USING HIGH RESOLUTION LASER SCANNING TO INDICATE MECHANISMS OF STABILISATION UNDER VARYING SUB THRESHOLD FLOW EXPOSURES

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ABSTRACT

Laser displacement scans were taken over an area of a 116 mm x 100 mm using a new rapid scan sensor yielding high resolution data (0.1 mm). Two laser scans were taken before and after a 1-16 hour period of antecedent flow run at shear stresses below that of sediment entrainment (stress history). The aim was to quantify any changes to both particle stability and surface topography. Data indicate that prolonged antecedent periods lead to increased particle stability by up to 14.50%. Specifically, uniform beds are more responsive to antecedency than bimodal beds. This appears to be related to the grain size distribution and its influence on the *in situ* repositioning of grains. It is suggested that uniform beds may have the freedom to rearrange to a greater extent due to larger pore spaces and poorer imbrication, whilst the finer particles within graded beds reduce pore space size and restrict *in-situ* particle movement of the larger grains. This is substantiated by grain orientation results showing that exposed surface particles pivot around an axis to reorientate into a more stable position through imbrication and streamlining in the direction of flow.

Keywords: Stress history, Laser scanning, Surface organisation

1. INTRODUCTION

Accurate prediction of river bed surface characteristics is of fundamental importance for fluvial geomorphology and river hydraulics since they govern flow velocity, turbulent intensity and sediment transport. Yet the broad grain size distributions typical of gravel bed rivers allow for considerable selective entrainment and dynamic textural response to local perturbations of sediment supply and transport capacity. River bed surfaces are therefore often highly irregular with complex spatial heterogeneity. Consequently evaluation of particle resistance to entrainment requires an understanding of not only the bed surface composition but also the structure of that bed surface together with knowledge of the fluid flow regime to which the bed has been exposed (Robert, 1990; Nikora *et al*., 1998).

Whilst changes to river bed structure, composition and fractional stability are relatively well-known during full or partial transport conditions, there is emerging evidence to suggest that it is also responsive to sub-threshold flow (stress history). Stress history describes antecedent flow conditions; that is, those commonly applied during the sub-threshold period of flow that occurs prior to a sediment-transporting flood event. Recent experimental studies (Paphitis and Collins, 2005; Monteith & Pender, 2005, Haynes & Pender, 2007) show that sediment subjected to an extended duration of sub-threshold flow may locally reorganise into a structure more resistant to subsequent entrainment. Further, research has shown that the effects of stress history are not only affected by the duration and magnitude of applied shear stress but also by the surface grain size distribution (Ockelford and Haynes, 2008; Haynes and Ockelford, 2009); interestingly, graded beds are observed to be less responsive to antecedence than uniform beds. This is primarily reasoned to be due to the uniform bed having larger pore spaces and hence having a greater freedom to rearrange as compared to graded beds where finer particles restrict *in situ* movement of the larger grains. Thus, whilst this research has provided some quantification of the stability imparted, there is only limited, qualitative and mainly speculative information on the mechanisms that underpin this stabilisation process (Paphitis and Collins, 2005; Haynes and Pender 2007; Ockelford and Haynes 2008).

In order to be able to interpret meaningful morphological and sedimentological information from gravel surfaces acquisition of 3D data is vital. This has been primarily limited to photogrammetry (Butler *et al.*, 2001; Smart *et al.*, 2004); however, more recently laser displacement scanning has been used across a variety of scales to provide quantitative 3D descriptions of river bed surfaces, typically in the region of 1mm resolution (Rumsby *et al.*, 2008; Measures and Tait, 2008; Hodge *et al.*, 2009). One fundamental issue still to be resolved is the resolution with which surfaces can be described. Often high image resolution has been traded off against acquisition time of data collection. Thus, the laser displacement scanner used in this research provides one of the first insights into using a new rapid-scan sensor yielding far higher resolution data (~0.1 mm). This paper therefore not only offers insights as to the potential use of rapid scanners but also offers the first real insights into the relationship between stress history and the associated changes to bed topography and particle repositioning.

2. METHODOLOGY

Bed topography measurements were captured using a *Micro Elipson* scanCONTROL2800 where a laser beam is projected onto the bed surface in the cross-stream (x) direction via a linear optical system. This profile uses the laser light that is diffusively reflected back to the sensor to simultaneously read the x, z co-ordinates (z = vertical displacement) of 1024 discrete points along the laser beam; this is then replicated on a CCD array for quantitative evaluation. Along a single laser profile the x-direction resolution ranges from 0.109 mm in the centre of the beam (with a standard deviation of 0.09 mm) to 0.120 mm at the edges of the beam (with a standard deviation of 0.150 mm); this is due to lateral splay in the emitted beam trajectory and the roughness of the bed surface. In the z direction the resolution is controlled by the CCD array of the sensor. For the presented investigations, the number of data points gathered in the z direction was set at 512 over 122.9 mm vertical distance; this yielded a resolution in the z direction of 0.239 mm. The downstream (y) component is generated using an *Arrick Robotics* stepper table and motor system. This automatically moves the laser in the downstream direction at a prescribed speed, hence a known number of steps per distance. In the present investigation the stepper motor was configured to approximately maintain the aspect ratio of the x, y, z image; 800 profiles were therefore taken per 100 mm length translating into a y-direction grid resolution of 0.125 mm. With the laser reading 204800 data points per second, the prescribed y-direction resolution results in a scan rate of 25 mm downstream distance per second; as such, a 116 mm (x) by 100 mm (y) area takes only 4 seconds to scan. Additionally, the exposure time of the laser is determined according to the nature of the surface being scanned. High levels of light were scattered from the surface due to the moisture retained in some pore spaces; thus, a longer exposure time (5 ms) was chosen so as to increase the uniformity of light across the image and maximise the image quality.

2.1 Experimental Procedure

Threshold experiments were performed within a glass-sided flow-recirculating flume of rectangular cross-section (13 m long × 1.8 m wide × 0.35 m deep). To prevent scour and induce turbulent boundary conditions 2 m of immobile sediment was placed directly downstream of the flume inlet. Immediately downstream of the immobile sediment the bed comprised the mobile test sediments (effective working length 8 m) composed of natural sand and gravel approximating to sub-rounded shape.

Employing a bed slope of 1/200, test beds of uniform and bimodal (σ_g = 2.08) sediment grades of comparative D_{50} (4.8 mm) were exposed to a range of stress histories of 0, 60 and 960 minutes duration. The bed was screeded to a depth of 60 mm and slowly flooded. An initial *bedding-in period* employed a flow depth of 10 mm for 30 minutes duration; this was designed to remove any air pockets or unstable grains generated within the bed screeding process. Similar to the methodology of Monteith & Pender (2005), flow was then increased to apply a shear stress of 50 % of the critical threshold for entrainment of the median grain size. This second flow stage constituted the *antecedent period* where beds were exposed to stress histories of 0, 60 and 960 minutes duration; runs of 0 minutes antecedency were used as benchmark runs for stress history assessment. The critical shear stress of entrainment threshold was established using a quantitative visual technique (Neill and Yalin, 1969). The critical shear stress at threshold was established using the depth-slope product where the energy slope (or channel slope for uniform flow conditions) and the hydraulic radius, or water depth is measured in order to compute an average shear stress from the section of channel studied calculated according to Equation 1;

$$\tau_{c50} = \rho g R_b S \qquad \text{(Eq. 1)}$$

where, S is the channel slope (0.005) and R_b is the hydraulic radius, corrected for the roughness effects of both the side walls and the bed according to Manning's, derived according to the methodology followed by Monteith and Pender (2005).

Two laser scans of the bed surface were taken prior to and after the antecedent period to quantify any changes to surface topography and composition. Before the laser scans were run flow was decreased so that a water table below the bed surface was established; this ensured minimal disruption to the bed surface, specifically reducing the disturbance to the fine material within the bimodal bed. After the scan was completed flow was increased back to the pre-scan discharge. Finally in order to ascertain the effect of the antecedent period on entrainment threshold, the subsequent *stability test* incrementally increased flow discharges. Each step of the stability test was 10 minutes in duration to allow flow stabilisation and visual assessment of whether or not the new entrainment threshold had been reached.

3. RESULTS

3.1 Stress History

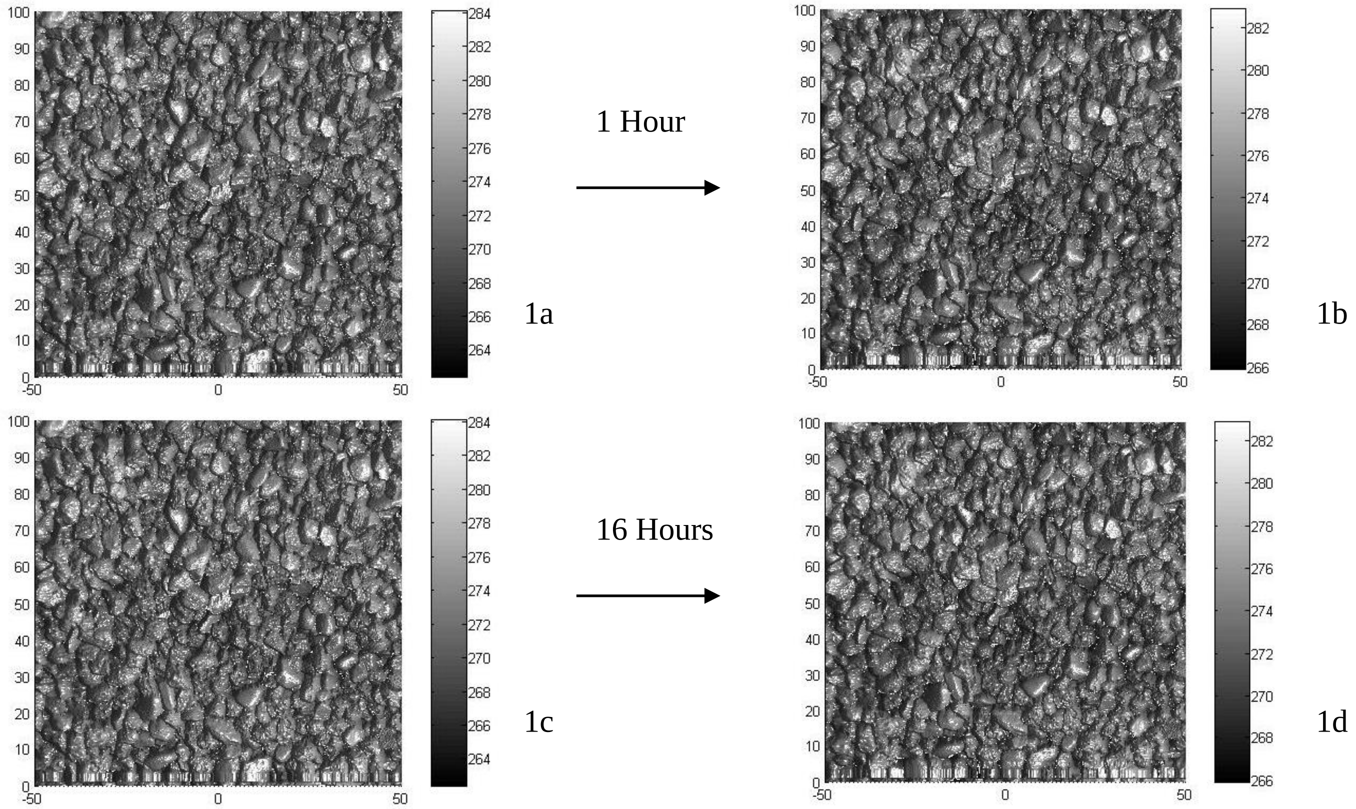
Previous data from stress history investigations has shown an increase in the shear stress of entrainment following prolonged periods of sub-threshold flow (i.e. the antecedent period). This paper supports these findings noting a 14.5 % increase in average bed shear stress between 0 (2.36 Nm^2) and 960 (2.76 Nm^2) minutes in the uniform bed. Similarly the bimodal bed also shows a response to stress history with average bed shear stress increasing from 2.52 Nm^2 under benchmark conditions to 2.81 Nm^2 after 960 minutes antecedent flow, a 10.43 % increase. This is in line with the 10% increase in shear stress reported by Ockelford and Haynes (2008) using the same grain size distribution but over shorter antecedent periods (ranging from 0 to 60 minutes duration). In both beds the shortest antecedent durations are proportionally seen to have the greatest influence in increasing the strength of the bed. Such data are supportive of previous stress history research, specifically the results from Ockelford and Haynes (2008) who noted clear evidence that the effects of stress history are highly responsive to sediment grade. Thus, it is pertinent to evaluate the mechanisms underpinning stress history induced stability gains and explain why uniform beds illustrate a greater response than bimodal substrates.

3.2 Bed Topography

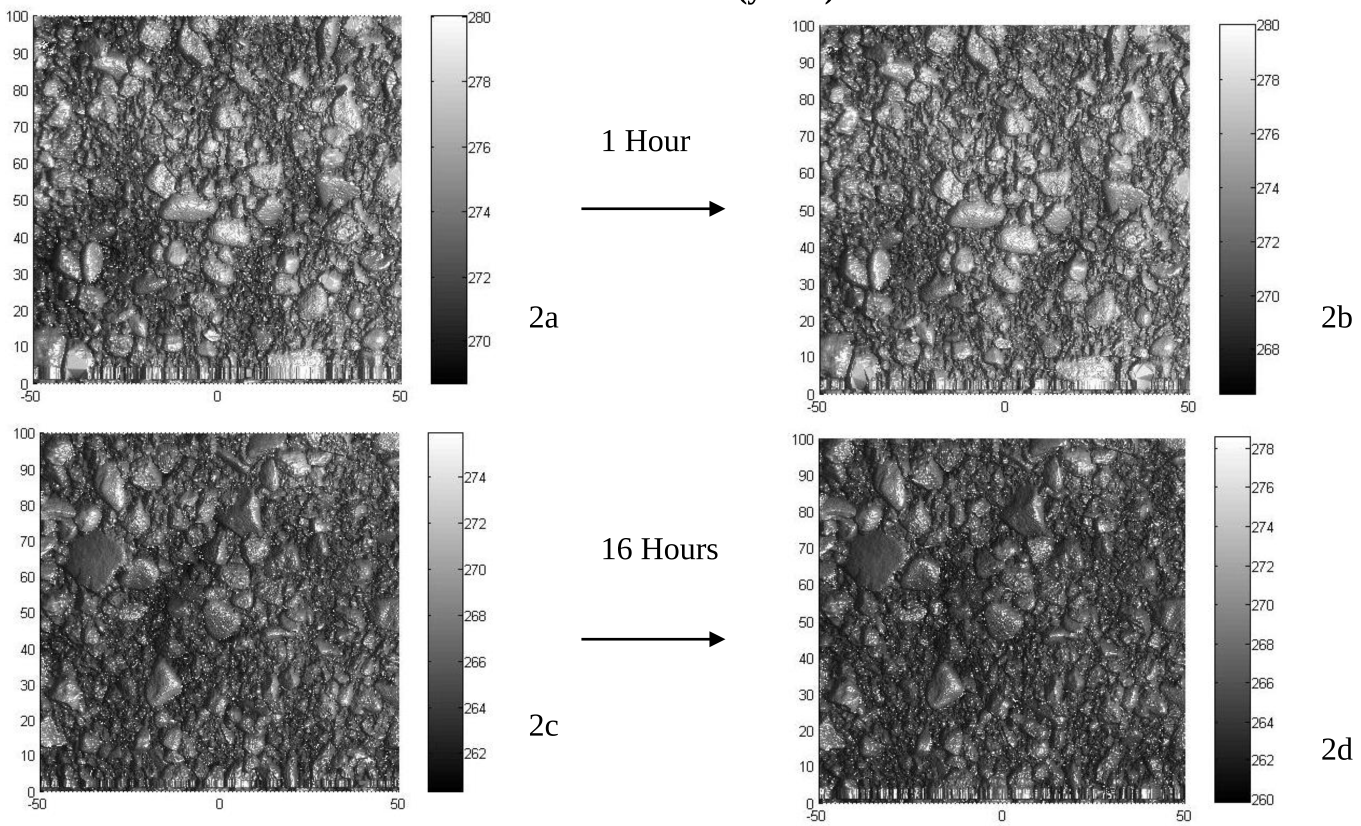
3.2.1 Average Data

Previous qualitative data (Haynes and Pender, 2007, Ockelford and Haynes, 2008, Haynes and Ockelford, 2009) has postulated that stress history induced stability gains may be due to the ability of the bed to locally rearrange into a more stable configuration without the entrainment or transport of grains *per se*. Specifically, it has been suggested that the larger pore spaces in single-size beds (uniform) permit greater localised movement of surface particles than graded beds where fine particles fill some of the void spaces (Haynes & Ockelford, 2009). This theory is based upon higher bed packing density permitting less freedom for individual particles to rearrange into more stable positions during the antecedent period. Thus, the laser data collected during this research enables the first truly quantitative interpretations as to specific topographical changes occurring during the antecedent period; this is aimed at explaining why beds becomes more resistant to entrainment even under sub-threshold flows (Section 3.1).

In order to assess the bed surface, laser displacement data was post-processed by linear interpolation in *Matlab* onto a 0.1 mm grid. This produced a digital elevation model measured in mm above an arbitrary datum. Figures 1 & 2 show the grey scale output data for the uniform and graded bed samples respectively both before and after the antecedent period for the 60 and 960 minute data. However, it is evident that such small-scale changes to the bed surface are difficult to evaluate without further post-processing and statistical analysis.



Figures 1a:1d –Digital Elevation Models of the uniform beds before and after the antecedent period of 1 hour (1a and 1b) and 16 hours (1c and 1d). The x and y axis are labelled in mm with the elevation measured in mm above an arbitrary datum. 0 on the x axis represents the channel centre line with flow in the 100 to 0 direction (y axis)



Figures 2a:2d – Digital Elevation Models of the bimodal beds before and after the antecedent period of 1 hour (2a and 2b) and 16 hours (2c and 2d). The x and y axis are labelled in mm with the elevation measured in mm above an arbitrary datum. 0 on the x axis represents the channel centre line with flow in the 100 to 0 direction (y axis).

Statistical analysis of Figures 1 & 2 is presented in Table 1; this considers both the change in mean bed elevations and the range of bed elevations for the scanned bed surface before and after each antecedent period. Mean bed elevation data (Z_b) clearly indicate a small vertical settlement of all beds during the applied antecedent period, ranging from -0.02 mm to -0.11 mm average elevation changes over the scan area. This suggests increased packing density within the sediment bed (as solids are compacted into a smaller volume) which may result in higher pivoting angles and enhanced particle stability, thus explaining some of the stability gains outlined in Section 3.1. The uniform bed indicates only limited settlement of -0.02 to – -0.04 mm (Table 1) whilst the bimodal bed suggests that settlement occurs to a greater extent (-0.05 to - -0.11 mm). This difference is the expected consequence of sediment grade effects. For uniform beds, the as particles are of similar sizes none are able to exploit the pore spaces between each particle; as such, it is likely that the slight vertical settlement is most likely by small scale grain reorientation increasing imbrication (Section 3.3). For bimodal beds, vibration of the smallest particles during the antecedent period (together with small scale grain reorientation) permits their infiltration into the bed pores spaces of the largest particles; this effect becomes exacerbated as the period of antecedent flow is increased and leads to better bed consolidation and enhanced stability after 960 minutes of applied flow antecedency.

The range of bed elevations (k; Table 1) also yields insight into how sediment grade affects stress history induced bed stability. Firstly, previous studies (Cooper and Tait, 2008) have noted that the range of elevations is a surrogate for geometrical roughness, where a smaller range is seen to indicate particle imbrication or infilling of the interstices between gravel particles by sand within the mixture. Looking at the absolute values in Table 1, the bimodal bed does support this theory at the start of the antecedent period where bimodal beds offer a lower k value than uniform beds due to grade effects. Secondly, the difference in range should, theoretically, represent developing bed roughness and hiding effects; these will increase where positive (+k) values are noted. As expected, settlement of finer material during the antecedent period applied to the bimodal bed increases the elevation range; hence the range of bed surface elevations within the bimodal bed is seen to show an increase of +3.97 to +4.85 mm. Conversely, uniform beds indicate a decrease (-2.64 to -2.92 mm) in bed elevation range between the beginning of the antecedent period and the end of the antecedent period; this appears to be reflective of grain reorientation (Section 3.3) and streamlining of grains to limit their roughness and exposure to destabilising fluid drag.

Grain Size Distribution	Descriptor	Antecedent duration (hours)	Start of Antecedent Period	End of Antecedent Period	Difference
Uniform	Z_b	1	275.33	275.29	- 0.04
	k		22.16	19.52	- 2.64
	Z_b	16	276.14	276.12	- 0.02
	k		23.27	20.35	- 2.92
Bimodal	Z_b	1	276.05	276.00	-0.05
	k		11.46	16.04	4.85
	Z_b	16	268.33	268.22	-0.11
	k		17.43	21.40	3.97

Table 1- Summary of the bed surface properties of the DEMs of the uniform and bimodal beds where Z_b is the mean surface elevation and k is the range.

3.2.2 Spatial Data

Given that only those grains that are initially unstable actually need to rearrange into a more stable location, only local sub-areas of the image will indicate elevation change; this means that the use of average statistics (Section 3.2.1) has the potential to be misleading, particularly in suggesting that changes to the bed surface are only very small in magnitude. As such, it is pertinent to analyse the scan data as spatial images to provide a more accurate interpretation of bed changes due to flow antecedency. Figure 3 presents Digital Elevation Models (DEMs) that spatially represent the relative change in bed topography after each antecedent period for each bed. These DEMs were calculated in *ArcGIS* software, where the interpolated grid from the end of the antecedent period was subtracted from the interpolated grid derived from the beginning of the antecedent period. Although detailed discussion is beyond the scope of this paper it is clear that local topographic changes are far in excess (up to +11.4 mm and down to -13.2 mm) of those implied by Table 1. In addition, it is evident from Figures 3a & 3b that particle reorientation is observed in the uniform bed; for example, the overturning of a grain manifests as blue area mirror image of neighbouring red area. This type of change is less noticeable in the bimodal bed (Figures 3c & 3d), specifically within the 60 minute data, most likely because there is larger emphasis on rearrangement by settlement and hiding effects.

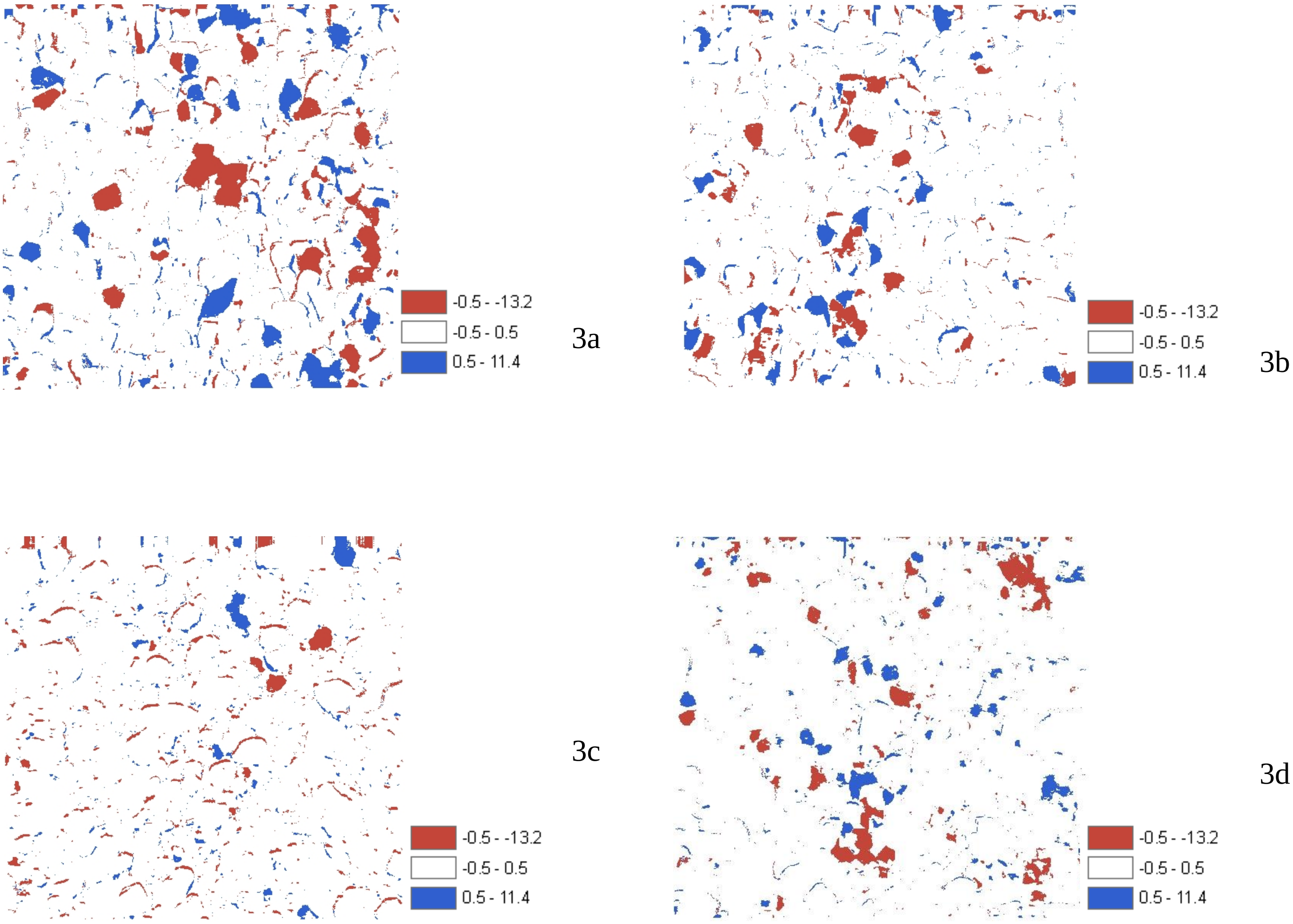
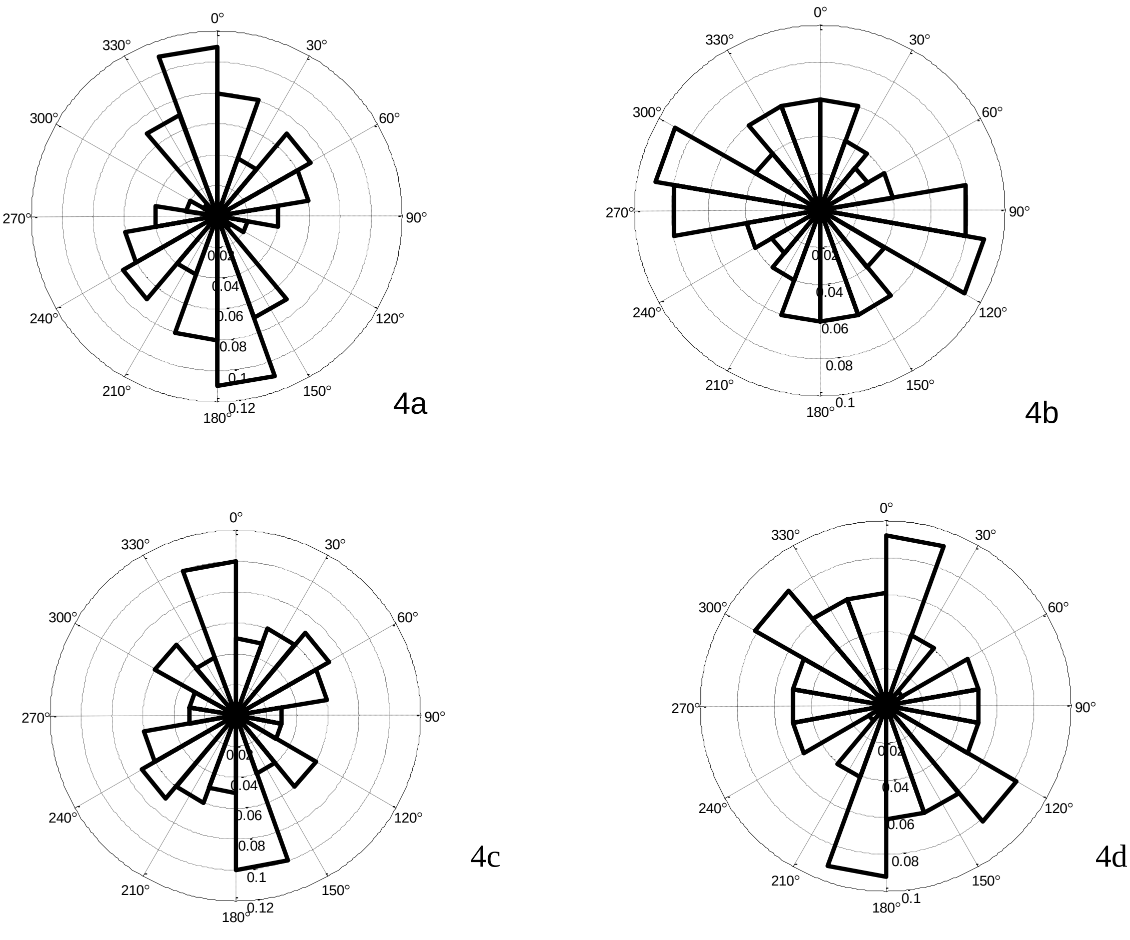


Figure 3 – DEM's of difference after flow antecedency for (a) uniform bed subjected to 60mins; (b) uniform bed subjected to 960mins; (c) bimodal subjected to 60mins; (d) bimodal bed subjected to 960mins

3.3 Particle Repositioning

Figure 3 therefore suggests that local topographic changes may be related to local (in-situ) repositioning of individual grains. Paphitis and Collins (2005) proposed that if it is accepted that a certain level of particle movement can occur even in sub-threshold antecedent flows, then the most unstable grains can re-orientate into positions where they have improved positions from the overlying flow. Thus it should follow that the longer the antecedent period, the more opportunity grains have to reorientate. As such, particles should either: (i) display a progressively increasing degree of flow alignment as antecedent duration is increased; or (ii) if the reorientation is a rapid one-off motion, then a greater proportion of grains on the bed surface will show alignment as the antecedent duration is increased. Therefore, in order to begin to quantify reorientation fifty grains were manually digitised from each laser scan surface to analyse the orientation of the longest exposed axis, relative to the direction of downstream flow. Li & Komar (1986) clearly state that a grain preferentially aligns its intermediate axis with the flow (typically within 0-15° of the flow direction); this means that the long axis will be orientated perpendicular to flow direction. The location of the long axis would be expected to align within the angles 75°-105° and 255°-285° when most stable. Yet, this type of analysis must however be applied with caution as the longest axis may not always be measurable on a surface scan; this situation would occur if the long axis is buried vertically into the bed and would result in the researcher analysing the intermediate axis without realising.

Figure 4 shows that both the uniform and bimodal bed show progressive reorientation of the long axis with increasing antecedent duration. For uniform beds, 60 minutes of antecedent flow (4a) does not show stable long axis orientation; instead it indicates high relatively instability with the long axis orientated with the flow. Interestingly, a similar pattern is observed in the bimodal bed after 60 minutes (4c); the strong similarity of Figures 4a and 4c may suggest that grain orientation is determined to a large extent from the artificial screeding process of the bed and 60 minutes of antecedent flow is insufficient duration to permit notable reorientation. This theory is currently under further investigation by the authors. However, after 960 minutes (4b), the long axes have rotated significantly (~60° from Figure 4a to 4b) such that the grain appears more streamlined and stable as defined by Li and Komar (1986). Yet, the bimodal beds do not appear to follow such a strong reorientation trend with antecedent duration; this is demonstrated by increased scatter in Figure 4d. This supports the supposition that the smaller grains present within the bed reduce the pore size and restrict the in-situ movement of the grains (Section 3.2). This data seems to confirm earlier data proposing that vertical settlement and hiding are more important in stability gains in graded beds, whilst reorientation is more critical to stability gains in uniform beds.



Figures 4 a-d; Orientation of the long axis of grains; flow is along the 0-180 line

4. Discussion

Data clearly demonstrate a stabilising influence of below-threshold antecedent flows on non-cohesive sediment beds; this confirms the concept of stress history in both uniform and graded beds as previously documented by Paphitis and Collins (2005), Haynes and Pender (2007) and Ockelford and Haynes (2008). However given that previous research only speculated upon the underpinning mechanism of stress history induced change to bed stability, the ultimate aim of this paper was to begin to address this deficiency by quantitatively analysing topographical changes and particle repositioning.

Surface statistics derived from the laser scans reveal topographical changes indicating vertical settlement, localised changes to bed roughness, pockets of more pronounced development of hiding effects, and particle repositioning. However, the grain size distribution of the bed clearly causes significant differences in the degree to which each mechanism is important in determining stress history induced bed stability. In the *uniform bed* the imposed turbulent flow caused observed vibrations of some surface particles. When the drag and lift forces acted on an unstable particle, the data presented in Section 3 suggests that particle reorientation was the dominant mechanism of stability gain. This appears possible due to large pore spaces in the framework permitting freedom of movement. The result is that particles streamline in the fluid flow (Li & Komar, 1986; Dietrich *et al.*, 1989) and increase grain imbrication and pivoting angles so as to enhance a grain's resistance to entrainment. Conversely, laser scan data for the *bimodal bed* matrix indicates that fines settle vertically into low relief pore space of the bed surface so as to consolidate the bed into a tighter packing arrangement (Reid *et al*., 1985); this increases hiding effects sheltering the fine grains from entrainment and also increases grain pivot angles so as to enhance the resistance of material to entrainment (Frostick *et al.*, 1984). It is also worth reiterating that particle reorientation in bimodal beds appears restricted due to the fine content of the bed surface, whereby larger clasts are 'rooted' around their base by high grain packing densities preventing their freedom of rotation. As such, vertical settlement and hiding effects appear to be the primary mechanisms of stability gains in bimodal beds subjected to antecedent sub-threshold flow.

5. Conclusions

This paper has provided two main insights. Firstly, this paper has provided insight into a new high speed laser technology to acquire topographic data from gravel bed surfaces that is suited to high resolution quantitative analysis. Typically previous research has had to trade data acquisition time with image resolution and quality; yet, this research has shown that the new technology has the capabilities to accurately and rapidly describe bed surface of different grade, size and composition whilst maintaining data quality. Secondly, this paper has shown the first real insight into the mechanism of stress history induced stability by way of quantifying the associated changes to bed topography and particle repositioning. Results have proved that the degree to which structural stability can be afforded to the bed is seen to be limited by the degree to which the bed can re-arrange into a more stable configuration. However by varying the surface grain size distribution the structural strength derived will be contingent upon not only the antecedent period applied to the bed but moreover the particles that are available on the bed surface, a function of grain size distribution. Specifically, this paper has identified that uniform gravel beds increase stability under antecedent flows primarily through particle reorientation, whilst graded bed stability is more a function of vertical settlement and relative grain effects.

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