Anisotropy Characteristics of Exposed Gravel Beds Revealed in High-Point-Density Airborne Laser Scanning Data

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Abstract—The aim of this study was to examine the relationship between the anisotropy direction of exposed gravel bed and flow direction. Previous studies have shown that the anisotropy direction of a gravel bed surface can be visually determined in the elliptical contours of 2-D variogram surface (2DVS). In this letter, airborne laser scanning (ALS) point clouds were acquired at a gravel bed, and the whole data set was divided into a series of 6 m × 6 m subsets. To estimate the anisotropy direction, we proposed an ellipse-fitting-based automatic procedure with consideration given to the grain size characteristic d50, to estimate the primary axis of anisotropy [hereafter referred to as the primary continuity direction (PCD)] in the 2DVS. The ALS-derived PCDs were compared to the flow directions (for both high and low flow) derived from hydrodynamic model simulation. Comparison of ALS-derived PCDs estimated from an elliptical contour of the 2DVS exhibited a similar orientation when the contours of the 2DVS reveal the clear anisotropic structure, demonstrating the robustness of the technique.

Index Terms—Airborne laser scanning (ALS), flow direction, spatial continuity, 2-D variogram surface (2DVS).

I. INTRODUCTION

The geostatistical variogram function has been recognized as an important tool for detecting spatial anisotropy in exposed gravel bed structures [1]–[6]. The anisotropy indicates that the spatial correlation pattern changes with orientation, and it can be represented by the elliptical contours in a 2-D variogram surface (2DVS).

In the last two decades, substantial studies have investigated the anisotropy directions derived from a 2DVS in the exposed gravel beds and suggested that the anisotropy directions exhibited in the gravel bed surfaces reflect the dominant grain orientation [1]–[4]. Various studies have examined the relationship between gravel orientation and flow direction [7]. It has been reported that particle imbrication would occur naturally in a direction parallel to the flow [3], [7], [8]. Moreover, the anisotropy directions failed at being conclusive on the surface-forming flow direction [3]. The latter is notoriously difficult to determine accurately from in situ visual observations [9].

The determination of flow direction is essential to trace the water paths and sediment transportation. Alignment of bed particles transverse to the flow can be associated with transport mode by rolling and sliding [8], while bed structure longitudinal to the flow can be attributed to deposition of saltating particles after contact with the upstream front of stable grain and particle imbrications [2], [3]. It is thus of interest to explore the relationship between the anisotropy of gravel bed surfaces and flow direction across large areas. However, comparison of anisotropy direction determined visually from a 2DVS, extracted for laboratory and field gravel surfaces, to flow direction determined from subjective observation [1]–[4] revealed no common consensus about the relationship between anisotropy direction and flow movement in exposed gravel beds. This is possibly due to the limited numbers of data and the small spatial extents available to earlier researchers.

In this research, we examined the anisotropy characteristics of a very high-point-density ALS data of an exposed gravel bed, that has a much larger spatial extent than past researches, by comparing its anisotropy direction with simulated flow directions under high- and low-flow scenarios based on fixed-bed hydrodynamic modeling. To better reveal the variation of the anisotropy characteristic within the river channel, the whole ALS data set was divided into a series of 6 m × 6 m subsets, which results in 324 subsets of ALS point data. In order to consistently derive the anisotropy direction for each 6 m × 6 m subset, we devised an ellipse-fitting-based automatic procedure with the consideration of the grain size characteristic d50, which is the median of particle size distribution, to determine the primary axis of anisotropy [hereafter, referred to as the primary continuity direction (PCD)] in the 2DVS.

II. METHOD

A. 2DVS

The variogram has been used widely to quantify the spatial variability in gravel bed surfaces [2], [3], [6]. The empirical variogram, which is half the mean squared difference between

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pairs of data points separated by the lag vector \( h \), can be expressed as

\[
\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2
\]

where \( \hat{\gamma}(h) \) is the semivariance, the lag (distance and direction) vector \( h \) is the separation between two data points, \( N(h) \) is the number of point pairs separated by lag \( h \), and \( z(x_i) \) is the bed elevation at the location \( x_i \).

The empirical variogram is a function that relates semivariance \( \gamma(h) \) to lag \( h \) and is usually expressed as a set of 1-D plots, where different plots represent different directions. An alternative is to plot all directions together as a 2DVS, i.e., a raster map of semivariance values \( \gamma(h_x, h_y) \) representing the empirical variogram for all available lag vectors \( h = (h_x, h_y) \) [10].

Previous studies suggested the removal of possible large-scale topographic trends (i.e., the bed slope), which causes the spatial basis in the collected spatial data, before calculation of the 2DVS [3]. In this research, the planar detrending was applied to each ALS 6 m \( \times \) 6 m subset, and the elevation residuals were used for calculation of the 2DVS.

**B. Automatic Determination of Anisotropy Direction by Ellipse Fitting**

The 2DVS expressed as a contour plot can facilitate the analysis of spatial continuity (i.e., spatial autocorrelation) by visualizing the spatial variability along all directions simultaneously [10]. Therefore, the anisotropy direction can be determined by tracing one of the elliptical contours in the 2DVS [10].

The procedure for determining the PCD is described as follows. First, because the magnitude of the contours of the 2DVS is influenced by the actual semivariances \( \hat{\gamma}(h_x, h_y) \), the semivariances \( \hat{\gamma}(h_x, h_y) \) in the 2DVS were standardized (divided by the variance of the elevation residuals for each ALS 6 m \( \times \) 6 m subset), which implies that the contour levels in the 2DVS range theoretically between 0 and just greater than 1 (the maximum theoretical value is equal to the \textit{a priori} variance not the sample variance). Then, we applied an ellipse-fitting procedure to all elliptical contours of the 2DVS such that the PCD, which represents the direction of greatest spatial continuity, is estimated as the direction of the major axis of the fitted ellipse. Since the number of available contour levels in the 2DVS is inherently affected by the spatial autocorrelation property of the subject under investigation (in our case, the ALS point cloud of a exposed gravel bed), this raises difficulties in choosing the contour with a specific contour level for each ALS 6 m \( \times \) 6 m subset. As a result, the PCD is determined when the semimajor length of fitted ellipses falls in a given range derived by the grain size characteristic \( d_{50} \). We chose the \( d_{50} \) value as a physically based guidance in the ellipse-fitting procedure, rather than an arbitrary measurement value, with the hope to maximize the transferability of this procedure to other study areas. The test results for determining the range constraint are shown in section Determination of ALS-derived PCDs.

**III. DATA**

The study area [Fig. 1(a)] is an exposed gravel bed (denoted as the black polygon) near the confluence of the NanShih Creek and PeiShih Creek, northern Taiwan, with latitude and longitude of 24°54′10″ N and 121°33′24″ E, respectively. The gravel bed was occasionally submerged and migrated by severe floods caused by typhoons that occurred between May and November of each year. It is noted that low discharges would temporarily cause a submerged area, which is denoted by the gray rectangle in Fig. 1(a).

Fig. 1(b) shows one of the 22 image samples, which were taken from the 50 cm \( \times \) 50 cm acrylic frame in the exposed gravel bed in Fig. 1(a). We applied the photo-sieving technique developed by Graham et al. [11] to derive the particle size distribution aggregated from the 22 image samples, and the resultant \( d_{50} \) is equal to 5.5 cm.

**A. ALS**

An ALS survey was conducted on May 7, 2009, at the above ground level of 650 m along the river channel using an Optech ALTM 3070 system onboard a helicopter with nominal elevation and horizontal accuracies of 15 and 32.5 cm, respectively. The average point cloud density was 247 pts \cdot m\(^{-2}\). Furthermore, aerial photographs were also collected by a medium-format digital camera, integrated with an Optech ALTM 3070, simultaneously with laser scanning in order to generate georectified orthophotos with a spatial resolution of 5 cm \( \times \) 5 cm, as shown in Fig. 1(a).

For the ALS data of the exposed gravel bed, first, the extreme high points were removed manually. Then, the whole point data were divided into a series of 6 m \( \times \) 6 m subsets, each of which was aligned with the longitudinal and transverse directions in the mainstream of NanShih Creek. The mean spacing between the centers of 6 m \( \times \) 6 m subsets is 8 m. The specific 6 m \( \times \) 6 m subset size was chosen because our previous study [6] demonstrated that, using this size, reliable anisotropy patterns can be obtained for each subset while maximizing the number of available subsets. Furthermore, in order to avoid the potential bias caused by vegetation (sparse and short Miscanthus) on the gravel bed, we calculated the 2DVSs of ALS 6 m \( \times \) 6 m data sets only where the cumulative vegetation area was smaller than 1 m\(^2\) with the help of the 5-cm resolution orthophoto. This leads to 324 subsets available for 2DVS calculation.

The ALS data are also used to produce the DEM of the dry surfaces within the study area with a resolution of 1 m \( \times \) 1 m, where the point clouds belonging to vegetation were removed by visual inspection in Terrscan environment. Due to the infrared wavelength of 1064 nm operated by the ALTM 3070, water absorption prevents ALS measurement for underwater
surfaces. The underwater elevations were thus measured using a total station and surveying prism pole in wadeable areas, while a shipboard single-beam SONAR was used to survey deeper areas in June 2009. To facilitate the integration of a complete DEM of the study area, all surveying, including ALS, was referenced to TWD97 datum, the national coordinate system of Taiwan. The DEMs of the wet surfaces of a resolution of 1 m \times 1 m were interpolated from total station and SONAR data. The complete DEM of the study area was created by mosaicking the two DEMs of the dry and wet surfaces, respectively, and was further used for hydrodynamic modeling.

B. Hydrodynamic Modeling

To explore the relation between the ALS-derived PCDs and flow directions, we simulated the depth-averaged 2-D flow fields under high- and low-flow scenarios using a finite-element (FE) hydrodynamic model developed by Wu et al. [12]. The computational domain, extending 600 m to the Hsintien Creek and 700 m and 500 m to the NanShih and PeiShih Creeks [Fig. 2(a)], contained 17105 elements and 9000 nodes with a mean spacing of 4 m. The ALS-derived DEM was mapped to the FE grids via a triangulated irregular network shown in Fig. 2(a). The model was validated with the observed water levels [13]. The calibrated parameter values were then used for the scenario simulations. The upstream boundary conditions (BC) were specified with the flows from the NanShih and PeiShih Creeks, while the downstream BC was specified with the water depth at the Hsintien Creek. For the high-flow scenario, the specified flows (3400 and 1230 m$^3$s$^{-1}$) are equivalent to a flood event with seven-year return period; for the low-flow scenario, the specified values (23 and 18 m$^3$s$^{-1}$) correspond to flows with a 50% probability of exceedance. These two scenario simulations exhibited different extents of bar submergence and distinct patterns of 2-D flow field [Fig. 2(b) and (c)]. The simulated velocity vectors at the FE nodes were interpolated to the centers of the 6 m \times 6 m ALS subset, allowing direct comparisons of the ALS-derived PCDs and flow directions.

IV. Results and Discussion

A. Anisotropy Property of 2DVSs

The 2DVSs of the 324 ALS 6 m \times 6 m subsets were computed using the R software, and the contour map of the 2DVS was generated using a purpose-written MATLAB program. Based on internal testing, the lag distance of the 2DVS and the contour level interval in the contour plot were set to 15 cm and 0.05, respectively, to best reveal anisotropic structures.

Most of the 2DVSs of the ALS 6 m \times 6 m subsets revealed a clear anisotropic structure similar to the contours shown in Fig. 3(a). It is thus appropriate to apply the ellipse-fitting procedure to a specific contour to determine the PCD. While a small number of subsets show fewer [Fig. 3(b)] or no [Fig. 3(c)] elliptical contours in their 2DVS, the anisotropic structure is still prominent. Based on visual inspection, the 2DVSs similar to Fig. 3(b) and (c) appeared to be in the area covered by silt and gravel, which is highlighted by the white rectangle in Fig. 1(a).

Due to the requirement of ellipse fitting, the ALS-derived PCDs are only available for those 2DVSs similar to Fig. 3(a) and (b).

B. Determination of ALS-Derived PCDs

To further examine the insignificance of PCD bias caused by the choice of semimajor axis length constraint in the ellipse fitting, we generated three sets of ALS-derived PCDs determined from the semimajor axis length constraint within three ranges, i.e., 7–10 d$_{50}$, 9–12 d$_{50}$, and 11–14 d$_{50}$, and compared these PCD results with the simulated high- and low-flow directions. The choice of these constraint ranges was made in order to maximize of chance of having at least one available contour for each constraint.

C. Comparison of ALS-Derived PCDs and Simulated Flow Directions

The angle differences of the ALS-derived PCDs and simulated flow directions were calculated. The positive angle
to determine the PCDs. The black and gray lines are the PCDs determined from the fitted ellipse with the semimajor axis lengths equal to 8.0 $d_{50}$ and 9.5 $d_{50}$, respectively. The contours of the 2DVS in (b) and (c) show a clear anisotropic structure, but there exist only parallel contours in (c), which prevents application of the ellipse-fitting procedure to obtain the PCD.

As observed in Fig. 4, the distributions of the angle differences with three different semimajor axis constraints for high and low flow are, respectively, similar. To further demonstrate the similarity between each distribution of angle difference, for high and low flow, respectively, we applied the nonparametric Kruskal–Wallis test, with the null hypothesis that the three sets of angle differences come from the same distribution. The resultant $p$-values are 0.60 and 0.68 for high and low flow, respectively, both of which failed to reject the null hypothesis at the significant level of 0.05. This implies that the angle differences calculated from the three sets of ALS-derived PCDs and simulated flow directions do not reveal statistically significant differences. It is thus suggested that the ALS-derived PCDs derived from any elliptical contour of the 2DVS should exhibit similar orientation when the contours of the 2DVS reveal the clear anisotropic structure. The ALS-derived PCDs determined with the semimajor axis length constraint of 7–10 $d_{50}$ are discussed as it gave the largest number of comparison pairs.

Fig. 5(a) and (b) demonstrates the comparison of ALS-derived PCDs and simulated high- and low-flow directions, respectively. The gray polygon in Fig. 5 shows the extent of exposed gravel bed [also shown as the black polygon in Fig. 1(a)]. The white segments in Fig. 5 represent the simulated flow directions. We observed that the simulated flow directions for high flow are primarily parallel to the main stream direction in Fig. 5(a). Moreover, the simulated low flow primarily flows through the temporarily submerged area in Fig. 5(b) [c.f., the gray rectangle in Fig. 1(a)]. The red, yellow, green, and blue segments in Fig. 5 denote the absolute values of angle difference of $0^\circ$–$15^\circ$, $15^\circ$–$30^\circ$, $30^\circ$–$45^\circ$, and $45^\circ$–$90^\circ$, respectively, of the ALS-derived PCDs with respect to simulated flow directions.

We noted a good agreement between the ALS-derived PCDs and simulated high flow in the right portion of the exposed gravel bar [Fig. 5(a)], where the white segments become invisible due to the insignificant angle difference between the ALS-derived PCDs and simulated high flow. However, an area with notable discrepancies of the ALS-derived PCDs and high-flow direction is also presented [denoted as rectangle A in Fig. 5(a)]. For the temporarily submerged gravel bed area, we observed that the ALS-derived PCDs showed better agreement with the simulated low-flow direction than the high-flow direction.
on the angle differences. The results suggest that the ALS-derived PCDs estimated from any elliptical contour of the 2DVS should exhibit similar orientation when the contours of the 2DVS reveal a clear anisotropic structure. Furthermore, the comparison of the ALS-derived PCDs and simulated flow directions shows good agreement, which suggests that ALS-derived PCDs could be used to infer flow direction at different flow rates.

The process for determining the PCD in the 2DVS is largely automatic and is scalable. It is expandable and scalable to the whole ALS scenes where the river can be adequately demarcated. Thus, this letter points to the potential of determining flow direction across large areas, at both high and low flow, without the need for in situ measurement or simulation modeling. Future research should demonstrate this ability across a range of different flow conditions and for a wider range of gravel bed surfaces.

V. CONCLUSION

We have explored the relationship of the anisotropy direction of exposed gravel bed and simulated flow directions. We have determined the PCDs from the 2DVSs by applying an ellipse-fitting procedure with consideration given to the grain size characteristic $d_{50}$. The angle differences between the ALS-derived PCDs and simulated flow directions were calculated, and the Kruskal–Wallis test was performed

REFERENCES