ESTIMATION OF LANDSLIDE-INDUCED RIVERBED ROUGHNESS VARIATION BY USING LIDAR DATA

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Key words: morphological analysis, surface roughness, digital elevation model, LiDAR.

ABSTRACT

With advancement in efficiency and accuracy on investigation techniques and equipment, the remote sensing technologies have been widely employed in river circumstance investigations. In the past, quantifying the morphology along a river channel has been proven difficult till the airborne laser altimetry technology, Light Detection and Ranging (LiDAR), has started providing high-resolution and high-accuracy topographical data. Data derived from airborne LiDAR has been adopted for analyses in recognition of riverbed morphology. The “roughness index” in this study is defined as the standard deviation of residual topography. The variable moving window was used in deriving the smoothed DEM. The standard deviation of residual topography was used as a measure of roughness where the residual topography is the difference between the original and smoothed DEM. Roughness data derived from pre-disaster riverbed by different reaches were compared with the post-disaster data. Results showed that the upper-reaches demonstrate higher roughness values than lower-reaches. Thus, the post-disaster riverbed surface relief was close to the derived smoothed relief. Such characteristics were also reflected in the major differences evaluated by slope measurement for riverbed morphological analysis; of which the location of the peak value also appeared to have changed after the disaster. It concluded that these remote sensing techniques have become vital in assisting the ordinary survey for regional investigation through its rapid and accurate construction of an integrated plane-wise fluvial circumstance of a river watershed area.

I. INTRODUCTION

Geomorphometry, which is defined by Chorley [3] as the science “which treats the geometry of the landscape”, attempts to describe quantitatively the form of the land surface. In a general sense, roughness refer to the irregularity of a topographic surface. The terrain roughness can be measured by significant wavelengths. The significant wavelengths of topography are termed as grain or texture, while amplitudes associated with these wavelengths correspond to the concept of relief. The relationship between the horizontal and vertical dimensions of the topography is embodied in the land slope and the dispersion of slope magnitude and orientation, while vertical distribution of mass under the topographic surface is contained of hypsometry [12].

According to previous studies, evaluating the surface roughness by using LiDAR data has been proved to be an useful approach on detecting landslide areas [2,4,6,14]. However, the surface roughness of a landform is nevertheless dependent upon the material properties, processes acting upon it, and the time elapsed since formation. The river characteristics have played an important role for hydrological models [13]. Sediments supplied from landslides may affect the river channel morphology changes in different reaches or magnitude; namely, the riverbed morphology can be related to disaster events. Benda and Dunne [1] had analyzed the transportation of debris flow sediment in the first and the second order channels, and predicted the landslides in different channel reaches for the next 3000 years.

II. STUDY AREA

1. Study Area

The study area, with 5.5×7 km\(^2\), is located at the northeast portion of Kaohsiung City, Taiwan; is situated in the sub-basin of the Kao-Ping Catchment (see Fig. 1). The high-accuracy and high-resolution images of the Kao-Ping Catchment, taken with airborne LiDAR, were adopted for pre-disaster and post-disaster riverbed roughness evaluation and analysis.
2. Landslide Event

Hsiaolin village, located at the northeast part of Kaohsiung City, sustained heavy damage during a catastrophic landslide event in August, 2009. Induced by Typhoon Morakot, the Hsiaolin Landslide was recognized as a wedge type slope failure. The failure wedge was formed by a N26°W/22°W bedding plane of Pliocene-Miocene Tangenshan Sandstone and a N80°E/84°N high angle fracture; thus, generated a sliding oriented in the west-southwest direction (262/21) [10].

3. Regional Geological Setting

The riverbed geological setting of Hsiaolin village reach was primarily consisted with alternation of sandstone and shale. Serious landslides occur after typhoons and rainfall, especially the area surrounding the river banks and the proximity of local main highway.

III. PROCESSING METHODOLOGY

In some hydroclimatic regions, channel adjustment is strongly forced by colluvium sediment inputs (and thus an imposed sediment size distribution) to channels through landslides and debris flows. In these regions the influence of climate on the network-wide distribution of step-pool channels may be more closely linked to climatological events that deliver sediment to channels through mass movement. The amount and frequency of colluvium material delivery to channels may directly influence the effectiveness of channel forming events [5]. Montgomery and Buffington [15] had success distinguishing between bedrock and alluvial channels in forested drainages using a slope-area plots. The roughness configurations or energy dissipating features that distinguish these channel types reflect downstream changes in sediment supply relative to capacity.

1. Topographic Data

The materials used in this study included the airborne LiDAR Digital Elevation Model (DEM) and the derived roughness data. The LiDAR DEM was derived from point clouds and then resampled with 1-meter grid. LiDAR data were collected both before and after the disaster caused by Typhoon Morakot in August, 2009.

![Image: Pre-disaster LiDAR DEM of Hsiaolin village, the study area.]

2. Surface Roughness

The surface roughness is an expression of the variability of a topographic surface at a given scale. The roughness is described using surface-elevation values. It can be used to characterize landforms over a variety of different scales. In remote sensing, the roughness can also be quantified by using the reflections of electromagnetic radiation, ranging from specular to diffuse, from landform surface. In geomorphometry, roughness is described using surface-elevation values and can be used to characterize landforms over a variety of different scales [11]. This indicates that a single definition of surface roughness may not be sufficient. Surface roughness is treated here as a geomorphometric variable, not a parameter. A variable is a measurable property of a phenomenon (e.g., slope angle), while a parameter is a summary measurement of the characteristics of a population (e.g., mean slope angle) [7]. Several methods have been developed for the definition, calculation, and application of surface roughness [2, 6].

3. Slope Gradient Index

As previous mentioned, the landscape can be treated as a measurable phenomenon. The landforms of the surface roughness are most quantified by slope measurement. The slope is the rate of change of elevation. Slope have been regarded as the most important geomorphic parameters, as they not only efficiently describe the relief and structure of the land surface[17], a simple definition of slope describes as follow:

$$S = \arctan\sqrt{f_x^2 + f_y^2}$$  \hspace{1cm} (1)

where $f_x$ and $f_y$ are the gradients at W-E and N-S directions, respectively describes as follow:

$$f_x = \frac{(z_3 - z_1) + 2(z_6 - z_4) + (z_9 - z_7)}{8 \times \text{cell size}}$$

$$f_y = \frac{(z_7 - z_1) + 2(z_8 - z_2) + (z_9 - z_3)}{8 \times \text{cell size}}$$  \hspace{1cm} (2)

where $z$ is the topographic elevation, it employs a third order finite difference technique using the eight neighboring elevation values bordering the central elevation cell. This method uses eight grid points to calculate each gradient value by 3x3 moving window. This algorithm was developed by Sharpnack and Akin [16] and modified by Horn [8]. This algorithm was
proved with lower RMS (root mean square) residuals in topographic analysis[17].

4. Slope-Based Roughness Index

In the present study, the roughness index was defined as the standard deviation of residual topography (illustrated in Fig. 2). The variable moving window was exploited to derive the smoothed DEM. Standard deviation of residual topography was regarded as a measurement of roughness where the residual topography is the difference between the original and a smoothed DEM. The LiDAR DEM was performed by moving window with 5x5 cells (5 times the grid size of the DEM). Each cell is corresponding to the mean DEM value of the 25 neighborhood cells. The interval of the moving window for roughness index is also given by 5x5 cells; these values have been considered to identify the upper limits of analysis, the range upper of the limits are corresponding to the river topography characteristics from 2.5m to 5m [2, 9]. Some studies have shown a relationship between the standard deviation of residual topography and riverbed roughness [2], the formula describes as follow:

\[ r = \sqrt{\frac{\sum_{i=1}^{25} (x_i - x_a)^2}{25}} \]  

(3)

where \( r \) is the roughness index and also the standard deviation of residual topography, \( x_i \) is the value of the specific cell, \( x_a \) the mean value corresponding to the specific cell (\( x_i \)), 25 is the mean of the 5x5 neighborhood cell value of the DEM.

The spatial variability of geomorphometric variables is important -- it is not enough to know that a given area is “rougher” or “smoother” than another but rather how much and where this difference happens since it may be related to geological features such as lithological boundaries and tectonic structures [7].

The surface roughness index was derived from LiDAR DEM by the standard deviation of the residual topography \( r \) method, and the roughness index was also used for generating slope then comparison with elevation-based slope. A third-order finite difference weighted by the reciprocal of the squared distance algorithm was performed for slope gradient assessment.

\[ S_r = \arctan \sqrt{f_x^2 + f_y^2} \]

\[ f_x = \frac{(r_3 - r_1) + 2(r_6 - r_3) + (r_9 - r_7)}{8 \times \text{cell size}} \]

\[ f_y = \frac{(r_2 - r_1) + 2(r_5 - r_2) + (r_9 - r_3)}{8 \times \text{cell size}} \]  

(4)

where \( r \) is the standard deviation of residual topography and the slope-based roughness was then computed within a 3x3 moving window.

5. River Change Characteristics Analysis

Change analysis of the riverbed area would provide significant information on the disaster. The analysis was performed by calculating the area change between pre-disaster and post-disaster. The result would appear with three statuses on riverbed; i.e., gain, unchanged and loss. Meanwhile, a cross sectional profile (Fig. 3) survey was also conducted to assess the riverbed morphology change.

Fig. 3 Two roughness index measurements; (a) Slope Gradient, (b) Slope-Based.

IV. RESULTS AND DISCUSSION

The slope-based roughness index was used for pre-disaster and post-disaster analysis. Different river reaches were compared using this method. Indices of slope gradient and surface roughness were joining to be compared with. The results show that both methods reflect the variability of a topographic surface. Fig. 4 indicates that the stream topographic in slope gradient and slope-based roughness are showing a significant curve feature matching at streams and flood land areas. However, the slope gradient index at the boundary of a stream appears higher value than in slope-based roughness index. It indicates that the slope-based roughness index shows smoother reflections than slope gradient index.
In the other point of view, the slope gradient index can only reflect the peak value clearly; yet, the slope-based roughness index will show more detailed curvilinear feature variations in topographic characteristics.

Fig. 4. Comparison of roughness indices in different river reaches.

Both indices have shown an increasing tendency in roughness when breaks of topography are occurring. In particular, slope gradient index appears more sensitive than slope-based roughness when the break point shows. Fig. 4 and Fig. 5 indicate significant differences in spectrum profile; as mentioned previously, slope shows larger amplitude than roughness index in vertical dimension. In uniform area where the slope value less than 10 degrees (Fig. 4), the slope-based roughness index appears smoother than slope gradient index; but shows more detail variability of topographic and reflects a continued relief.

Fig. 5. The box plots for roughness measures of different river reaches; 2005 for pre-disaster and 2010 for post-disaster; (a) Slope Gradient Index, (b) Slope-Based Roughness Index.

Fig. 5 shows the box plots for these two indices. Fig. 5(a) indicates the slope gradient indices in pre-disaster (2005) and in post-disaster (2010). They are showing the same topographic features for the upper river reach as well as for the lower river reach. It means that slope in two reaches was reduced after the disaster, and the largest value for the slope and slope-based roughness was reduced rapidly; due to the uplifted changes in elevations of these reaches. This may be related to the landslides material supported from upper-reach and also great contribution made from flooding area increase.

The major difference between slope gradient index and slope-based roughness index on riverbed measurement can be observed in the case of analysis (Fig. 5). The slope-based roughness method has smoother value than the slope gradient method on pre-disaster and post-disaster.

The results for using two periods data with LiDAR technique are shown in Table 1. After the typhoon event, the flood land area increase reaches 63%; the slope is also affected by material supported from the upper-stream.

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<tbody>
<tr>
<td>Area (m²)</td>
<td>1614029</td>
<td>2631741</td>
<td>63%</td>
</tr>
<tr>
<td>Mean Slope (degree)</td>
<td>7.6</td>
<td>6.2</td>
<td>-22%</td>
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The slope-based roughness index shows smoother surface after the disaster occurred; the pre-disaster presents higher values of the median than post-disaster for slope.

The analysis of riverbed area changes, shown in Fig. 6, the typhoon provides huge materials from upper-reach, the most significant contribution on riverbed are from landslide materials, of which the net gain obviously greater than the net loss (Table 1).

Fig. 6. Materials gained and lost on riverbed.

The Fig. 7 presents the cross sectional profile surveying results. All of the profiles indicated that the post-disaster riverbed elevation rise. The maximum elevation rise was more than 10 meters. Also, the profiles indicated that the major elevation change occurred in upper-reach, the wide river channel provides larger sediment deposition space and it may...
exhibit higher elevation values in the upper-reach (Profile 4 and Profile 5 in Fig. 7). The morphologies of the riverbed also affected by landslide sediments input; namely, the sediments turned the river deeper in upper-reach and broaden in lower reach. The post-disaster roughness of the river channel also appears to be smoother than that of the pre-disaster. The velocity of the stream flow will decrease when sediment input.

Fig. 7. Comparison the disaster effect of channel morphologies on riverbed.

V. CONCLUSIONS

The slope-based roughness index can be used for disaster and river circumstance investigations. The river roughness can be treated as a parameter, and be used for hydrological models. The results have shown two methods were capable of reflecting the riverbed morphologic characteristics.

The major difference between slope-based roughness index and slope gradient index for describing topographic morphology has shown in the spectrum pattern. The slope-based roughness appears smoother than slope gradient index; it may relate to the slope-based roughness is the standard deviation of residual topography such that this index reflects the whole river feature. It has shown the continuous properties of river channel as well as the pattern of riverbed. It also provides important hydrological parameters for river channel. The post-disaster roughness of the river channel showed smoother morphology than pre-disaster; thus, it makes river deeper in upper-reach and broaden in lower reach.

The aim of this study was readily been evaluated that the multi-temporal LiDAR DEM derived data can be used as a quantitative tool when the disaster occurred. The results also show that the LiDAR data can be considered as a rapid and a useful investigation tool for river circumstance survey.

REFERENCES