Topographic Laser Scanning of Landslide Geomorphology System: Some Practical and Critical Issues

Khamarrul Azahari RAZAK, Rozaimi CHE HASAN, Mohd Azwan ABBAS, Lau CHONG LUH, Lim CHOR SHENG, Rabieahtul ABU BAKAR, Zulkepli MAJID Suhaimi JAMALUDIN, Wan Abdul Aziz WAN MOHD AKIB, Malaysia

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SUMMARY

Modern surveying technology, notably topographic laser scanning system (TLSS) has been widely used for understanding the geophysical phenomena underlying natural hazards. Advanced and modern TLSS is a promising tool for mapping, monitoring and modeling landslides in the tropics. Understanding this geomorphic processes is an important step forward given the economic losses and fatalities globally. This paper aims at providing better insight into the use of TLSS captured from airborne- and ground based platform, coupling to advanced point cloud- and image-based processing for a detailed landslide investigation in a mountainous tropical region (Gunung Pass, Perak). This paper deals with some critical issues of laser scanning – from the field to the finish, for collecting landslide topographic data, and outline recommendation mapping practices for a better understanding of geomorphic problem and permutes the operational needs at national, state and local jurisdictions. Notable laser scanning-facilitates products are carefully addressed in the context of tropical landslide geomorphology system. Multi-scale stereoscopic visual analysis of TLSS derived images unveiled much better landslide geomorphology features and activity than that of previously mapping techniques. A series of field investigation explicitly indicated the distinctive morphology, disrupted drainage and vegetation anomalies across the unstable area. We evaluated a series of topographic surveying techniques to understand their spatial capability, time efficiency and effectiveness. Multisensor laser scanning data enabled identification and classification of complex landslides, but attention is needed to integrate them in a densely forested area. As a conclusion, TLSS can be a very important new data source and mapping tool to characterize landslides even in a complex environment. The increased prevalence of modern TLSS system and advanced point cloud processing has led the ways to improve future landslide maps and subsequently reduce possible risk. The emergence of TLSS enables the surveyors to more effectively play a vital role in such complex and changing environment.

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1. INTRODUCTION

The importance of landslides in the tropics has long been underestimated and some of these movements progress so slowly in such their presence is scarcely understood (Sharpe, 1968). According to the United Nations International Strategy for Disaster Reduction (UNISDR) and the Centre for Research on the Epidemiology of Disasters (CRED) international disaster databases (EM-DAT, 2011), landslides are ranked 3rd in terms of number of fatalities among the top ten natural disasters. Landslides have killed more than 80000 people around the world in the last 10 years (Petley, 2011). The data in such catalogues are only an indication of the general trends, and should be interpreted as a minimum given the incompleteness of the database. In the past 34 years, the total economic losses due to landslides in Malaysia are estimated about RM 3 billion and without a comprehensive mitigation plan; it will substantially cost 17 billion over the next 25 years (PWD, 2009).

As an important geomorphic process in shaping major landscape in humid mountainous regions (Thomas, 1994), landslides play a significant role for disturbing the heterogeneity of forest ecosystems (Frolking et al., 2009). Landslides represent one of the most acute hazards in mountainous landscapes, and their impact is largely under-represented (Hewitt, 1997). Combined with anthropogenic activities, especially the development and settlement on unstable tropical terrain, landslides, natural processes in the first place have become natural disasters. Given that landslides often cause extensive damage to infrastructure and many casualties, it is important to identify extent of slope failures, define their characteristics, and estimate their activity (McKean and Roering, 2004).

Despite the importance of landslide inventory maps for mitigation and planning, they are rarely created (Guzzetti et al., 2012). The compilation of landslide inventory maps is a tedious procedure due to the fact that each individual landslide has to be mapped and described together with their characteristics (Van Westen et al., 2006). The complexity and time consuming nature of landslide inventory mapping led to only a small portion of the terrain mapped for landslides. Paucity of reliable information on landslides, therefore, hampers the possibility of assessing landslide susceptibility, hazard and risk at the regional, national continental scales. Brardinoni et al. (2003) reported that ‘not visible’ or undetectable landslides from aerial photos can represent up to 85% of the total number of failures and significant volume (up to 30%) of debris to the amount mobilized.

In an equatorial forested region, vegetation growth causes the signature landslides (e.g. small and shallow) obscured very quickly (e.g. months or seasons). Hence soon after their occurrence, the evidences of landslides signature cannot be recognized and not easily seen on the images. Synoptically landslide activity assessment remains problematic, as slope failures are often covered by complex undergrowth and multi-storey forest canopies, and hampered by the prolonged and heavy low altitude cloud cover. Inescapably, it is essential to utilize an advanced and modern airborne remote sensing for mapping and classifying complex landslides, and estimating their spatial occurrence and activity in the tropics.

Modern remote sensing based approach has revolutionized the landslide investigation at different spatiotemporal scales, ranging from detection, and monitoring to spatial analysis and hazard prediction (Metternicht et al., 2005). Landslide-based remotely sensed data is mainly associated to the morphology, vegetation, and drainage conditions of the slopes (Soeter and Van Westen, 1996). Of these, vegetation characteristics are by far less highlighted, as often limited by the capability of passive remote sensing instruments for detecting variability of forest structure (Frolking et al. 2009). Therefore in this study, we investigate the suitability of topographic laser scanning system (TLSS) data for characterizing complex landslides using morphology and vegetation percularity and address some practical and critical issues. in a lowland evergreen rainforest region in Malaysia.

2. MULTISENSORS LASER SCANNING FOR TROPICAL LANDSLIDES

To highlight the potential of TLSS in assessing landslides and its activity, we selected one study area located in Gunung Pass area, about 26km of the Pos Selim, Perak to Kg Raja, Cameron Highlands (see Fig. 1.1). The study area covers a height range between 930 and 1600 m above the mean sea level. The annual rainfall is between 2500 and 3000 mm per year and daily maximum rainfall of approximately 100 mm. The temperatures are lower than the rest of Malaysia, with an average daily temperature of 23˚ C and night-time average of 10˚ C (MMD, 2011). Geologically, the area is dominantly covered by metasedimentary schists and small portions by Quaternary and Devonian granite (Bujang et al., 2008). The forest types are largely consist of *hill dipterocarp*- and *upper dipterocarp forest* (Wyatt-Smith, 1995).

Landslides in Gunung Pass, Perak have been intensively investigated (e.g. Jamaludin et al., 2008; Fung et al., 2010; Lateh et al., 2011; Jamaludin et al., 2012) using several mapping and monitoring techniques. However, only few attempts have been made to utilize airborne remote sensing data for mapping and characterizing the complex landslides particularly in investigating the morphological and vegetation indicators for landslide activity assessment.

2.1 Airborne laser scanning campaign

In this study, we used a point cloud of about 17.2 million points with a mean point density of 4.31 points m^{-2}. The ALS data was acquired by the WIB Integrated Sciences Sdn Bhd over the Gunung Pass in August 2010 using RIEGL LMS-Q560 system. Metadata of ALS campaign and an overview of the data is given in Table 1.1 and Fig. 1.2, respectively.

ALS data was projected onto the local Malaysia Rectified Skew Orthomorphic (Malaysia

RSO) projection system (Mugnier, 2009). Some important points shall be taken into consideration in acquiring data for landslide investigation; i) pre-stage (e.g. selection of ALS sensor including the GPS and IMU system, flight platform either at aircraft or helicopter, data collection schedule peferably after monsoon season, and flight planning parameters – point density, flight altitude, swath width etc), GPS reference system, and calibration area), ii) during data acquisation stage (e.g. guidance flight system, data handling and synchronization, and GPS measurement techniques), iii) Post-stage (e.g. data processing, data visualization, data management, customized derivatives products, and data quality asssesment). The aforementioned parameters are dependent on the landslide types, processes and activity.

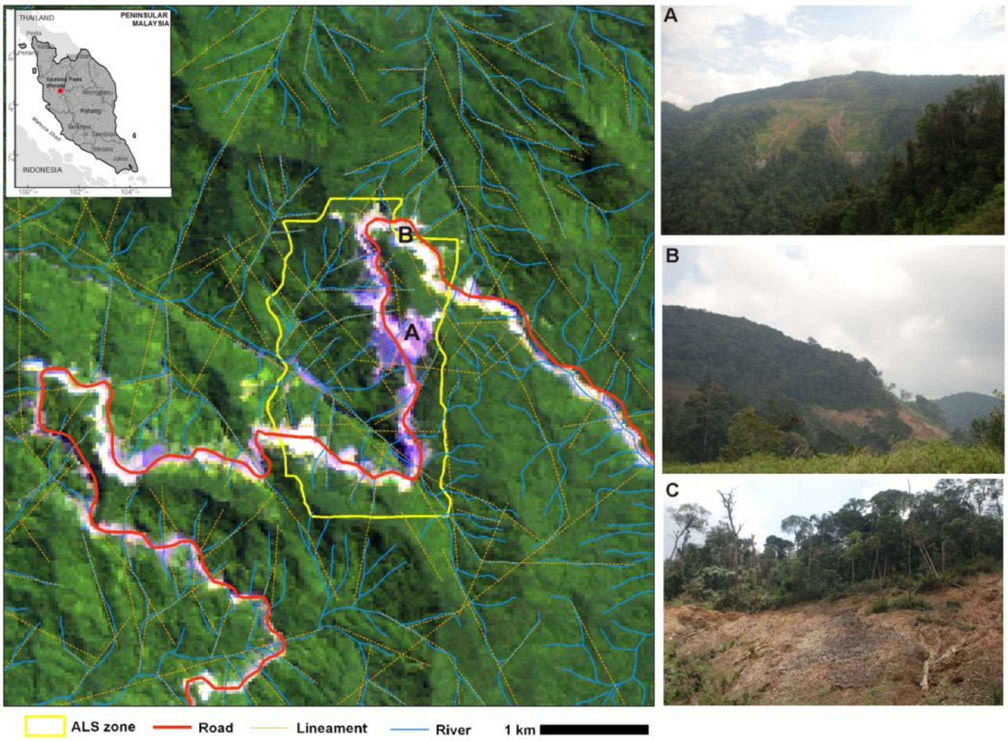

Fig. 1.1: Study area in Gunung Pass, Perak. A yellow polygon showing the ALS zone with location of prevalent landslides indicated as B) C). Respective field photos of rockslide and debris flow with apparent of main road crossing the area (A), retrogressive and rotational landslide (B) and a close view of gully and sheet erosion (C) where TLS data are available.

2.2 Terrestrial laser scanning (TLS) campaigns

In this study, we used two set of laser scanners; RIEGL VZ1000 and Leica ScanStation C10 for measuring 3D landscape data. A detailed of TLS specification and field photos of data acquisation is presented in Table 1.2, Fig. 1.3 and Fig. 1.5A, respectively.

Table 1.1: Metadata of airborne laser scanning measurement

Airborne laser scanner and its	Riegl LMS-Q560; average horizontal accuracy

accuracy	0.20 m; vertical accuracy 0.15 m at 1200 m
Inertial measurement unit (IMU) system and its accuracy	IGI IMU-lld records at 200 Hz with an accuracy of 0.015^o roll/pitch and 0.03^o heading
Laser pulse repetition rate	100 kHz (up to 100 000 pulses per second)
Beam divergence	Dual divergence 0.3 mrad
Laser beam footprint	0.08 m at 250 m
Scan angle	Up to 25^o
Swath width	83%
Scanning method	Rotating polygon mirror

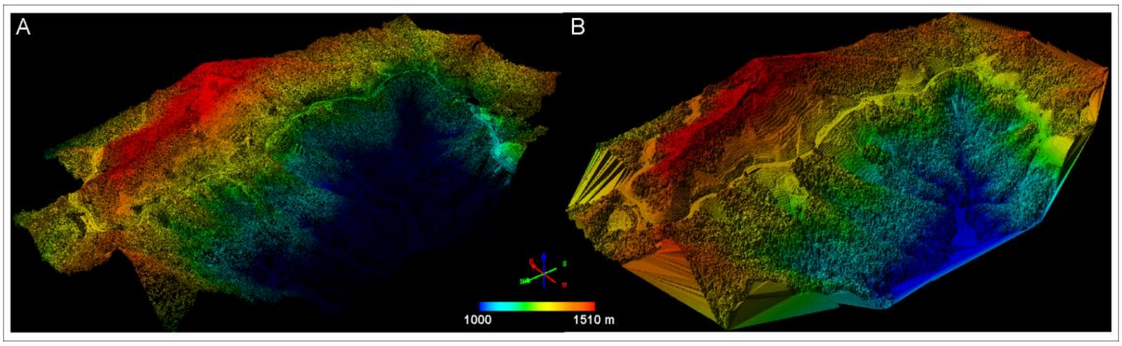

Fig. 1.2: An overview of ALS data. A) 3D point clouds. B) 1m gridded ALS image

TLS-RIEGL system uses a narrow infrared laser beam and a fast scanning mechanism. It can measure up to 1.4 km under adverse atmospheric conditions and multiple target echoes by utilizing the echo digitization and online waveform processing. RIEGL scanning mechanism is based upon a fast rotating multi-facet polygonal mirror, which provides fully linear, unidirectional and parallel scan lines. TLS Leica ScanStation C10 is developed with a 10-times boost in maximum instantaneous scan speed with more scanning coverage in a vertical direction, but a limited range of data capture. The SmartScan Technology™ firmware allows automated sequencing of scans and unattended operation, coupled with a series of pre-processing routines embedded in Cyclone^{TM} processing software.

For the best practise in gaining reliable topographic data associated to landslides, we recommend to put efforts and time on the site evalution, which is necessary to determine the crucial information, such as the landslide flow direction, dimension, processes, types, and recent activity. The planning of a TLS survey can be very useful with the help of preliminary low-resolution data over the area of interest. This leads to a proper survey design, e.g. determine the number and correct position of laser scanner and time required to complete the survey. The design influences the quality of 3D registration data. This step also assists the evaluation of complexity of the sites and local morphology of the scanning area. Moreover, a detailed scanning can be made for the critical landslide features, e.g. active main scarps, transverse cracks, depletion and accumulation zones.

Table 2: Metadata for terrestrial laser scanning characteristics

Laser scanner system	**RIEGL VZ1000**	**LEICA C10**

Single point accuracy	8 mm at 450 m	6 mm at 300 m
Scan density (spot size)	6 mm at 40 m	4.5 mm at 50 m
Speed (pts/second)	122000	50000
Field of view (V x H deg)	100 x 360 deg	270 x 360 deg
Software	Riegl software RiScanPro	Cyclone^{TM} SCAN

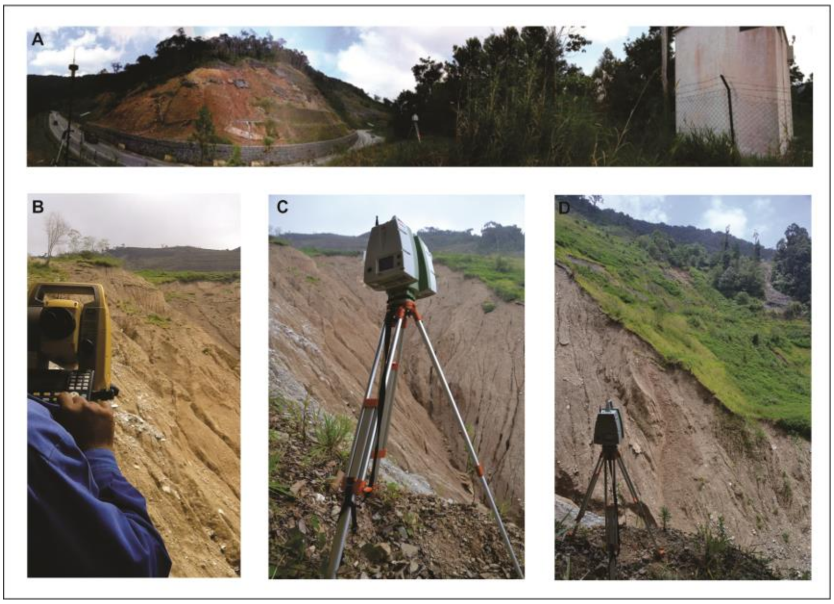

Fig. 1.3: TLSS field campaigns with various laser scanning systems. A) Laser scanner and GPS are used to collect the topographic landslide data. Also, a housing of robotic total station and real-time monitoring system used by PWD. B) Reflectorless total station used in the assessment. C) & D) Leica C10 collecting data over the most active landslide area.

2.1.3 Topographic landslide data: A reflectorless total station approach

In this study, we also carried out an assessment on the use of different surveying techniques for collecting topographic related landslide data. A reflectorless total station was used to acquire the physical properties of the landslide profile (Fig. 1.3B). A reflectorless total station is normally applied by surveyors to perform detail survey without the need of reflector/prism at the target, thus provide a fast and cost efficient method as compared to the normal total station (i.e. with prism target). A Topcon reflectorless total station was used in this campaign, with the non-prism measuring mode can range up to 500 m (3 mm + 2 ppm accuracy). Ideally we evaluated the performance of two different surveying methods, which aim at providing better representation of landslide topographic and its attributes. An effective approach was determined based on acquisition time, data quality, and practicability. Fig. 1.3(A) shows the real-time landslide monitoring system managed by the Public Works Department of Malaysia (PWD) using a robotic total station, with several monitoring prisms installed on the landsliding area. However, in this study, no quantitative assessment is made between the data collected by the robotic total station and laser scanner, and subjected to the further study.

2.2 ALS-derived DTM of tropical landslides

We used the mapping approach presented in Razak et al. (2011, 2013) to generate DTMs suitable for landslide recognition under dense forests. The bare-Earth extraction was performed using the hierarchic robust interpolation (HRI) algorithm implemented in SCOP++ with the modified landslide filter (MLF) parameterizations (see details in Razak et al., 2013). HRI-MLF filtering approach was used to extract the ground points that likely belong to landslide morphological features beneath forests in a tropical environment. The quantitative and qualitative assessment of other filtering algorithms specifically done for forested landslides is described in Razak et al. (2011) and an optimal filter parameterization with appropriate surface interpolation for tropical landslide identification in Razak et al. (2013).

2.3 Mapping tropical landslides using TLSS data

In this study, we used multi-scale stereoscopic image of visual analysis to recognize the diagnostic landslide features, and map the extent of slope failures. 3D point cloud TLS data was also used to carefully identify the macro- and micromorphology of landslide features. For example through an analysis of cross-section over the diagnostic landslide features, e g. major and side scarps can be properly evaluated. A digital stereo on-screen interpretation was used at different scales depending on the interpretability of morphological landslide features and disrupted drainage pattern. Methods for generating stereoscopic ALS images for landslide visualization under forest and extracting elements at risk for landslides is described in Razak et al. (2011, 2011b), respectively. The data generated in this study can be a good reference data for evaluating the quality of landslide maps produced by means of automatic landslide detection methods (e.g. semantic object-oriented and random forest classification).

Based on the landslide classification by Varnes (1978), several landslide types were identified and the direction of movement of the mapped landslides was carefully indicated in the landslide inventory. We also relatively estimated the landslide activity based on diagnostic morphological features coupled to the vegetation anomalies. The stereoscopic TLSS data was also useful to recognize the lineaments and geological setting across the study area.

2.4 Disrupted tropical vegetation characteristics: ALS approach

2.4.1 Locating and measuring trees in the tropics

Prior to extraction of disrupted vegetation characteristics induced by slope failures, we performed a preprocessing step of point cloud in order to eliminate isolated points, such as on the flying birds, water droplets from low-level clouds, and points below the ground surface. We detected the dominant single trees and estimated tree height and crown width based on the variable window filters (VWF) algorithm implemented in TreeVaW (*Tree Va*riable *W*indow) software (Popescu et al., 2002). TreeVaW method works on 1 m gridded ALS-derived canopy height model (CHM), which was computed by subtracting the DTM and DSM.

VWF algorithm determines the location of each tree by passing a series of local maxima (LM) filters over the CHM. Herein, the size of each LM filter is a function of the height of each pixel and it is determined based upon an allometric relationship between tree height and tree crown diameter. So far, no allometric relationship is available for tree species in the study area. Therefore, we adapted a species specific relationship developed by Osunkoya et al. (2007) based on 22 tree species collected in the Borneo tropical rainforest. We chose the aforementioned allometric relationship (slope=-0.27; intercept=23.54; r^2=0.23) because it was produced in an equatorial region where the area shares relatively similar climatic regime, forest ecosystem, topographic condition and the dominant tree species in the study area.

2.4.2 TLSS data for retrieval disrupted vegetation induced by landslides

We evaluated the ALS data representing the group of trees that might be affected by landslides. Firstly, an interactive visualization based on ALS–derived products (e.g. 3D TLSS point cloud, monoscopic and stereoscopic digital terrain and surface models) was used to allocate the potential hillslopes prone to landslides. To get an overview of forested terrain that have signature of disturbance to vegetation, we used forest canopy gaps and denuded area which were visually identified based on ALS data. This step also assists us in selecting the relevant disrupted trees. We also utilized a cross-section analysis performed directly on 3D TLSS point cloud of trees associated to distinctive landslide morphological features. The results provide a better picture of disrupted vegetation and subsequently limit the intensive field investigation in a rugged tropical landscape. Interestingly, a more detailed data captured by TLS can be an additional input for extracting the irregular shapes of disrupted trees.

3. TLSS for tropical landslides: A new tool for an old problem

3.1 Landslide DTM and mapping in the tropics

Bare-Earth extraction was successfully implemented based on MLF parameterization following the method explained in Razak et al. (2013). Fig. 1.4 shows an IDW-derived DTM visualized as a shaded relief (A) and a stereoscopic image (B) generated from the 6.4 million points, represents a significant detailed terrain surface over the area of 1.1 km^2. It is worth mentioning that the method of Razak et al. (2013) is capable of recognizing 10 times more landslides compared to that of previously published. The existing inventory was developed based on aerial photos-, satellite image interpretation and field visits (Pradhan and Lee, 2010).

To our knowledge, the produced DTM in this study area is the recent and accurate terrain information available in the area and can be used later to examine the amount of materials displaced from the hillslope to the channel, and quantify the sediment budget across the landscape (e.g. Mackey and Roering, 2011). The stable and unstable areas were critically identified and verified in the field. Several landslide morphological features and relative activity were indicated. A slope facing south shows a high activity of landslide, described as a large rockslide. The slope instability is identified by large cracks, undulating topographic, disrupted drainage network, coupling with relatively low vegetation on predominantly bare soil as the original slope had been intensively modified during the remedial works (Fig. 1.4A(a)). The area was firstly recorded in September 2003 (Jamaludin et al., 2008) due to the massive earthwork for constructing a cut slope of the highway. The slope failures have been landscaping the down-slope area (Fig. 1.4A(b)) and detrimental to the structure of main roads and current stream network (Fig. 1.4A(e)).

Similarly, the north-facing-slope (Fig. 1.4A(c)) is still largely covered by woody vegetation and has been faced with several landslide reactivations. From the visual data analysis and field verification, we reported that the area is affected by the rotational landslide with a retrogressive style. This process caused the geometric of woody vegetation, which can be easily seen in the vicinity of affected zone. The terrain has undergone severe weathering processes and largely affected by the gully and sheet erosion with exposed rocks have been found at the landslide scarp area. Jamaludin et al. (2012) noted that additional remedial works (e.g. structural reinforcement) may not be the only solution without a detailed understanding on the processes. Herein, a combination input between morphological indicators and disrupted vegetation, as revealed from airborne active remote sensing data particularly in assessing the landslide activity is critically needed given the availability of precise landscape data.

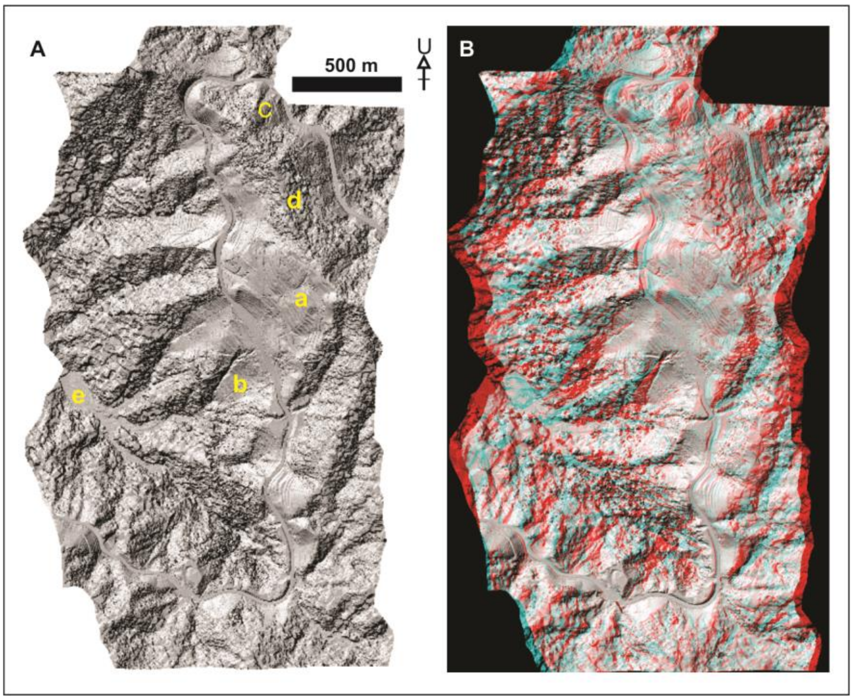

Fig. 1.4: TLSS-derived landslide precursors in Gunung Pass, Perak with indication of precursors a-e in A, and stereoscopic visualization in B. See text for an explanation.

The existing landslide map only indicated the landslide location (Aziman and Husaini, 2001; Husaini et al. 2005) which was produced by interpreting aerial photographs 1:10000 scale and field visits. However, in this study, we accurately recognized the landslide morphology and its activity from TLSS data. Fig. 1.5(A)(B) show TLS data observation and output, respectively with an indication of a profile (D) crossing one of the most active landslide scarp in the area (a cross section is shown in Fig. 1.5C). It is also important to quickly assess the landslide dimensions (e.g. width, length, and height). In the particular area (see Fig. 1.5C), we also computed the volume of displaced materials of debris flow resulted in 190260 m^3.

3.2 Topographic data for landslides: Reflectorless Total Station and TLSS

As expected, a reflectorless total station was less useful in collecting landslide topographic data. It resulted in 700 points completed within 4 hours to observe the profiles. It is worth mentioning that the data acquisition was carefully done in such a way that it can be used later as a reference topographic data. Contrarily, we collected about 86 million points using RIEGL TLS covering the entire mountainous area captured from a distance of 1.2 km. An equipment setup, pre-scanning and data acquisition (e.g. image and point cloud) took about one hour of data observation. A high accurate topographic data was used to analyze the diagnostic landslide morphologic features, disrupted drainage pattern and irregular vegetation.

A reflectorless total station is only capable to observe a single measurement at one time while TLS can easily capture millions of points from a single scanning. Consequently, good planning for capturing the data is needed to observe the landslide profile. Two types of data capturing methods using the total station were performed for this reason; 1) using a grid system at a specific offset distance, (i.e. each horizontal and vertical axes), and 2) tracking the patterns of landslide scarps. The latter approach was applied to map in details all the major scarps (i.e. more dense) that may provide additional information such as the extent and coverage of the landslide areas. The former method was aimed to map the overall size of the landslide region in general (i.e. sparse point). Both methods complement each other in order to obtain sufficient information of the landslide profiles. With respect to capability of a Leica TLS system, it failed to capture the data from 1.2 km distance. Therefore, the equipment was hardly positioned close to the landslide depletion area (see field photos in Fig. 1.3(C)(D)) with a total of three scanning stations.

3.3 Vegetation indicator from TLSS data

As a result of individual tree detection, we extracted about 40500 trees, with height ranged up to 80 m (Fig. 1.6). In the upper part of Gunung Pass, we identified substantial number of trees with relatively lower height and scattered over the area (see Fig. 1.6B(a)). Moreover, a large number of tall trees distributed at the vicinity of landslide and stable terrain. Most of survive trees in the aforementioned area have been disturbed with irregular shapes. We also found that very old trees are likely to preserve the signature of several landslide activities. The vegetation anomalies were verified in the field. Healthy forests are shown in relatively stable terrain (Fig. 1.6B(b)).

Interestingly, the tree heights are higher in the accumulation (see c, d) although some trees are located at landslide transport zone. Contrarily, tree height at area (e) depicted different spatial patterns. This is a subject to further works by evaluating the Skel-skeletonization method using tropical trees data and analyzing the quality of extracted vegetation irregularity (e.g. tree inclination and orientation) (Razak et al. 2012, 2013b).

In this study, a series of field investigation coupling to the morphological and vegetation analysis revealed by TLSS data allows us to understand the hillslope processes in a complex environment. Macro- and micro-morphology of landslides can be accurately mapped and classified based on various diagnostic features. In particular, the ‘silent witness’ - a result of vegetation anomalies characterization, provides informative clue to landslide activity. This study also addressed the possibility of high resolution TLSS images to carefully characterize the geodynamic features as predominantly observed in the field, e.g. uplifted slope mass including the failure scarps above the moved bodies, irregular tension cracks, discontinuities features, and disrupted drainage pattern. Razak et al. (2013) recently discovered substantial evidences from the airborne remote sensing data on the newly found neotectonic features in the Cameron Highlands. Surprisingly, no single record is available on the tectonic event and its activity in this area. This finding is subjected to the further research and can be directly contributed to the regional seismotectonic study in Malaysia using the modern multisensor spaceborne data coupled with subtantial expert knowledge (e.g. Abu Bakar et al., 2013).

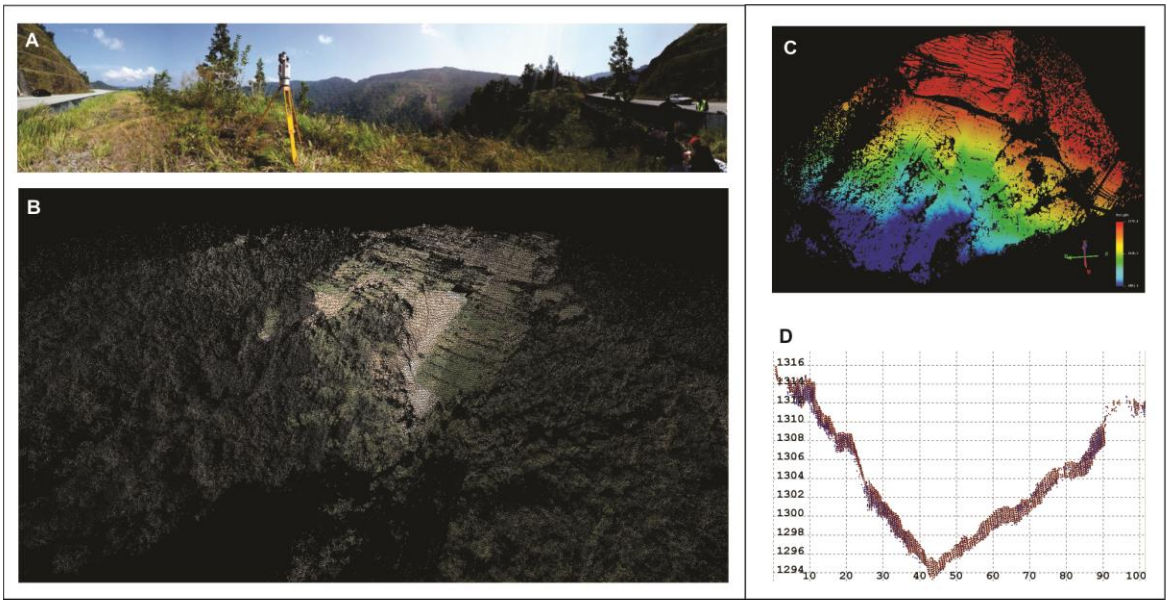

Fig. 1.5: A derivative product of TLSS associated landslide data. A) Data collection using RIEGL VZ1000 captured landslides at 1.4 km. B) 86 million point clouds covering entire mountain including instable slope, C) D) Cross-section analysis of active landslide scarp.

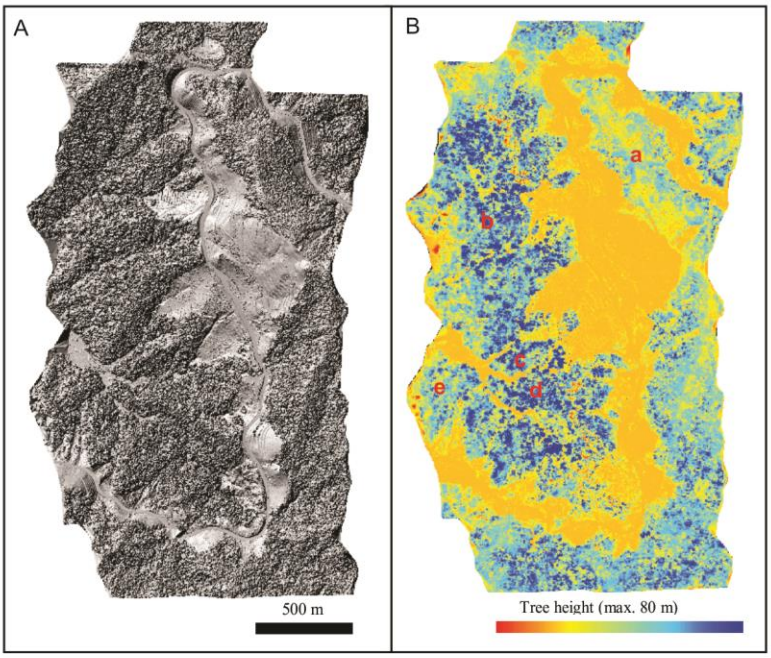

Fig. 1.6: TLSS estimated landslide vegetative indicator. A) High resolution Digital Surface Model generated from laser data. B) Estimated TLSS tree height indicating vegetation clue to landslide activity (a-e) in a complex hillslope environment. See text for an explanation.

4. Conclusions

In this study, we showed the utilization of TLSS data for characterizing morphology and vegetation peculiarity in Gunung Pass, Perak and supported by field evidences. It is a state-of-the-art for physically retrieving morphological and vegetation structures, which can be a good assessment input in landslide geomorphology system. Airborne remote sensing data provides synoptic view of large inaccessible areas, made it useful to integrate with ground based data to accurately map landslide features in the tropics. Stereoscopic ALS-derived images allowed mapping and classifying a large number of landslides in a complex environment. Topographic- and vegetation based ALS analyses can be an effective method to quantify peculiarity of superficial features and characterize the complex tropical landslides. The method presented in this study is superior than the existing aproaches, for examples using the surveying method (e.g. Jamaludin et al., 2012) and TerraSAR- X (e.g. Lateh et al., 2011).

Active remote sensing data has proven to be a very important new data source to map, classify and predict future tropical landslides. It is a rapid and accurate mapping technique, which creates a substantial step forward into the use of a full-waveform recording mode. High resolution TLSS data captured at different epoch allows a complete analysis of landslide deformation. However, special attention is required to integrate the multi platform data for spatiotemporal data analysis.

With the advancement of TLSS and point cloud processing routine, it is capable of producing and updating landslide maps, as more rapid re-vegetation take places for unstable terrain in the tropics than in temperate forests (Douglas et al., 1999) and becoming a more popular mapping tool for emergency response and disaster management. Using a platform based on unmanned aerial vehicle, the spatiotemporal of landslide deformation can be consistently determined in the mountainous regions dominated by hillslope processes. Automation of the landslide inventory in the tropics remains challenging. TLSS-derived products can be informative data input for landslide hazard modelling (e.g. GIS-based slope stability model), source and spreading of debris flow (e.g. DFGrid Prob) and landslide susceptibility modelling (bivariate- and multivariate statistical models), and quantitative multi-hazard risk assessment.

REFERENCES

Abu Bakar, R., Jamaluddin, T.A., Mohd Omar, K., Razak, K.A., 2013. *Geodynamic activity of Malaysia: Insight from Space-based technology and knowledge driven approach.* In: Proceedings of the IEEE International Geoscience and Remote Sensing Symposium 21-26 July 2013, Melbourne Australia.

Aziman, M., Husaini, O., 2001. *Influence of discontinuity sets on slope failures at Pos Selim Highway, Malaysia*. In: Proceedings of Annual Geological Conference, Perak, Malaysia, 2001, pp. 237–242.

Brardinoni, F., Slaymaker, O., Hassan, M.A., 2003. *Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data*. *Geom. 54*, 179–196.

Bujang, B.K.H., Faisal, H.A., David, H. B., Harwant, S., Husaini, O., 2008. *Landslides in Malaysia: Occurrences, Assessment, Analysis and Remediation*. *Penerbitan Universiti Putra Malaysia, pp. 406–421.*

Douglas, I., 1999. *Hydrological investigations of forest disturbance and land cover impacts in South-East Asia: A review*. Philosophical Transactions of the Royal Society of London, Series B 354, 1725-1738.

EM-DAT., 2011. *The CRED International Disaster Database, Natural Disasters Trends*. http://www.emdat.be/natural-disasters-trends.

Fung, W.H.T, LeGoff D., Krishnan, S. 2010. Instrumentation data monitoring system for slope safety monitoring in Malaysia. In: Proc. of the International Conference 2010. Chiang Mai, Thailand. Pp. 309-315.

Frolking, S., Palace, M.W., Clark, D.B., Chambers, J.Q., Shugart, H.H, 2009. *Forest disturbance and recovery: A general review in the context of spaceborne remote sensing on aboveground biomass and canopy structure*. Journal of Geophysical Res. 114, 27 p.

Guzzetti, F., Mondini, A.C., Cardinali, M., Fiorucci, F., Santangelo, M., Chang, K.T., 2012. *Landslide inventory maps: new tools for an old problem*. E.Sci. Reviews, 112, 42-66.

Hewitt, K., 1997. *Regions of risk: a geographical introduction to disasters*. Addison Wesley Longman, Harlow, UK, 389 pp.

Husaini, O., Daud, M., Zohadaie, M. B., Maail, S., Azizi, A. A., Muniandy, R., 2005. *Failure of cut slopes during construction of highways in mountainous area*. Pertanika Journal of Science and Technology, 13, pp. 73–83.

Jamaludin, Jaafar, K.B., Abdullah, C.H., Mohamad, A., 2008. *Landslide warning system for Mount Pass, Malaysia based on surface monitoring technique*. In: Proc. Of the

International Conference on Management of Landslide Hazard in the Asia-Pacific Region, Sendai, Miyagi Prefecture, Japan, pp. 354-365.

Jamaludin, S., Abdullah, C.H., Jaafar, K.B., Anuri, M., 2012. *Monitoring of slow moving landslide at 46th km of Simpang Pulai – Gua Musang highway, Malaysia*. In: Eberhardt et al. (Eds), Landslides and Engineering Slopes: Protecting Society through Improved Understanding, Taylor & Francis.

Lateh, H., Jefriza, Rauste, Y., 2011. *Monitoring Slope based on SAR-interferometic technique and ground measurement*. In: Proceeding in the International Conference on Environment, vol. 8, IACSIT Press, Singapore.

Metternicht, G., Hurni, L., Gogu, R., 2005. *Remote sensing of landslides: an analysis of the potential contribution to geo-spatial systems for hazard assessment in mountain environments*. Remote Sensing of Environment 98, 284–303.

McKean, J., Roering, J., 2004. *Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry*. Geomorphology 57, 331-351.

Mackey, B.H., Roering, J.J., 2011. *Sediment yield, spatial characteristics, and the long-term evolution of active earthflow determined from airborne LiDAR and historical aerial photographs, Eel River, California*. Geo. Soc. of America Bulletin 123(7-8), 1560-1576.

MMD., 2011. *Malaysian Meterological Department*. http://www.met.gov.my/.

Mugnier, C.J., 2009. *Grids and Datums: Malaysia*. Photogrammetric Engineering & Remote Sensing, 345-346.

Osunkoya, O.O., Omar-Ali, K., Amit, N., Dayan, J., Daud, D.S., Sheng, T.K., 2007. *Comparative height-crown allometry and mechnical desing in 22 tree species of Kuala Belalong Rainforest, Brunei, Borneo*. American Journal of Botany 94(12), 1951-1962.

Petley, D.N. , 2011. *The landslide blog*. http://blogs.agu.org/landslideblog/.

Popescu, S.C., Wynne, R.H., Nelson, R.F., 2002. *Estimating plot-level tree heights with lidar: local filtering with a canopy-height based variable window size*. Computers and Electronics in Agriculture 37, 1-95.

Pradhan, B., Lee, S., 2010. *Regional landslide susceptibility analysis using back-propagation neural network model at Cameron Highlands, Malaysia*. Landslides *7*(1), 13-30.

PWD., 2009. *National Slope Master Plan 2009-2023* (381 p). Kuala Lumpur: The Public Works Department Malaysia, ISBN 978-983-99552-9-3.

Razak, K. A., Bucksch, A, Straatsma, M, Van Westen, C. J., Abu Bakar, R., de Jong, S., 2013b. *High density airborne lidar estimation of disrupted trees induced by landslides.* In: Proceedings of the IEEE International Geoscience and Remote Sensing Symposium 21-26 July 2013, Melbourne Australia.

Razak, K.A., Santangelo, M., Van Westen, C.J., Straatsma, M.W.**,** de Jong, S.M., 2013. *Generating an optimal DTM from airborne laser scanning data for landslide mapping in a tropical forest environment*. Geomorphology 190, 112-125.

Razak, K.A., Bucksch, A., Damen, M., van Westen, C.J., Straatsma, M.W., de Jong, S.M., 2012. *Characterizing tree growth anomaly induced by landslides using LIDAR.* In: Proceedings of the 2nd World Landslide Forum, Vol. 1, 03-09 October, Italy. Springer.

Razak, K. A., Straatsma, M. W., Van Westen, C. J., Malet, J. P., de Jong, S. M., 2011. *Airborne laser scanning of forested landslides characterization: Terrain model quality and visualization*. Geomorphology, 126, 186-200.

Razak, K.A., van Westen, C.J., Straatsma, M.W., de Jong, S.M., 2011b. *Mapping of elements* *at risk for landslides in the tropics using airborne laser scanning*. In: FIG working week 2011: bridging the gap between cultures: Technical programme and proceedings, Marrakech, Morocco, 18-22 May 2011. 16 p.

Soeter, R., Van Westen, C.J., 1996. *Slope instability recognition, analysis, and zonation*. In: Turner AK, Schuster RL (eds) Landslides, Investigation and Mitigation. Transportation Research Board, Special Report 247, Washington D.C., USA, 129–177 pp.

Thomas, M. F., 1994. *Geomorphology in the tropics: a study of weathering and denudation in low latitudes* (482 p), Chichester, New York: John Wiley & Sons.

Van Westen, C.J., Van Asch, T.W. J., Soeters, R., 2006. *Landslide hazard and risk zonation-why is it still so difficult?*. Bull Eng Geol Env 65, 167-184.

Van Westen, C.J., Castellanos, E., Kuriakose, S.L., 2008. *Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview*. Engineering Geology, 102, 112–131.

Varnes, D. J., 1978. *Slope movement types and processes*. In: R.L. Schuster & R.J. Krizek (Eds), Landslides Analysis and Control (pp. 11-33), Nat. Acad. Sci., Trans. Res. Bd., Special Report, 176, Washington DC.

Wyatt-Smith, J., 1995. *Manual of Malayan silviculture for inland forest* (pp. III-7/1-III-7/58), Malayan forest record, 23(1). Selangor: Forest Research Institute Malaysia.

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