GRAVEL BED ROUGHNESS DETERMINED FROM AIRBORNE LASER SCANNING

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ABSTRACT:

We use the airborne laser scanning (ALS) to scan the exposed dry surface of Nan-Shin river in Taiwan with a nominal point density of 100 points/m^2. Numerous studies showed that the fractal dimension is a good measure of the roughness of the gravel surface. The fractal dimension can be estimated from the slope of the log-log plot of the variogram. Because the gravel surface exhibits the anisotropic property, we first use variogram maps of the gravel surfaces to determine the anisotropic directions. Since the gravel surfaces show the self-affinity property, the directional variograms are then used for calculating the fractal dimension in the directions of maximum and minimum continuity. This study may lead to a better understanding of the roughness of the gravel surface using ALS data for the large-scale areas.

1. INTRODUCTION

The roughness of the gravel surface is an important characteristic for fluvial geomorphology and river hydraulics. Existing methods of quantifying gravel-bed roughness can be classified into two categories: the grain-size characterization approach and the random field approach (Nikora *et al*., 1998). The grain-size characterization approach uses percentiles of particle size distribution as a single grain-size index (e.g., d_{50}, d_{84}, or d_{90}) to represent the roughness. The use of a single grain size index is under the assumption that the particle size distribution, particle shape, orientation, and bed-form arrangement is constant at all sites and flow conditions (Butler *et al*., 2001; Nikora *et al*., 1998; Robert, 1988), while this assumption may not hold at all sites. For the random field approach, the gravel-bed elevations are viewed as the random filed of realizations of water-worked process, and the roughness is characterized by the distinct slopes at different scales in the variogram that is plotted on a log-log scale (*Butler et al*., 2001). The random field approach provides detailed description of the gravel-bed roughness at different scales; thus, it has attracted numerous studies to investigate the mixed fractal behavior of the gravel surface (Aberle and Nikora, 2006; Butler *et al*., 2001; Carbonneau *et al*., 2003; Hodge *et al*., 2009a; Nikora and Walsh, 2004; Nikora *et al*., 1998; Robert, 1988)

The detailed measurement of the gravel surface is an essential prerequisite for the scaling analysis. Due to advances in photogrammetry and laser scanning techniques, a growing number of studies are available on measuring in-situ gravel-bed surface elevation. For example, photogrammetry (Butler *et al*., 1998; Carbonneau *et al*., 2003) and terrestrial laser scanning (TLS) (Heritage and Hetherington, 2007; Heritage and Milan, 2009; Hodge *et al*., 2009b; Wang *et al*., 2011) has been employed to gather the 3-D surface elevations (i.e., in-situ DSM). However, most studies require physical presence of equipment at the gravel sites within the river. These gravel sits are usually difficult to access or can be quickly covered by weeds after a flood event. Moreover, the information obtained through few gravel sites may be insufficient to provide the synoptic analysis for a large area, i.e. a river section or a watershed. Thus, we propose using the airborne laser scanning (ALS), which can measure the 3-D point data of the gravel-bed surface from an airborne vehicle, to gather snap-shot information for the gravel-bed roughness for a large area.

Until recently, gravel-bed roughness has only been performed over the small areas. Moreover, the properties of gravel-bed roughness derived from ALS data have yet been discussed. In this study, we identify the anisotropic directions derived from the variogram maps of ALS data, and then calculate the fractal dimension using directional variograms. We show the variability of the gravel surfaces over a gravel bar. The results of this study should be useful to investigate the gravel-bed roughness for a large area.

2. METHOD

The fractal dimension *D*, which is estimated from the log-log variogram, has been widely used to describe the scaling characteristics of the gravel surface (Butler *et al*., 1998; Carbonneau *et al*., 2003; Hodge *et al*., 2009a; Nikora and Walsh, 2004; Nikora *et al*., 1998; Robert, 1988). The variogram, which is half the mean squared difference of paired data points separated by lag vector **h**, is given by:

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{i=1}^{N(\mathbf{h})}[z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})]^2 \tag{1}$$

where z(**x**) is the elevation at **x** and *N*(**h**) is the number of paired data points separated by the lag vector **h**. The lag vector **h** is specified with lag increment and lag tolerance for estimating semi-variance $\hat{\gamma}(\mathbf{h})$. The variogram provides a means of calculating fractal dimension of the gravel surface, and the scaling characteristics in the variogram of an isotropic surface is represented as

$$\hat{\gamma}(\mathbf{h}) = k\mathbf{h}^{2H} \tag{2}$$

where k is a constant, and H is equal to $3 - D$ (Butler *et al*., 2001). The fractal dimension D is estimated from the slope b of the log-log plot of variogram by $D = 3 - \frac{1}{2}b$. Since several studies have observed that the gravel surface reflects anisotropic component (Butler *et al*., 2001; Hodge *et al*., 2009a; Nikora and Walsh, 2004), directional variograms are appropriate to calculate fractal dimension in different directions. For the computation of a direction variogram, lag vector **h** is given extra settings of direction and angular tolerance.

Butler *et al*. (2001) and Robert (1988) have observed that two fractal bands are shown in the variogram of a gravel surface. The two fractal bands can be interpreted as the grain scale and form scale (Robert, 1988). In order to better identify the form scale, the trend surface is removed to ensure that stationarity prerequisite is fulfilled. And, the residuals from the planar trend surface are used for calculating the directional variogram and variogram maps in this study.

Butler *et al*. (2001) found that the direction of anisotropy in variogram map is seen to be relevant to the flow direction. The anisotropic directions are easily identified in the variogram map, which is a 2-D plot of the experimental variogram calculated for all available separation vectors (Deutsch and Journel, 1998). In the variogram map, the geometric anisotropy is visualized as an ellipse where the major axis and minor axis of the ellipse correspond to the directions of maximum and minimum continuity, respectively. The variogram map is standardized with the variance of residual elevations in this study.

3. DATA

The study area is located at the gravel bar near the confluence of the Nan-Shih River and Pei-Shih River, northern Taiwan (see Figure 1). The airborne laser scanning data were collected at a nominal point density of 100 points/m^2 by an Optech ALTM 3070 system fitted in a BK-117 helicopter, operated by a local survey company, at an altitude of 700 m on June 6th 2009. The airborne laser footprint has a diameter of approximately 45 cm on the gravel-bed surface. As shown in Figure 1, the ALS data were divided into 156 grids with a grid size of 8 x 8m. Moreover, the flow direction, which is derived from the characteristic dissipative Galerkin (CDG) upwinding scheme (Wu *et al*., 2011), is used to compare with the direction of maximum continuity of variogram map for each grid.

4. Results and Discussion

4.1 Variogram maps

The variogram maps of all grids are calculated, and we found that all of them show strong anisotropy. For example, Figure 2 shows the variogram map of grid number 894, and the elliptical contour lines demonstrate the pattern of anisotropy. Previous studies have shown that the variogram maps of the gravel surfaces have isotropic component at smaller lag distances and anisotropic component at larger lag distances (Butler *et al*., 2001; Hodge, 2009a), while our results shows no evidence of isotropic component. A possible explanation for this is that the point spacing of ALS data is too larger to present the isotropic component in the variogram map.

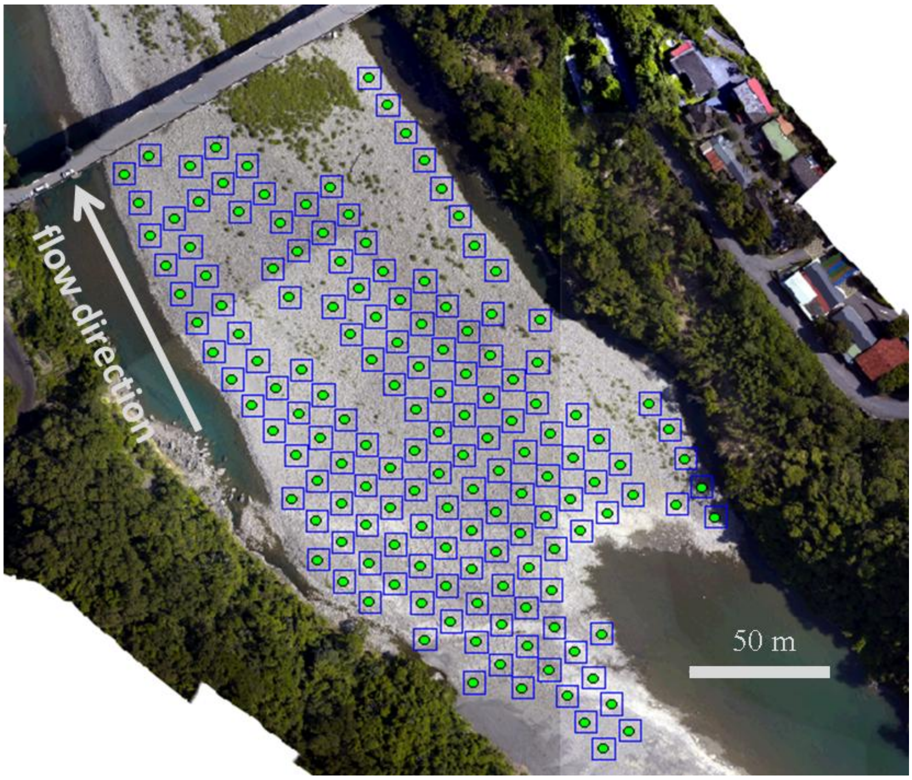


Figure 1. Aerial photo of the study area at the gravel bar near the confluence of the Nan-Shih River and Pei-Shih River, northern Taiwan. The blue grids have the size of 8 x 8m.

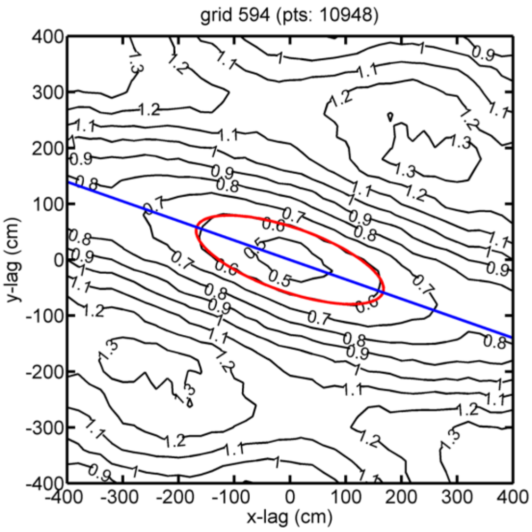
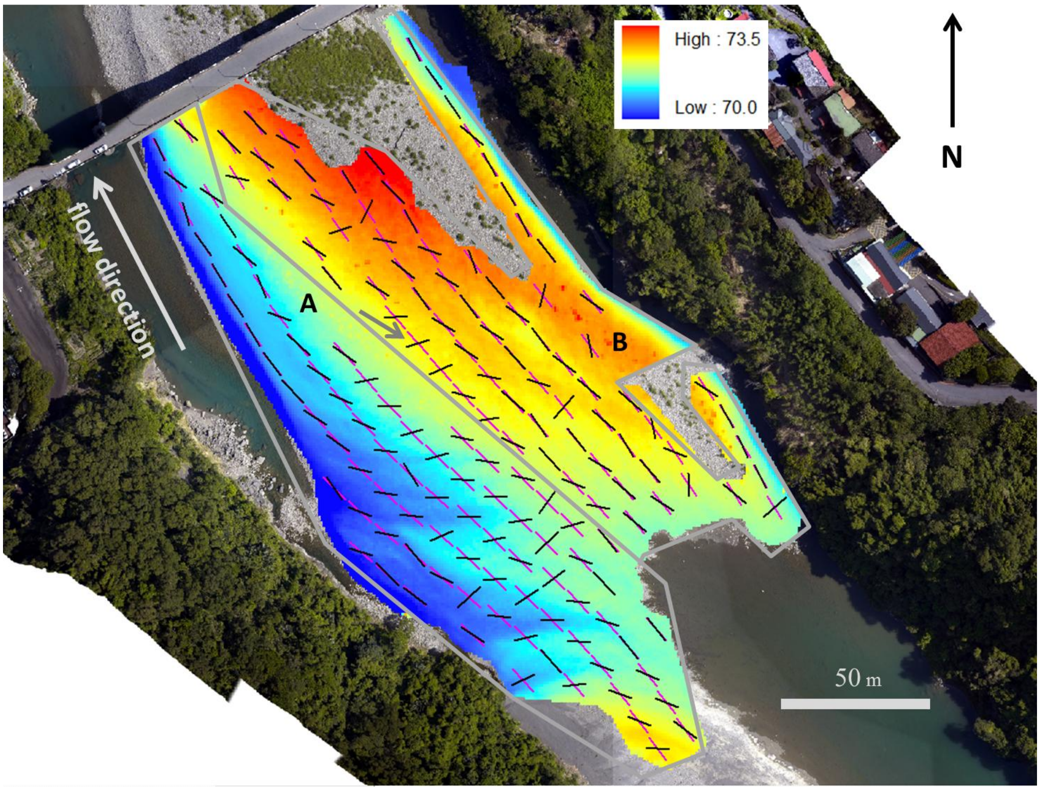


Figure 2. The varopgram map of grid number 594: The red line depicts the fitted ellipse, and the blue line represents the direction of maximum continuity (N70°W).

Isaaks and Srivastava (1989) have suggested that the apparent anisotropy shown in the contour line that crosses several lags can be used as a reliable indication of anisotropy. Therefore, an ellipse fitting procedure is used to fit the contour value at each grid. Human intervention is needed for choosing the contour value. As shown in Figure 2, the contour line with a value of 0.6 is chosen to ellipse fitting, and the blue line represents the direction of maximum continuity (N70°W).

(a)



(b)

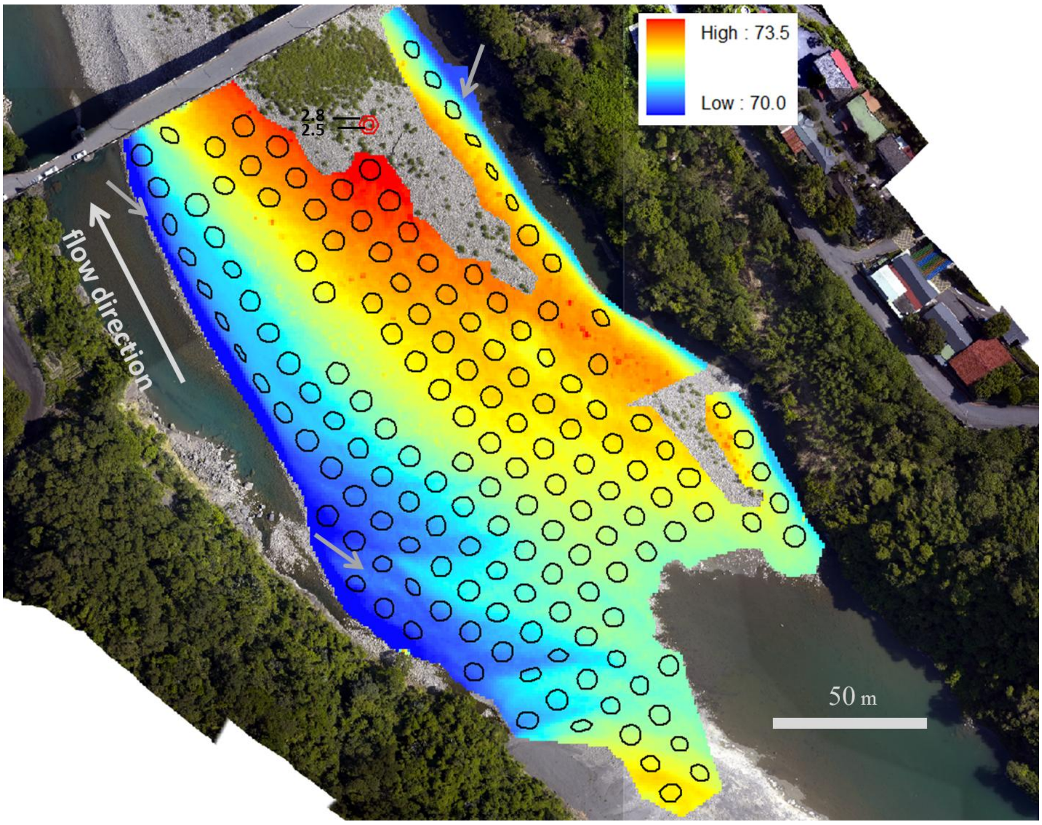


Figure 3. (a): The color map is the Digital Surface Model (DSM) derived from the ALS data. The DSM is divided into two regions (A and B). The black lines represent the directions of maximum continuity estimated from the variogram maps for all grids. The magenta lines are the flow direction derived from a CDG scheme for all grids. (b): The black circle is the rose plot of the fractal dimensions estimated from directional variograms for each grid.

Figure 3(a) shows the directions of maximum continuity determined from the variogram maps for all grids. The color map in Figure 3(a) is the Digital Surface Model (DSM) derived from the ALS data. We divide the DSM into two regions. In region A, the directions of maximum continuity changes from north-west to north-northwest. In region B, the directions of maximum continuity remain north-west. The results indicate a good agreement between the directions of maximum continuity and terrain relief. There is a significant difference between the directions of maximum continuity and the derived flow direction in the bottom of region A, while the difference is marginal in region B. Referring to Figure 3, the directions of maximum continuity of three grids (gray arrow) is west, which differs from those of grids in region B. However, the directional differences are not related to terrain relief.

4.2 Fractal analysis

A planar trend is fitted to the ALS data for each grid, and the residual elevations are used for the calculation of directional variograms to a maximum lag of 400 cm (which is half the grid size of the 8 x 8 m). Based on the results of variogram maps, the direction of maximum continuity for each grid is used for calculating the directional variograms. The lag increment and angular tolerance for the directional variograms is 20 cm and 15 degrees, respectively. After the directional variograms of all grids is examined, we reasonably conclude that only form scale is presented in ALS data. A typical example is show in Figure 4: the directional variograms of grid 635 in 125-degree direction. In Figure 4, the semi-variance value at the first lag is larger than expected due to the measurement uncertainty intrinsic to the ALS data. The first lag is not used for linear regression procedure to derive the fractal dimension using Equation (2), and only a slope (form scale) is obtained in Figure 4.

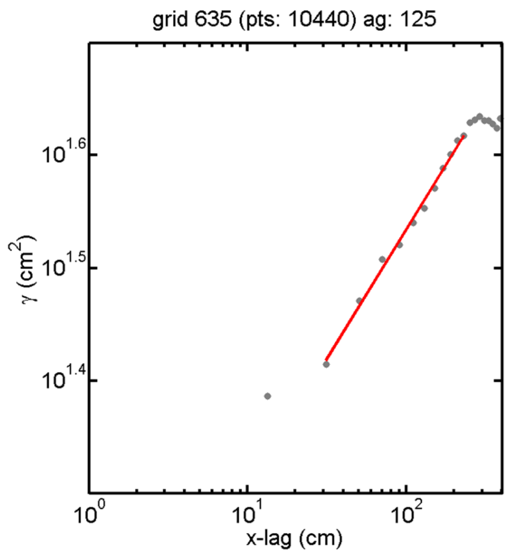


Figure 4.The directional variograms of grid 635 in 125-degree direction: The red line is the fitted result for calculating fractal dimension using Equation (2). The fractal dimension is 2.88.

Figure 3(b) shows the rose plot of fractal dimensions estimated from directional variograms of all grids. The fractal dimensions have notable differences between the directions of minimum and maximum continuity on the left and right side of the gravel bar (darker arrows in Figure 3(b)). The rose plot of most grids appears circular, which implies that the roughness is equally rough for these grids. Therefore, omni-direction variogram could be calculated for approximately deriving the fractal dimension. Moreover, the fractal dimensions for almost all of grids in all directions exceed 2.5, and the fractal dimension seems to be relevant to terrain relief.

5. Conclusions

Gravel-bed roughness is a key factor for understanding the fluvial geomorphology. In this study, we demonstrated the practicality of using ALS data to investigate the roughness properties over a gravel bar. Our results show that the direction of maximum continuity is close related to terrain relief. The roughness of most grids exhibits isotropic property, which implies that the fractal dimension derived from omni-direction variogram could be used for quantifying the gravel-bed roughness. Moreover, there are great differences of fractal dimensions between the direction of maximum and minimum continuity on the side of gravel bar. These findings suggest that the ALS data can be used for deriving the form scale over a large area in a cost-effective way.

6. References

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