Semivariogram analysis of gravel bed roughness with ground-based lidar data

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ABSTRACT: The roughness properties of the water worked gravel bed surfaces in the riverine environment acquired using ground-based Light Detection and Ranging (lidar) are investigated. The ground-based lidar can create highly detailed digital elevation models of gravel surfaces superior to traditional profiling methods. The roughness properties of the grain and form scales can be identified in the semivariogram when displayed in log scales. The effect of different patch sizes on the roughness properties was investigated by dividing the lidar data into two different patch sizes. The configuration of lidar stations was also tested using 6 m x 6 m patch size. The results showed that detrending on the lidar data is important when the form scale was of interest. Besides, four lidar scans obtained from the corners of a squared area is comprehensive for the water worked gravel surface.

1. Introduction

One of main factors that affect flow resistance and sediment transport is bed roughness. It characterizes the geometry shape and arrangement of gravels and is also important for ecology restoration and benthic organisms. The description of gravel bed roughness still remains poorly defined. The conventional characterization of bed roughness was represented by the grain size distribution. It implies that they are sample-size dependent and affected by the profile length or area extent (Butler *et al.*, 2001). In addition, the problems of the conventional approach are that particle size distribution is assumed constant at all sites and the assumption may not be held (Robert, 1988; Nikora, 1998). As a result, the random field approach which is independent from the sample size has been recently adopted for quantifying gravel bed roughness.

The random field approaches use a random field of gravel bed elevations to characterize roughness properties. The main advantage of random field approach is that it isolates scales of bed roughness. There have been many studies on the random field approach (Robert, 1988, 1991; Nikora, 1998, 2006; Butler *et al.*, 2001). These studies indicated that river bed roughness reveals phenomena of a number of different scales. The semivariogram approach can identify different scales, each reflecting a different source of bed roughness (Robert, 1988; Butler *et al.*, 2001). To this end, the stationarity assumption is required for modeling variogram. Thus, the gravel bed elevations refer to the residuals from fitting linear trend.

In order to use the semivaiogram method to quantify gravel bed roughness, the ground-based Light Detection and Ranging (lidar) were used to acquire the gravel bed surface in Nan-Shih river in Taiwan. Our lidar data can provide detailed three dimensional spatial descriptions than the traditional manual profiling method and can be conducted on larger area. To understand spatial properties of different sizes of gravel bed surfaces, our data were divided into two different patch sizes: 2m x 2m and 6m x 6m. We also compared the results of different lidar stations configuration.

2. Methods

Geostatistics was developed for spatial data analysis. It has also been extensively used for mining, hydrogeology and soil science (Matheron, 1965; Webster and Oliver, 2007). The semivariogram used to interpret the spatial variation is central to geostatistics. The Matheron's intrinsic hypothesis can be expressed as

$$E[Z(x) - Z(x+h)] = 0 \tag{1}$$

$$\gamma(h) = \frac{1}{2} Var[Z(x+h) - Z(x)] \tag{2}$$

where E denotes the expected value and $Z(x)$ is the random variable (Webster and Oliver, 2007). The semivariogram is the function of $\gamma(h)$, which is the semivariance function at lag h. The empirical semivariance is estimated as

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 , \tag{3}$$

where $N(h)$ is the number of pairs of data points which is separated by the particular lag h. The maximum lag h is half of the absolute maximum distance between data points.

When semivariograms of gravel bed profiles are plotted on a log-log scale, Robert (1988) found that they present two distinct linear increases of $\gamma(h)$ with lag distance h (Figure 1). The two straight lines on semivariogram correspond to grain scale and form scale roughness, respectively. Butler (2001) further applied the same method to the two dimensional data and found the similar results on two dimensional semivariogram. In this research, we used the above approach and conducted on a larger area to describe gravel bed roughness.

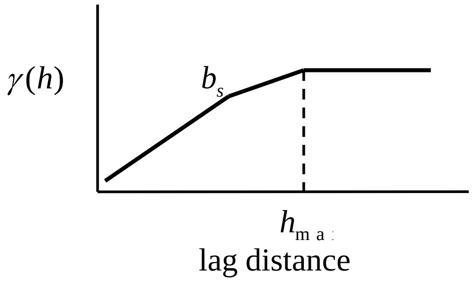

Figure 1: Statistical properties of gravel bed profiles on log-log scale. The break of slope b_s identified two different roughness characteristics at different scales. The range of the variogram is denoted as h_{max}, which implied no spatial dependence is found after h_{max}.

3. Results and Discussions

3.1 Data Collection

For analysis of the gravel bed roughness, it was necessary to obtain digital elevation model (DEM) from the field. We employ the ground-based lidar to capture three dimensional information of the gravel bed surfaces. Field measurements were conducted on three sites (96I, 97I, and 97II) in Nan-Shih river in Taiwan (Figure 2). Leica HDS3000 was used in site 96I and Leica HDS4500 was applied in site 97I and 97II. The configuration of lidar stations is shown in Figure 3. The station 5 and station 6 were used to enhance the data density of the central block (2m x 2m). The maximum number of stations used to measure the 6m x 6m area were six. We also collected the ground truth data by manual profiling method at 1 cm interval. The acrylic marks placed the sides of central block were the reference points in the registration process of lidar data and ground truth data. In order to extract top-view surface elevations, the noisy lidar data and the point data corresponding to the hidden surface should be filtered. In the research, we used the filter proposed by Wang *et al.* (2009). The comparisons between the filter results and the ground truth data are useful to understand the performance of the filter. After applying the filter, we obtained digital elevation models of three sites (Figure 4).

3.2 Effect of sampling sizes

Previous studies on characterization of gravel bed roughness were based on profiles or small area (Robert, 1988, 1991; Nikora, 1998, 2006; Butler *et al.*, 2001). In this research, we measure a larger area (6m x 6m). In addition, our data also were divided into two patch sizes in order to understand the effects of various sampling sizes. In order to satisfy intrinsic hypothesis, bed elevations were denoted as residuals from fitting linear trend. After applying semivariogram method to two different patch sizes, the results were shown in Figure 5. The offsets of the semivaiorgrams were adjusted in order to have the same intercept value on the y-axis. A number of characteristics were listed as follows. First, the grain scale slopes were similar for large and small sampling sizes in site 96I and 97I, which implied that the small sampling size is sufficient for grain scale description. However, the grain scale slope in site 97II revealed large difference for large and small sampling sizes. Second, the sill significantly helped identifying the range of form scale, which stated the importance of detrending data. However, if we only considered the grain scale, detrending was not needed. Third, the small sampling size was not sufficient for identifying form scale and further detrending was not helpful.

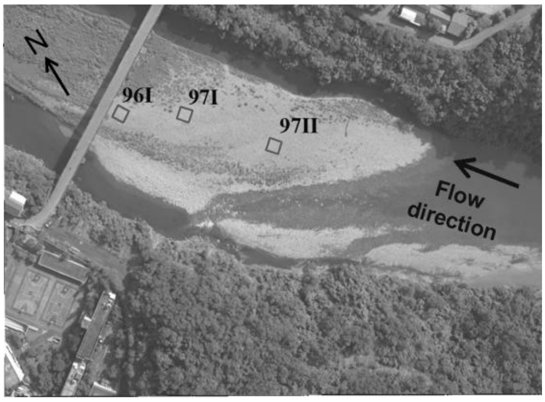

Figure 2: Aerial photo of study sites in Nan-Shih river in Taiwan. Three study sites with the sampling size of 6 m x 6 m are denoted as squares in the aerial photo. The inset shows the geographical location.

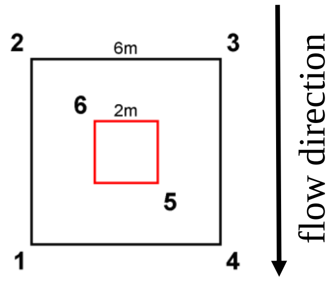

Figure 3: The arrangement of lidar stations. The number represents lidar station.

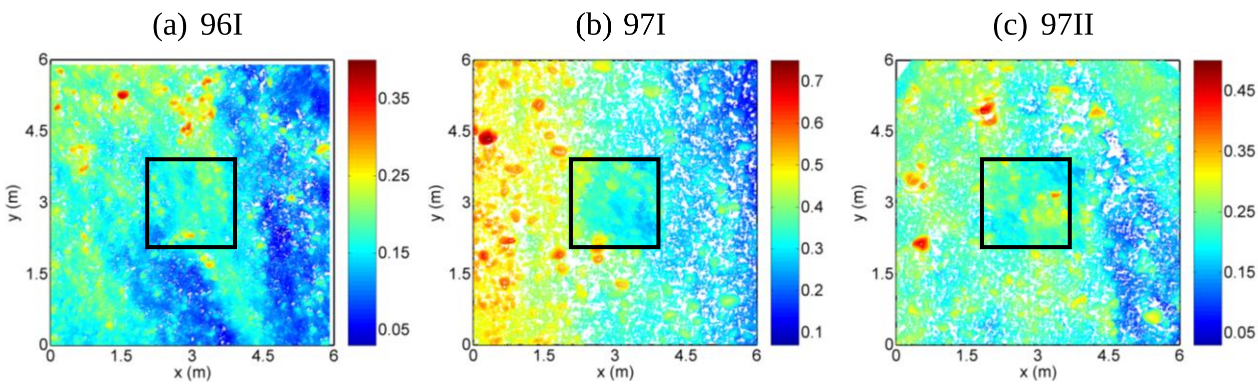

Figure 4: Digital elevation models of three sites. The black rectangle represented the small patch size (2m x 2m). The coverage of site 96I, 97I and 97II was 93.23%, 73.41%, and 80.65%, respectively.

3.3 Effect on the configuration of lidar stations

Given that the arrangement of lidar stations may cause the shadowing effect. We investigated the impacts of shadowing effect by changing the configuration of lidar stations in both sampling sizes. Figure 6 represented the semivariogram results of different lidar station configurations in large sampling area. In Figure 6, we found that the sill existed in three sites after detrending. The grain scale was similar in three sites. Site 96I showed consistent semivariograms, which suggested homogeneous gravel surface. The semivariogram of site 97I and 97II at grain scale grew faster than site 96I, which implied the two sites were more rough than site 96I.

The semivariogram of lidar station arrangement 123456 was always at the top and nearly the same with arrangement 1234 in Figure 6. However, the semivariogram of lidar station arrangement 13 or 24 was always at the bottom and this implied stronger shadowing effect in one direction than the other due to angular arrangement of gravels. The black rectangles in Figure 7 indicated that the lidar stations configurations caused stronger shadowing effect in specific directions.

(a) 96I (b) 97I (c) 97II

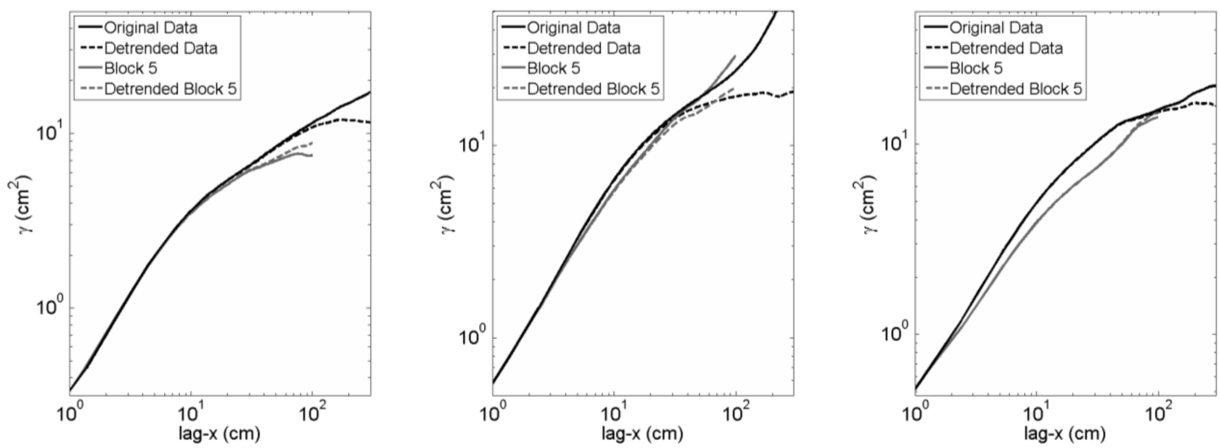

Fig 5: Original data is referred as the large sampling size (6m x 6m). Block 5 is the small sampling size (2m x 2m) at the center. Detrended parameters of block 5 used the same parameters applied for detrending the large sampling area.

(a) 96I (b) 97I (c) 97II

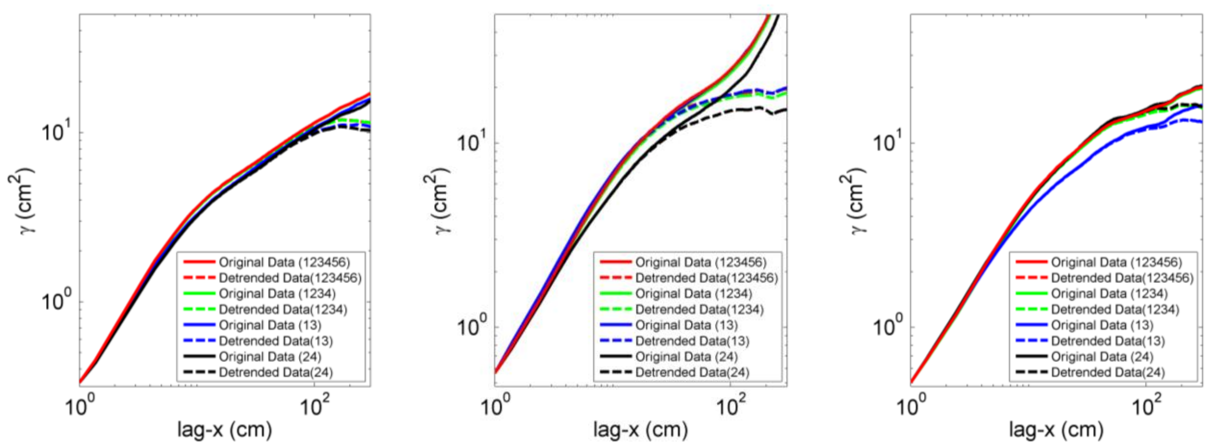

Fig 6: Semivariogram results of different stations configuration for large sampling area. The number represented the arrangement of lidar stations.

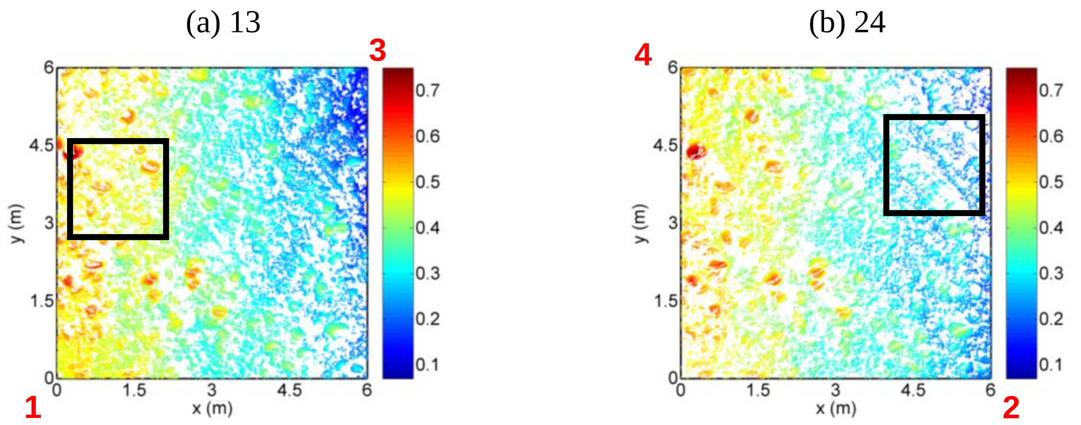

Figure 7: The DEMs of lidar station arrangement 13 and 24 in site 97I. The red number denoted the position of lidar station. The black rectangle denoted the shadowing effect.

4. Conclusions

The research used the semivariogram method to investigate gravel bed roughness. It showed that the semivariogram ploted on log-log scale could be used for the purpose. We found that the small sampling area is insufficient for characterizing the form scale and detrending is needed for identifying the range of form scale. Our results indicated that lidar station arrangement of 123456 is as good as that of 1234. In addition, four lidar scans obtained from the corners of a squared area can eliminate the shadowing effect. We suggest that lidar station arrangement of 1234 should be used for lidar point clouds collection for semivariogram analysis.

5. References

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