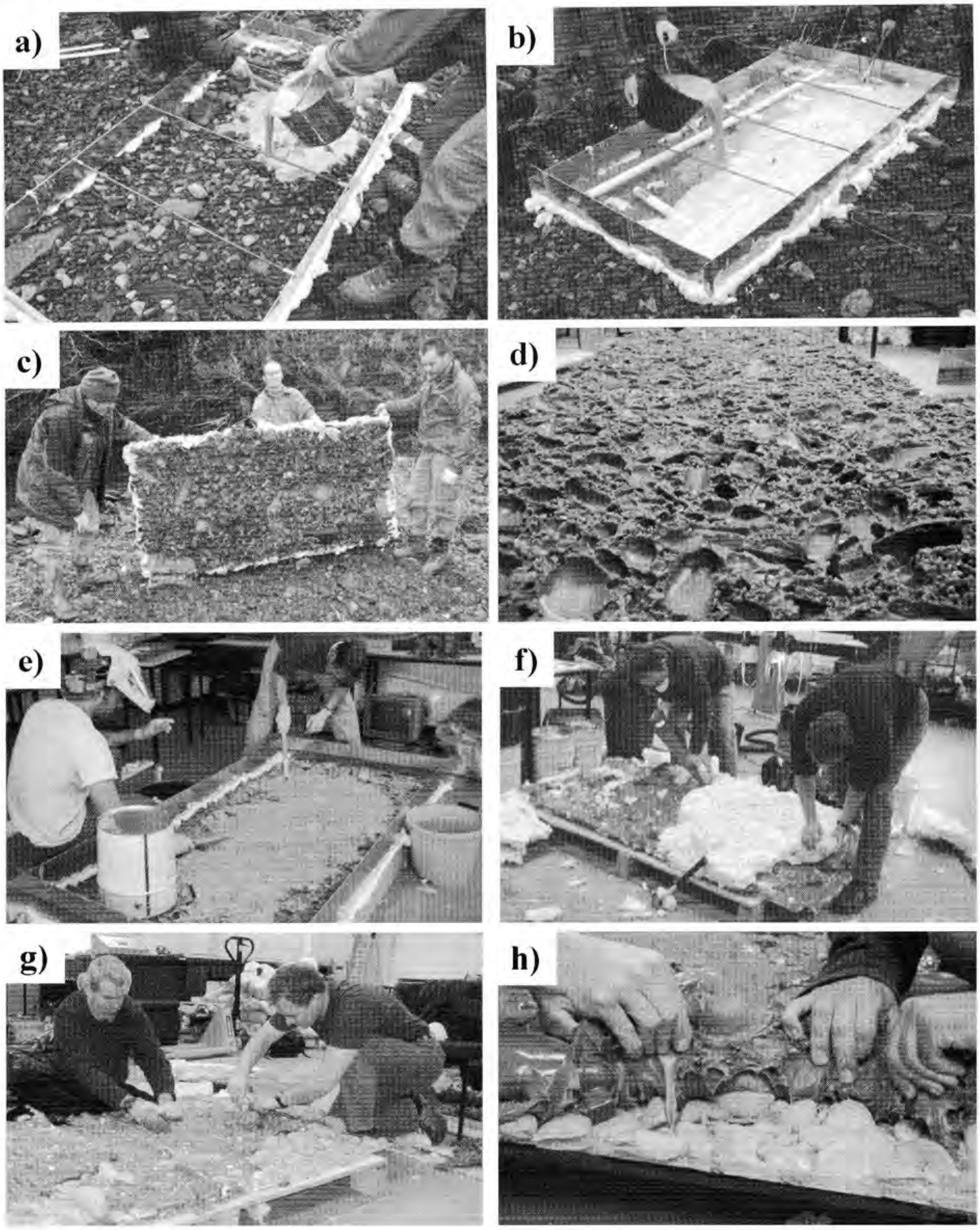

Figure 1. The different steps of the moulding–casting procedure. See text for details

temperature of *circa* 10 °C. Once set, this gave a thickness of about 200 mm. The foam cures in approximately 30 minutes. However, a curing time of one hour is recommended in order to ensure the foam is fully rigid.

As the foam expands and cures, surface irregularities in the underlying Gelflex™ ensure that it becomes mechanically locked so that the entire mould can be lifted onto its side, intact within its metal frame (Figure 1c). At this stage, the mould is heavy and requires careful handling because bed particles that are partially or completely surrounded by Gelflex™ will also come away from the bed. (For a mould as large as those produced here, four people were needed for safe lifting). Because of the self-lubricating properties of Gelflex™, most of the embedded grains are easily removed *in situ*. The mould can then be taken back to the laboratory where all the remaining gravel can be removed. When cleaned, the moulds present a fascinating negative impression of the gravel surface (Figure 1d), with coral-like Gelflex™ prominences that reflect variably deep and complex interstices.

Casting

Polyurethane resin has been used to create the cast. This is a common casting material and possesses several advantages for casts that are to be used in water: namely, it is inert, less brittle and much lighter than concrete and will not disintegrate when exposed to flowing water. However, polyurethane must be handled with care because of health hazards and because its vapours are explosive. Gloves and a respiratory mask should be worn when handling the resin mixture and the work must be carried out in a well-ventilated area.

Because of the properties of Gelflex™ and the size of the cast, a number of problems had to be overcome before we could pour resin into the mould (Figure 1e). Firstly, the self-lubricating and oily nature of the Gelflex™ surface affects the curing of the resin, leaving the cast with a sticky surface. To correct this problem, the mould was painted with a thin layer of epoxy resin prior to pouring in the polyurethane. Secondly, polyurethane resin is expensive so sand was used to bulk it up. In addition, the curing process of polyurethane resin is exothermic and large quantities may create a heat hazard. To avoid excessive heat (and thus prevent damage to the mould), a slow curing resin (involving less heat) was used. The cast was also built up in three or four layers, allowing one day for curing between each. Finally, large casts are heavy. In order to reduce the weight, solid Gelflex™ cubes were embedded in the layers of resin in such a way that they could be retrieved after curing was complete. This left voids in the underside of the cast and gave the added advantage of further reducing the amount of resin needed.

Unveiling the sculpted river bed

The moulds were turned upside down in order to remove the polyurethane foam and the Gelflex™ mould from the cast (Figures 1f and 1g). The foam comes away relatively easily. Removing the Gelflex™ is time-consuming as many parts of the mould are mechanically trapped within the cast's interstices (Figure 1h). It is significantly faster to remove the Gelflex™ from casts having larger particles than from those with smaller particles and small interstices. Judicious trimming of the filamentous Gelflex™ protruberances on the moulds (Figure 1d) prior to casting can reduce the time spent extricating small pieces of Gelflex™ trapped in the interstices that they create. This does not change the surface nature of the cast, only the formation of the deepest interstices.

The final cast surfaces are astonishingly natural in appearance. Figure 2 shows plan views – prototypes and casts – of two contrasting surface textures. Not only are the fabrics perfectly replicated by the facsimiles, the faithfulness of the Gelflex™ mould ensures that the fine detail (either surface microfeatures on larger clasts or sand-sized matrix) is retained.

COMPARING THE MANUFACTURED AND REAL SURFACES

Visually, the casts are identical to the natural surfaces that they represent. To quantify any differences between casts and prototypes, photogrammetric surveys were used to extract digital elevation models (DEMs) from one pair of natural and sculpted surfaces. The methods used are described fully elsewhere (Butler *et al*., 1998; Stojic *et al*., 1998; Chandler, 1999; Chandler *et al*., 2001) and only a brief summary of the technique is given here.

High-resolution digital imagery of a portion of the river bed was acquired directly using a Kodak DCS460 camera at a height of just 1·6 m; the camera was supported by a four-legged platform to ensure stability during

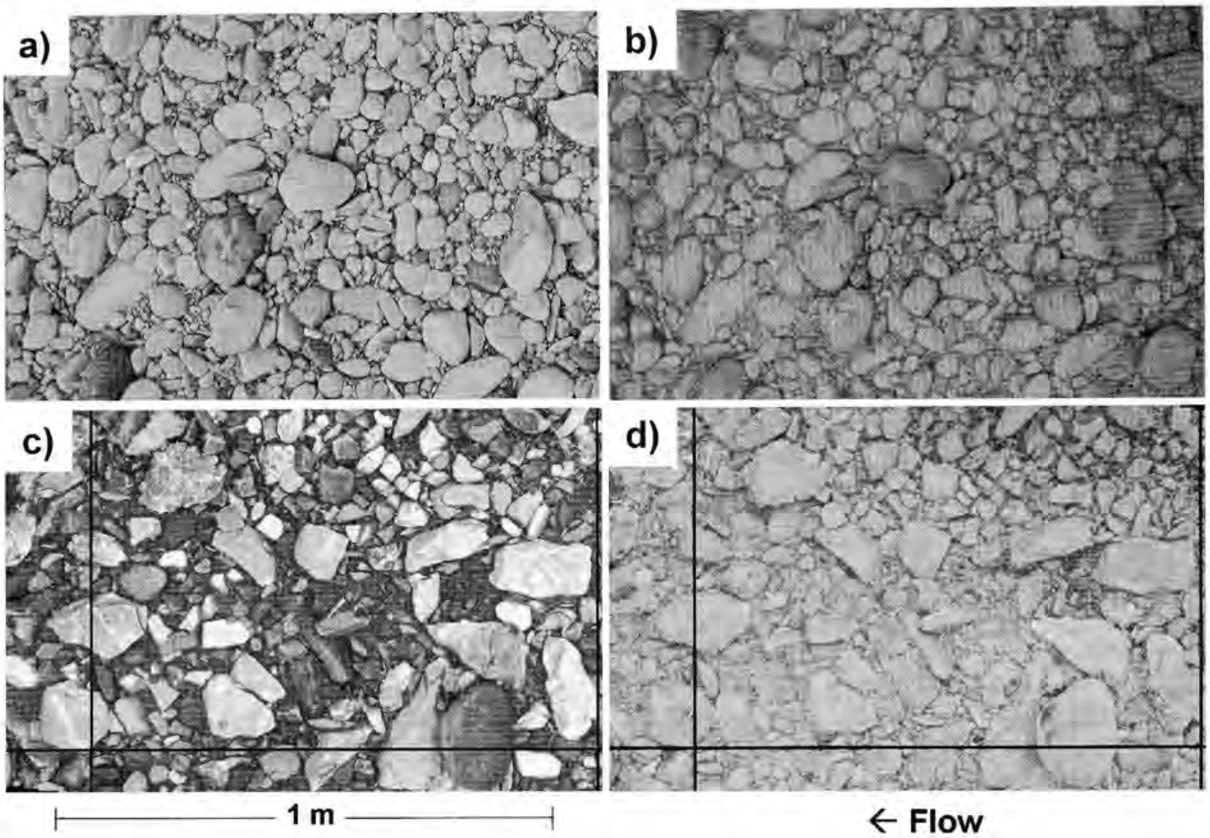

Figure 2. Plan view of two natural coarse-grained surfaces (a and c) and of their respective casts (b and d). Note that (a) and (b) are ordinary plan view photos and that (c) and (d) are orthophotos

exposure. Sixteen pre-marked photo-control points were placed on the object and coordinated to submillimetre precision using a digital theodolite. Eight of these points were constructed from proprietary targets, 5 mm in diameter; the other eight were used as 'check-points' and were simply the tops of small wood screws inserted into the stream bed. It was hoped that replication of the screw heads in the cast would provide a link between the field coordinate system and the subsequent laboratory coordinate system. Four vertical images of the test area were acquired, giving two stereo models, each with an overlap of 90 per cent. In addition, four oblique images were obtained, in order to provide appropriate geometry and redundancy to calibrate the non-metric camera (Chandler *et al.*, 2001). Processing of these data was achieved using Erdas OrthoBase Professional©, using the self-calibrating capabilities of the software to recover estimates of camera focal length, principal point offset and lens model. The root mean square error (RMSE) of the restitution process was 5 mm, as tested at the eight independent 'check-points'. A DEM at 5 mm resolution was then generated automatically to represent the original stream bed as it appeared in the field; RMSE of the DEM was 9 mm. Finally, an orthophotograph was created at 1 mm resolution. This has the spectral qualities of the original photograph but, because distortions due to photo-tilt and relief variation have been removed, it has the metric qualities of a map (Chandler, 1999).

The second phase of the photogrammetry involved extracting similar data, but using imagery acquired from the cast surface in the laboratory. The same camera platform and camera were used. Fortunately, three of the original screw heads and three of the original targets appeared in the cast, to which five additional new control points were added. As before, the positions of all of these targets were determined in a local 3D cartesian coordinate system. The points common to both the field and laboratory surveys were then used to compute the seven parameters of a 3D similarity transformation. This allowed the coordinates of the new photo-control points to be transformed to the same coordinate system as used originally in the field, thus allowing data extracted from

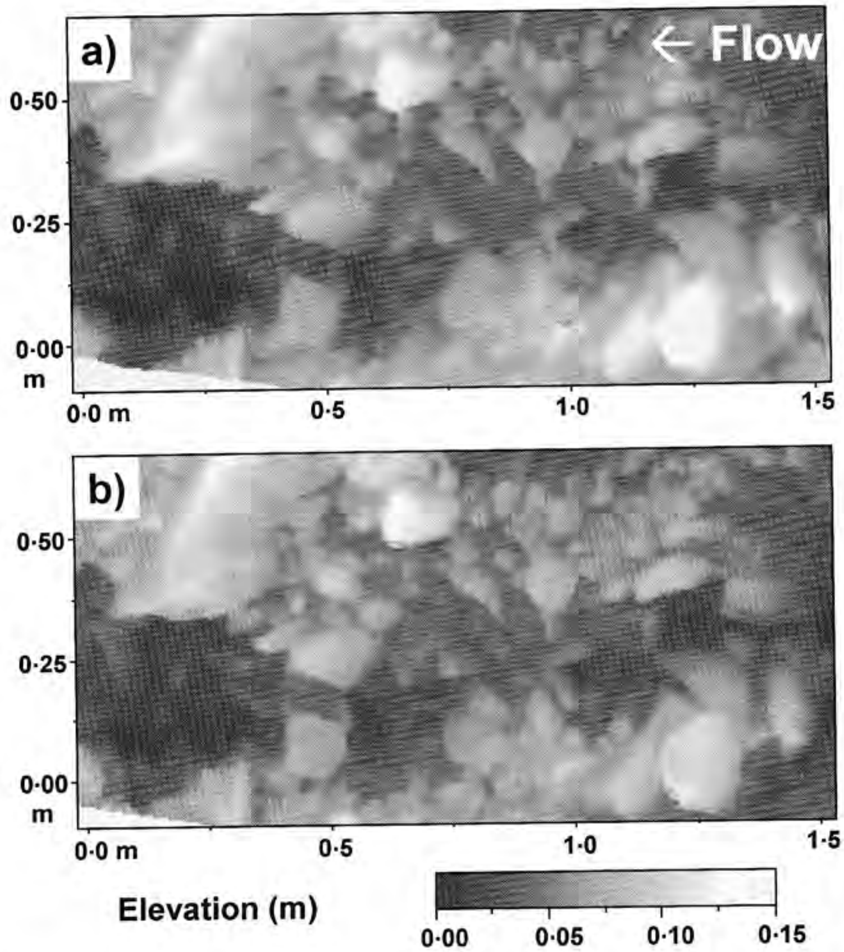

Figure 3. Digital elevation model of (a) the natural river bed and (b) the cast obtained from photogrammetry

the cast to be directly compared with the original field dataset. The four digital photographs were processed in a similar manner, all images being downloaded and measured with OrthoBase Professional© in less than two hours, including the extraction of the DEM and subsequent generation of the orthophotograph.

An animation that switches between the orthophotographs of the river and the cast (see http://snap.lut.ac.uk/Jim/Images/ManifoldMovie.gif) provides an effective method of demonstrating that major elements of the river bed were represented in the cast and appear at their correct and original geographical locations. Here, Figure 3 shows the strong similarity between the DEMs of the original river bed and of the cast surface. Note that the lateral slope of the river bar on which the mould was formed was removed from the DEMs in order to get a better visual appreciation of the roughness elements. The topographical differences between the original surface and the cast were assessed quantitatively by subtracting the DEM of the prototype from that of the cast. Figure 4a presents the resulting map of elevation difference. White and dark areas correspond to regions of the original bed that are, respectively, higher and lower than represented by the cast. Grey areas reveal regions of small difference between the two DEMs. On Figure 4a, elevation differences are smaller than 3 mm for 37 per cent of the surface and smaller than 5 mm for 50 per cent of the surface. An area towards the bottom right of Figure 4a and locations around the periphery of some clasts account for most of the largest elevation differences. As far as the former is concerned, we suspect that this is due to twisting of the mould, and consequently the final cast, during either transportation or the casting procedure. As for the lines of highest elevation difference, these occur on the vertical faces of clasts and can result from very small lateral distortion during the moulding

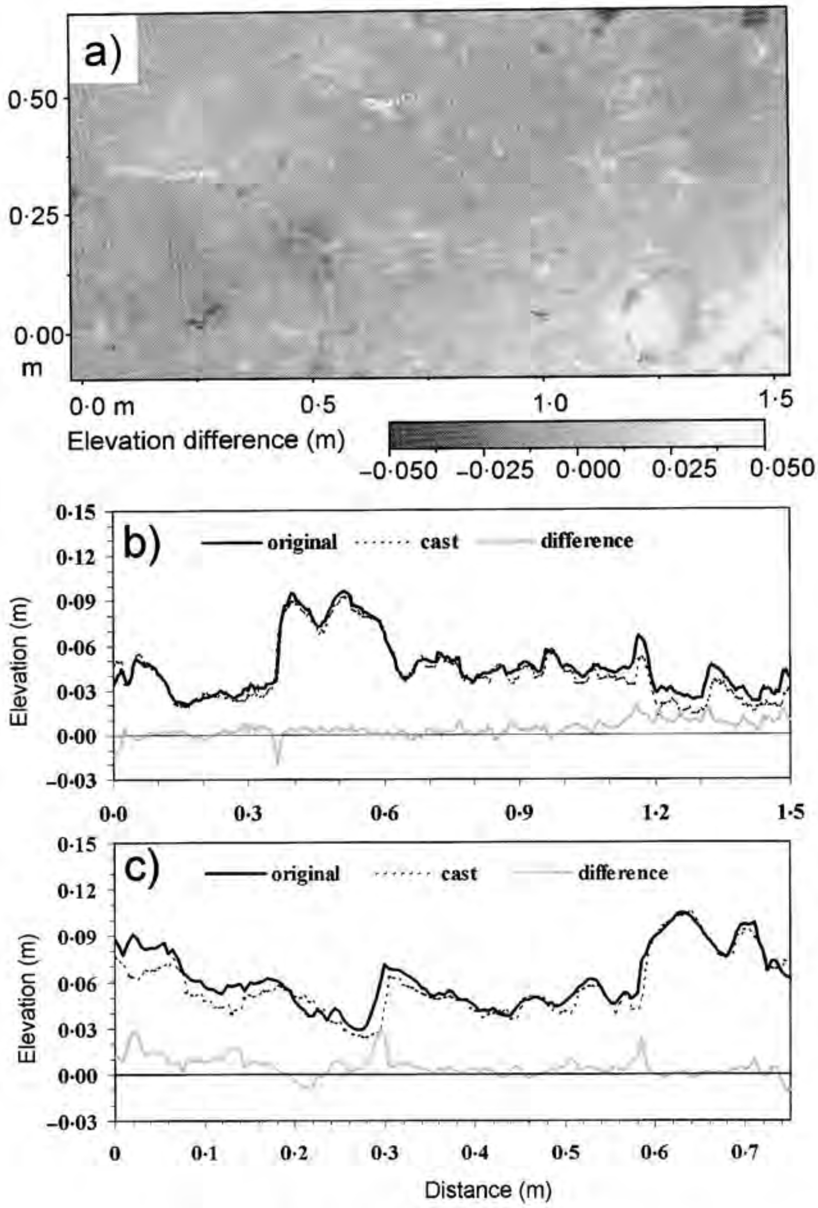

Figure 4. (a) Map of elevation differences between the DEMs of the original bed and of the cast shown in Figure 3. Elevation and elevation differences of (b) longitudinal and (c) lateral centre-line transects

process. They can also be attributed to small inaccuracies in the original DEMs arising from slightly different camera positions (Butler *et al.*, 1998). Figure 4b and c show the centre-line vertical profiles extracted from the DEM of the original surface and of the cast along both the longitudinal and the lateral axes. The grey lines represent the elevation differences. These figures once again reveal the relatively small discrepancies between the original and the cast surfaces. It is also apparent that the highest elevation differences occurred near the edges of clasts where a slight deformation may have occurred or where photogrammetric errors are likely to occur. This is instructive in indicating the importance of ensuring rigidity of the polyurethane foam. Subsequent to these experiments, we have introduced polyethylene pipes as stiffeners when creating the polyurethane foam mould. Four or five of these are inserted so that they lie just above the Gelflex™ and become encapsulated by the expanding foam.

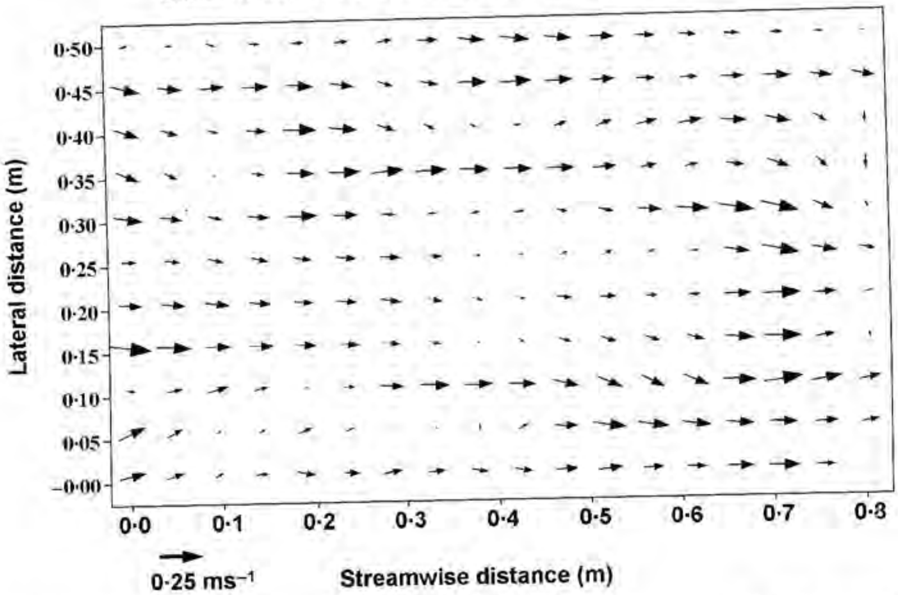

Figure 5. Vector of streamwise and lateral velocity components at 5 mm above local surface of a gravel-bed cast

CONCLUDING COMMENTS

Obtaining near-bed velocity measurements is a difficult task but has particular importance for several areas of fluvial geomorphology and benthic ecology. This paper describes a sculpting technique that has allowed us to recreate accurately the complexity of the natural coarse-grained surfaces found in gravel-bed rivers. Although some technical problems arose during the casting process, these have been identified and minor modifications introduced. Even with these imperfections, the differences between the facsimiles and prototypes are at millimetre scale. The quality of the resulting surface is sufficiently accurate for physical flow modelling experimentation and provides a highly realistic substrate for observing benthic organisms.

The casting technique allows the complexity of a natural coarse-grained river bed to be introduced to the controlled environment of the laboratory. This offers the potential for new and original experiments where an understanding of near-bed hydraulics is crucial. For example, the casts shown here are being used to study near-bed hydraulics and macroinvertebrate mobility above the casts in a large flume. Figure 5 shows a velocity vector map made from measurements taken locally at 5 mm above a cast placed in a 9 m long, 0·9 m wide experimental channel. The velocity measurements were made using an acoustic Doppler velocimeter and the vectors result from a combination of streamwise and lateral velocity components. The vector map shows the complex spatial variability of the velocity field in the near-bed region of a coarse-grained surface. Obtaining a similar map in the field would be very difficult. It would be even more difficult to obtain data at a variety of specific flow strengths; this is something which can easily be achieved in the laboratory. Furthermore, the velocity map can be matched against the movements of macroinvertebrates over the rough terrain under various flow conditions and can thus be used to elucidate factors which control macroinvertebrate behaviour in turbulent flows. This illustrates the great potential of the technique for near-bed hydraulic studies, including those that involve the behavioural ecology of benthic organisms.

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