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Mapping of post-event earthquake induced landslides in Sg. Mesilou using LiDAR

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Abstract. Earthquake is a common natural disaster in active tectonic regions. The disaster can induce cascading disasters such as debris flow, mudflow and reactivated old landslides. M 6.0 Ranau earthquake dated on June 05, 2015 coupling with intense and prolonged rainfall caused several mass movements such as debris flow, deep-seated and shallow landslides in Mesilou, Sabah. This study aims at providing a better insight into the use of advanced LiDAR mapping technology for recognizing landslide induced by earthquakes particularly in a vegetated terrain, assessing post event hazard and analyzing its distribution for hazard zonation. We developed the landslide inventory using LiDAR-derived visual analysis method and validated in the field. A landslide inventory map improved with the support of LiDAR derivative data. Finally, landslide inventory was analysed by emphasizing its distribution and density in such a way that it provides clues of risky zone as a result of debris flow. We recommend that mitigation action and risk reduction should be taken place at a transport zone of the channel compared to other zones. This study indicates that modern airborne LiDAR can be a good complementary tool for improving landslide inventory in a complex environment, and an effective tool for rapid regional hazard and risk assessment in the tropics.

1. Introduction

Earthquakes induce other major natural disasters such as landslide, tsunami, and volcanic eruption. These cascading hazards often resulted in large damages to infrastructure and even caused more injuries and casualties than the earthquake [1]. Earthquake-induced landslide is one of the common disasters



that occurs in a tectonically active region and its complete inventory either at national or global scales remain elusive and even more challenging in the anthropogenically tropical region. For examples, M 7 earthquakes in Nepal triggered 5,600 landslides [2]. The Ms 8.0 Wenchuan earthquake, induced 257 landslide lakes which were distributed along the fault rupture zone and river channels [3]. The 1994 Northridge earthquake triggered more than 10,000 landslides in the hills around Los Angeles [4]. On May 18, 1980, a magnitude-5.1 earthquake triggered the collapse of the north flank of Mount St. Helens, resulting in the largest landslide ever recorded [4]. The number, type, and size of landslides varies depending on magnitude of the earthquake, type and depth of the ruptured fault.

The type, activity and process of earthquake-induced landslides have similarities and differences from the previous studies of the prominent earthquakes. The recent Nepal earthquakes induced new and reactivated landslides [2]. The most common types of earthquake-induced landslides during the Wenchuan earthquake were rock falls, rock avalanches, and rock debris slides in the area [5]. Deep-seated large landslides were moderately common and abundant in the vicinity of the fault rupture [5]. Landslides caused by the Chi-Chi earthquake were new and retrogressive landslides, which the landslides were not reactivated by the historical landslides [6]. These studies show that large earthquakes can reactivate old, dormant landslides and cause new landslides with different landslide types, mechanisms and activities. To understand the characteristics of earthquake-induced landslides, it is crucial to carefully map, identify and characterize landslides induced by earthquakes using appropriate landslide mapping techniques resulting with sufficient accuracy in a relatively short time.

Landslide mapping for earthquake-induced landslide consists of field mapping, remote sensing technique with the support of local- and expert knowledge. A combination of these techniques can produce a reliable landslide map. Passive and active remote sensing such as optical satellite images and LiDAR (Light Detection and Ranging) images, respectively have been widely used to map and identify landslide induced by earthquakes [7]. In Sabah, M 6.0 earthquake that ruptured on 5th June 2015 is the second large earthquake after 1991 earthquake in Ranau. The earthquake induced rock avalanche occurred on the summit of Mount. Kinabalu caused 18 fatalities [8]. After intense and prolonged rainfall, aftershocks, and tremors, a devastated debris flow occurred on 15th June 2015 in Sungai Mesilou, which caused a house, homestays and roads damages along the Sungai Mesilou area and indirectly affect the socio-economic activity of the local community [9].

2. Study area

The study area is located in Ranau district and it is situated in a well-known touristic area with attractive remarks such as the first World Heritage Site in Malaysia, Mount Kinabalu. Several touristic places and infrastructures in the vicinity of Kg. Mersilau are Mount Kinabalu Golf Club, Mesilou Nature Resort, and Desa Dairy Farm. The study area is situated between 500 to 2,000 m above mean sea level on the southern flank of Mount Kinabalu (4,101m) as shown in Figure 1. Since the study area is located along the main channel, therefore the geomorphology is dominated by floodplain, river terraces and plateau. The study area is described as plains surrounded by mountains. Dusun is the main tribe who resides in Mesilou, who are mostly work as farmers, which makes the major land cover is plantation area aside from recreational and tourism area [10].

The geology of the upper and lower part of the study area consists of igneous rock and sedimentary rock, respectively. The oldest igneous rock of the study area is gabbro and ultramafic, followed by granodiorite. The oldest sedimentary rock is Trusmadi Formation, Crocker Formation, and Pinosuk Gravel. Trusmadi Formation is described as strongly folded and faulted grey and dark grey argillite, slate, siltstone and sandstone with volcanics, whereas Crocker Formation is referred as strongly folded and faulted sandstone, silstone, red and grey shale, mudstone and argillite. Pinosuk Gravel is poorly consolidated unsorted gravel up to boulder size in a sandy to clayey matrix [11]. The dominant lithology in the study area is sedimentary rock, specifically Pinosuk Gravel as shown in Figure 1. The main active

faults present in the study area are Mensaban Fault and Lobo-Lobo Fault segments. Mensaban Fault is a normal fault trending northwest-southeast and west-east. Lobo-Lobo Fault is left-lateral strike slip fault, which trends N20°E [12].

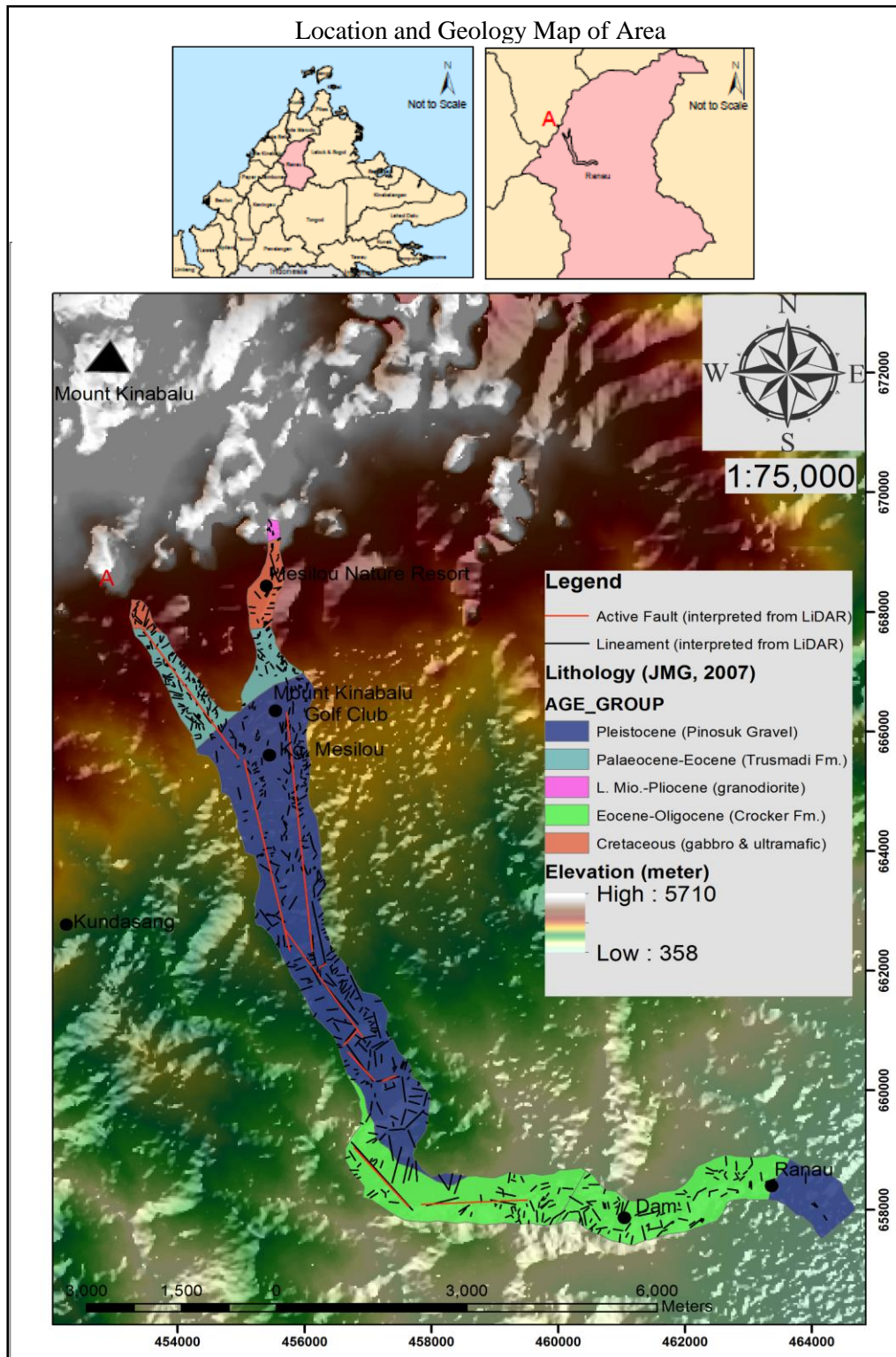


Figure 1. Location and geology map of the study area.

Mass movement investigation has been done in Mesilou area by monitoring Jalan Cinta Mata off Jalan Kundasang-Ranau because the road experienced constant damages of tension cracks, settling, and lateral movements [13]. Subsurface investigation and instrumentation indicated that the rate of ground movement is 21mm per week at maximum [13]. This high reading is caused by the massive creep movements of the post-glacial deposits and ancient mudflow [13]. Studies have been done on the origin of the huge granite boulders or Pinosuk Gravel lithology. The boulders make the dominant panorama in Mesilou. The earliest finding defines Pinosuk Gravel as piedmont fan from glaciation of Mount Kinabalu [14]. Later, the interpretation was improved by emphasizing the mechanism that brought down the boulder is mudflow by observing at the different sizes of boulders [15], [16]. Moreover, sources of boulders deposition were originated from four main channels, which are located at Desa Cattle, Mesilou Golf Club, Pusat Latihan Dakwah, and plantation area [10]. The latest work on Pinosuk Gravel is a proposal to gazette the area that are covered with this deposits as a geoh heritage place due to its remarkable geological origin and history [10].

Previous landslide mapping has been done in Kundasang to identify the causal factors of the ground instability and creeping mass movement in the area. The extensive and detailed landslide mapping using conventional methods resulted in a landslide complex of Kundasang [17]. However, the study area did not include Mesilou. The previous studies in Mesilou area revealed that most of the research activities were focused on debris flow in Sungai Mesilou and none of the landslide mapping has been done yet in the study area except landslide monitoring at Kampung Mesilou by JMG. Landslide has been occurring in the area on 2008, 2010, and 2013 with one recorded fatality [18]. After earthquake and debris flow events on June 2015, Mesilou becomes attention because of the high disaster impact.

The main objective of this paper is to implement post event hazard and risk assessment by mapping landslide spatially and analysing the landslide density for hazard zonation utilizing LiDAR technology. The scope of works include pre-processing LiDAR datasets for georectification, generating LiDAR-derived images for image visualization, interpreting landslides in a systematic GIS environment, preparing basemaps for field verification, and finally analysing landslide inventory for supporting landslide hazard and risk assessment.

3. Methods

3.1. Airborne LiDAR campaign

The airborne LiDAR data was captured on August 2015 using RIEGL system mounted in a helicopter. The acquisition and processing of raw airborne LiDAR data was carried out by BUMITOUCHplmc Sdn Bhd. It is worth to mention that this airborne LiDAR 3D point clouds recorded up to 120 points per square meter; the highest point density reported over the disaster area in Malaysia. The processed LiDAR data consists of classified 3D point clouds, 0.25 m digital terrain model (DTM), 0.25 digital surface model (DTM), and 0.07 m orthophoto of the debris flow area. These datasets are very high resolution and the best quality datasets.

3.2 LiDAR processing for visualization

LiDAR-derived datasets are re-processed for visualization in two-dimensional and three-dimensional models using several open-source and commercial softwares. One of the common LiDAR-derivatives for visualization is a default hillshade (azimuth: 315, altitude: 45), which is based on solar illumination from a single direction. Hillshade image is overlaid with slope and curvature images in ArcGIS software for a better visualization and interpretation. In slope image, steep slope indicates scarp area and flatter slope can be indicated as debris area. In curvature image, concave slope indicates denudation and scarp area and convex slope indicates debris or accumulation zone.

A new mode of visualization is topographic openness generated from SAGA-GIS software that visualizes the topographic dominance or enclosure from digital elevation models (DEM). Positive openness signifies convex topography and negative openness shows concave topography [19]. Another new technique of visualizing a LiDAR-derived DTM is known as a color composite image, which can be produced using ILWIS software [20]. This technique produces one color DTM into a combination of three shades of color (red, green, and blue), indicating the solar illumination of the image in three directions compared to the conventional hillshade. A 3D orthophoto is also used to identify recent landslide and observe the morphological- and disrupted drainage coupling with geoindicators in a forested terrain. These visualization techniques generate 2-D outputs for landslide interpretation. Another possibility of visualization is 3-D visualization generated from ILWIS by creating stereo pair images from DTM. The images are used to visualize landslide in 3D by highlighting the depth of landslide to differentiate between deep-seated and shallow landslides using 3-D glasses. These types of different visual are helpful to visualize landslide features for accurate interpretation.

3.3 Landslide interpretation using LiDAR-derived datasets

Landslide interpretation becomes easier with the help of image visualization and high resolution data. All the generated images are overlaid and the images are used alternately in GIS software for landslide interpretation. The landslide interpretation process was guided by a group of senior geologists and geomorphologists, who have been working in the area for several years and familiar with the landslide processes and activities in the study area.

In this study, we developed a landslide geodatabase consists of landslide ID, body, type, activity, speed of movement, and certainty. Body attribute consists of scarp area, accumulation area and undifferentiated. Landslide types attribute are divided into deep-seated, shallow, flow and rockfall and subdivided into translational, rotational, and complex landslide. Activity attribute contains active, stable, dormant, and stable. Speed of movement attribute consists of slow and fast, whereas certainty attribute has two options, which are certain or uncertain.

The first step of landslide interpretation is to identify geomorphology, geology, land covers, land uses, past landslide events, and topography of the study area to understand regional landslide process, causal and conditioning factors. Then, semi-circular or crown shape is delineated as a scarp. The shape varies depending on the type and activity of the landslide. Fresh, active, retrogressive landslide usually has semi-circular shape with tension crack at the scarp. Dormant and old landslide shows a perfect semi-circular shape. In certain cases for complex landslide, the scarp has incomplete semi-circular shape because it is overlapped and erased by the recent scarps. After recognizing the scarp, the next step is to identify the landslide accumulation area, which commonly signifies as hummocky and bowl-shaped feature. In non-forested and developed areas, the accumulation area is not clearly seen because the displaced material is often removed after the event, which makes delineating accumulation area is quite challenging.

3.4 Field observation

The field work was carried out after interpreting landslides for almost two weeks, the selected landslides were chosen based on the certainty attribute to be verified on the field. Fieldwork basemaps in A3 size were prepared by incorporating orthophoto and color composite overlaid with interpreted landslides. Field verification was accompanied by local expert from the Minerals and Geoscience Department Malaysia (JMG) and other senior geologists.

Landslide interpretation using remote sensing images is done before and after the field mapping to improve the landslide boundary mapping. Landslide validation through field mapping is useful to understand and visualize landslide in real correlated to remote sensing images. In addition, geological and geotechnical information, which are investigated during field mapping, can be a complement to

landslide inventory. Local and expert knowledge is essential for landslide mapping because these people witnessed the event. From these sources of information, a reliable landslide map can be produced. This map is important as an input for hazard and risk assessment. In addition, the map also can be utilized for post-event mitigation to identify possible avalanches and landslides.

3.5 Landslide inventory analysis

The interpreted, verified, and improved landslides are systematically stored in a GIS geodatabase environment. A landslide distribution, density and multi-temporal analysis can be derived from the database. Remarkably, the landslide inventory maps can be further utilized for analysing landslide susceptibility, assessing landslide hazard and associated risk. Landslide density map is produced by converting the interpreted landslides from polygon to point shape file. Then, the point density is classified into five classes (high, medium, low, very low and nil density) by applying 1 km² buffer.

Another important analysis is analysing multi temporal landslide from satellite images before and after the debris flow. Worldview image in 2011 is acquired to compare with the orthophoto to observe the condition of the disconnected road before and after the disaster. SPOT image in 2010 also used to compare multi temporal landslides. The selected area is located in Kampung Mesilou, where the landslide occurred in March 2008, March 2010, and July 2013 [18]. These observation are important for land planners and engineers to identify element-at-risks before planning and construction.

4. Results

LiDAR data covers 3m to 4m river banks along Sungai Mesilou. The upstream of study area is started at the Mesilou Nature Park and ended at Ranau town. The length of the selected Sungai Mesilou section is approximately 7 km. The main finding of this study is the first earthquake-induced landslide inventory created from LiDAR-derived landslide interpretation supported with field verification. The inventory is further analysed to generate landslide density map and relate with element-at-risk at the study area by using multi temporal images.

4.1. Image visualization from LiDAR-derived datasets

The initial step before landslide interpretation is image visualization, which consists of hillshade image (Figure 2a), color composite image (Figure 2b), and topographic openness image (Figure 2c). These layers are used alternately to visualize and identify landslide morphology such as semi-circular scarp, concave-convex, and hummocky topography. These images have their own advantages and disadvantages. A color composite image has better visualization than hillshade image because it brightens the shaded area in various perspectives. Topographic openness images emboss the concavity of the topography, whereas landslide scarp can be easily identified as shown in Figure 2. Visualizing landslide in various ways is an added value that only can be obtained from LiDAR datasets, which significantly helps the landslide interpreters.

4.2. Landslide interpretation diagnostic features

Landslide interpretation was carried out by recognizing the geomorphologic signatures to deduce type of landslides. Coupling with color composite DTM images, an orthophoto can be used to identify landslides by observing vegetation pattern, river course, and anthropogenic features. Tree density and pattern such as at the scarp and accumulation area are quite distinctive. Scarp area usually has tall and greener trees, whereas accumulation area shorter and less greener vegetation that indicating of re-growing process. Fresh landslide can easily be seen in the orthophoto as a brown patch. For high resolution orthophoto, tilted and backtilted trees can be seen as well. Thus, there are multiple and

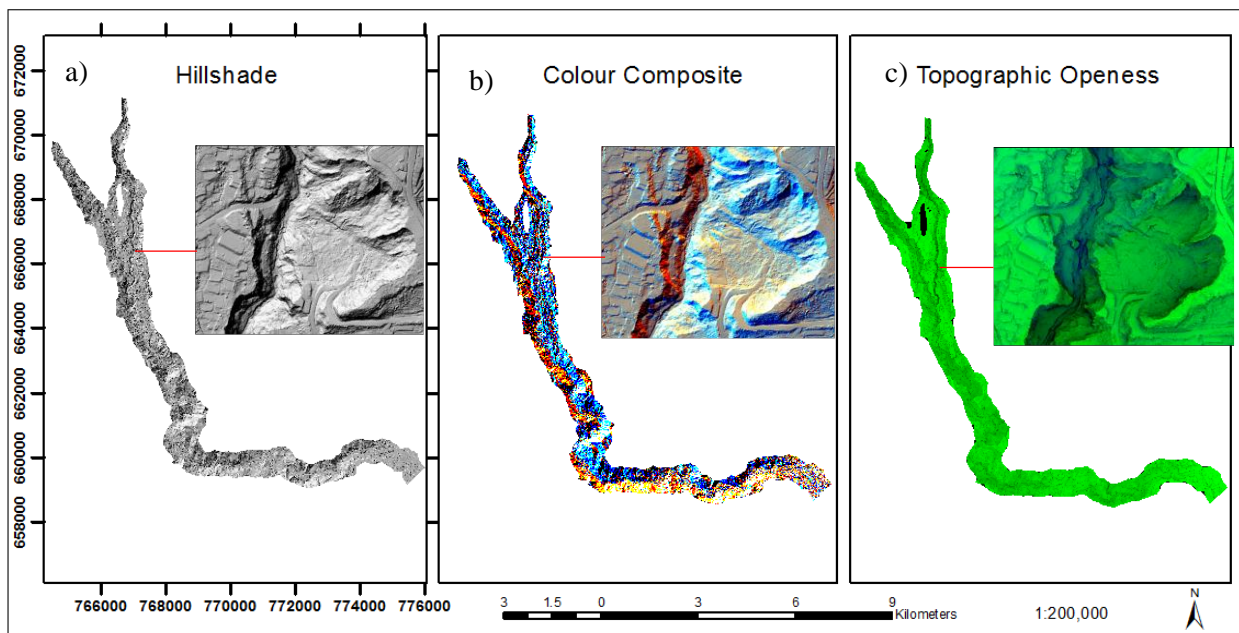


Figure 2. LiDAR-derived image visualization consists of (a) hillshade (b) color composite (c) topographic openness of debris flow channel in Mersilau, Sabah.

various methods to visualize and interpret landslide using LiDAR-derived datasets and the approach varies depending on the availability and resolution of the data. The diagnostic features as mentioned in Figure 3 is used not only to identify landslides but most importantly to infer landslide process, activity, type for further analysis. For examples, figure 3a is an earthquake-induced landslide at the Golf Club because this landslide presents after the M 6.0 earthquake. The type of landslide is rotational and retrogressive landslide characterized by semi-circular scarp, step-like slope, and hummocky deposition part. Backtilted trees can be seen on the orthophoto. Figure 3b is an active landslide at Kampung Mesilou. It is characterized by concave-convex morphology. Figure 3c is landslide complex and deep-seated rotational due to existing of multiple series of landslide events. Disrupted plantation terrace can be seen on 3c(i). The recent scarp is induced by the 5 June earthquake. Based on figure 3d, there is complex landslide in a forested terrain at Kampung Mesilou. Multiple scarps presents showing that the landslide is active. The recent scarp has the semi-circular shape but the older scarp does not have the perfect semi-circular shape. The multiple scarps shows that the landslide is active. The deposition part has hummocky and flow feature. The identified signatures are later compiled for field verification.

4.3. Field observation

The topography of the upper of study area is quite mountainous with steep terrain and the lower part is relatively flat and low-lying terrain. In general, the upper part of Sungai Mesilou is a straight river and the lower part of the river is a meandering river due to the presence of floodplain in the lower part compared to upper part of the river. The straight channel are related to the presence of active faults along and across the upper part of the river. The other dominant geomorphology of the study area are terraces, which can be observed along the river, and plateau at the right side of the river. The observation was made along the channel of the debris flow that occurred on 15th June 2015 in Sungai Mesilou. The event caused a house, homestays and roads damages along the Sungai Mesilou area. Based on field observation from the source zone, transport zone, and deposition zone, the rock boulders that filling up the channel are huge and the sizes are getting bigger towards deposition zone as shown in Figure 6. Another important observation is the recent debris flow event was not the first event from the evidence of older layer of rock boulders along the channel. The similar observation has been made at upstream of

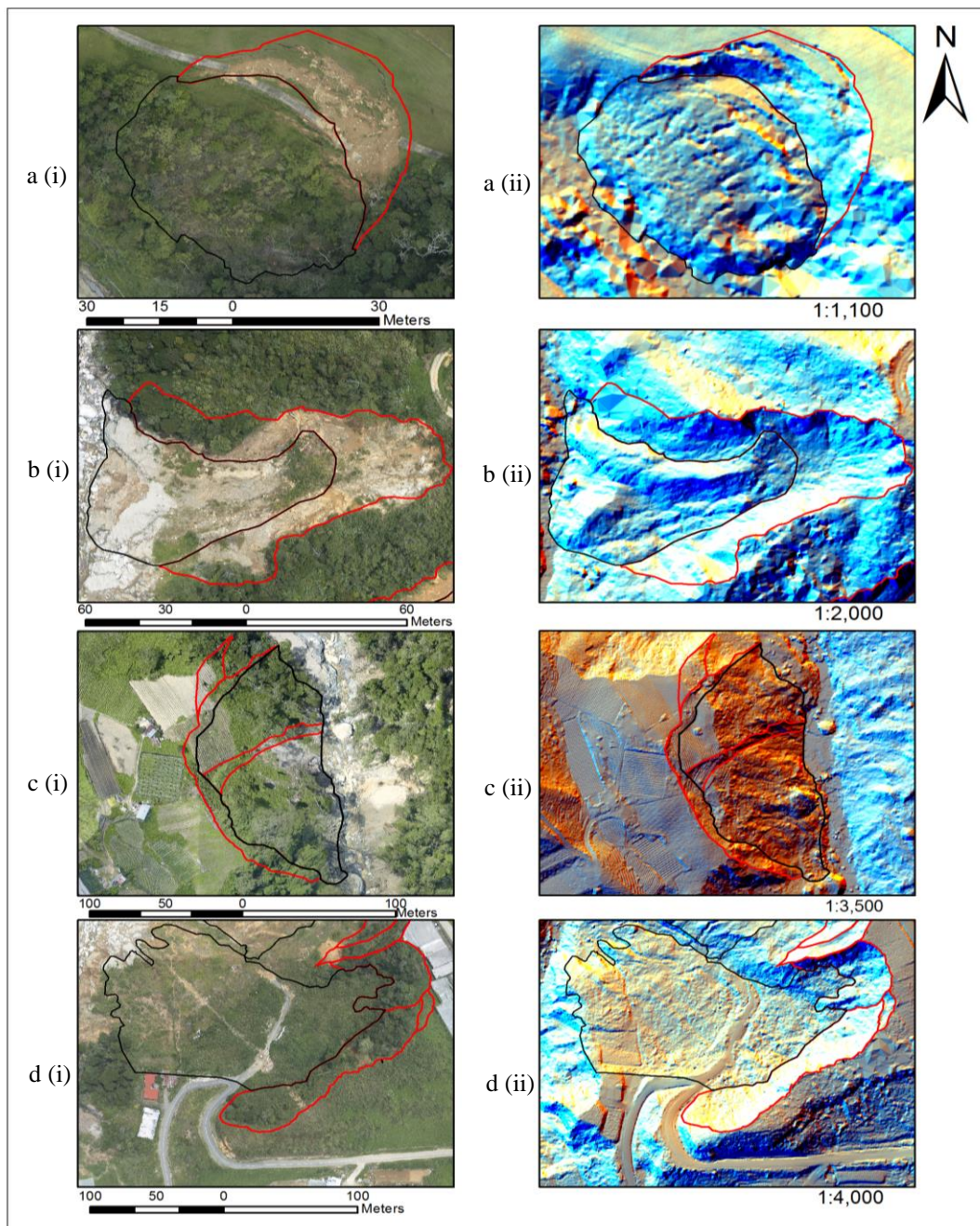


Figure 3. Landslide diagnostic features along Sungai Mesilou. 0.07 m orthophoto (left) and color composite DTM (right) are used to recognize landslide geomorphology. The landslide parts are scarp (red line) and accumulation zone (black line).

Sungai Mesilou as different sizes of granite boulders and weathered granite choked the main river [21]. The author added that the boulders are the deposits from Mount Kinabalu's summit carried down by the river over thousands of years [21]. This observation reveals the possibility of future debris flow event in Sungai Mesilou and in general, the possibility of landslides to occur again at the same location in

future. Thus, producing a landslide map of debris flow area is important to identify new, reactivated and historical landslides that were induced after the earthquake and debris flow event. About 70% of the interpreted landslides were verified in the field. The landslide boundary, type, activity and process are improved after getting input from local and expert knowledge and visualizing on the field as shown in Figure 4 and 5.



Figure 4. Field verification at Kampung Mesilou looking at landslides (see Figure 3b and 3d (right) and debris flow channel (left).



Figure 5. Field verification of a landslide (Figure 3c) indicating straight line of scarp by observing vegetation pattern and sudden drop of plantation area.



Figure 6. Debris flow observation at the source area (A), transport area (B), and deposition area (C).

4.4. Landslide inventory analysis

A final landslide inventory is systematically stored in ArcGIS geodatabase system and overlaid with multi temporal satellite images to observe the land use changes and the impact of the disaster. Along the debris flow channel, five disconnected roads and bridges are observed and the event significantly stripped off the vegetation along the channel as shown in Figure 7. Another impact of landslides towards land use changes is landslides at Kampung Mesilou. Figure 8 shows images of before- and after the landslides event. The landslides damages the roads and plantation area and caused road to be re-routed. Multi temporal images reveal the important of landslide inventory using LiDAR for land-use planning to avoid future damages and monetary loss. In addition, landslide inventory also can generate landslide density map to identify the distribution and intensity of landslides. Based on Figure 9, the landslide has high density at the transport zone, low to medium density at source zone, and no density at deposition zone. This finding correlated with the understanding of river incision, which it usually highly incises the sediment at the transport zone and deposits the sediment at the deposition zone.

5. Discussion

Landslide mapping using both techniques of remote sensing technique and field mapping is an efficient way of creating and updating an event-based landslide inventory. Landslide interpretation technique using different methods of landslide image visualization is helpful compared to the common hillshade image. High resolution LiDAR also helps to interpret landslides accurately by observing smaller geomorphologic features and differentiating source and deposition zone compared to 30m Aster GDEM and 10m IFSAR images. Interpreting landslides in a digital form is more efficient than done in a printed material because landslides and their specification can be visualized in multi scales and interactively. Thus, LiDAR is the best and superior technology for landslide recognition.

Landslide interpretation using LiDAR-derived datasets made possible to map and characterize recent landslide induced by earthquake, dormant, and historical landslides. The datasets show not only morphology features but other small-scale geodynamic features such as disrupted drainages and cracked- and displaced roads. This result indicates the possibility to develop other methods of detecting landslides in an objective manner and consider the vegetation anomaly. Bringing LiDAR into the field as a primary field material is quite challenging. This study proved that the LiDAR data was practically beneficial and can be directly assisted the field investigators Interpreting landslide using LiDAR is easier than verifying on the field because of different scales and physical constraints on the field such as forested area, plantation, and buildings. Identifying boundary for large landslide is quite difficult compared to small and new landslide. However, this problem can be avoided by viewing the landslides



Figure 7. Multi temporal images disconnected roads before debris flow from Worldview image in 2011 (top) and after debris flow from orthophoto in 2015 (below). 5m of road was displaced after the debris flow event.

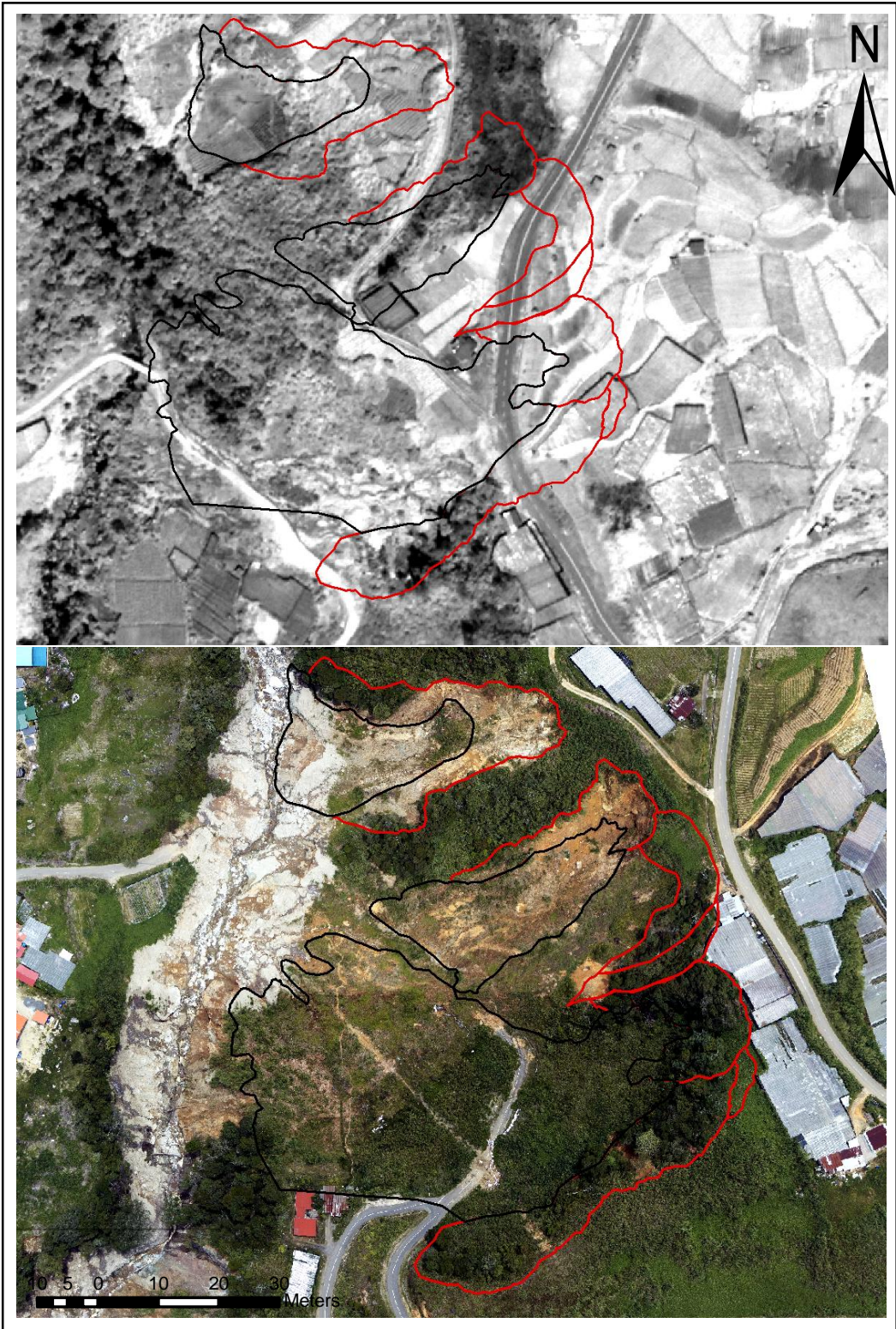


Figure 8. Scale 1: 1,400. Multi temporal images of SPOT (2010) and orthophoto (2015) of landslides in Kampung Mesilou. A very distinct and fast landscape changes within 5 years.

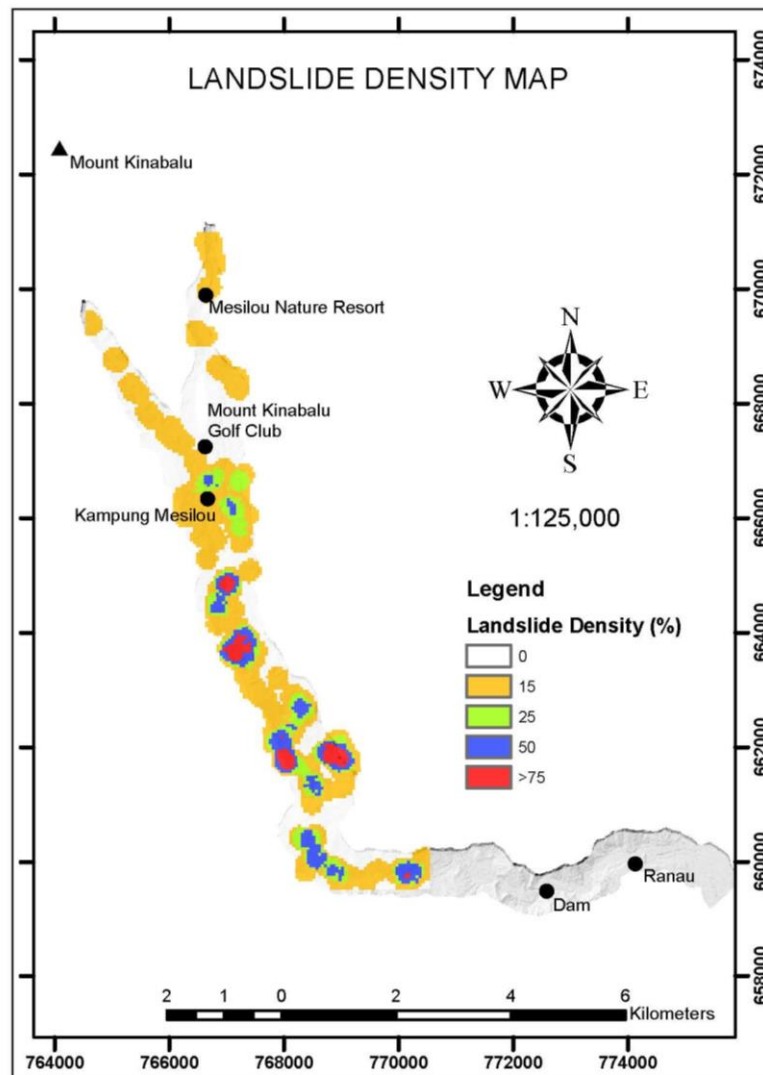


Figure 9. Landslide density map as a result of LiDAR-derived data validated in the field.

at distant and high place. Going to the field with experts and locals are quite helpful in guiding and understanding the past landslide events and regional geology.

Based on landslide density map, high density of landslide is concentrated in a transport zone of debris flow channel compared to source and deposition zones. The density map also reveals that the high landslide density are located in active river incision areas, fault zone, and characterized by Pinosuk Gravel lithology, which describes that the landslide activity along the Sungai Mesilou is mainly controlled by geological factors. Disconnected roads and damages houses can be seen at the transport zones compared to deposition zone. As a result of field observation, we found that transport zone is In terms of hazard and risk assessment, transport zone should be put in red zone for mitigation actions because there is possibility for debris flow to occur again at the same channel.

6. Conclusion

This paper presents an inventory analysis of landslides induced by earthquake in a tectonically active region in Kundasang (Sabah, Malaysia). It is a new landslide record and compiled based on the recent data relatively captured after the 6.0 Mw earthquake on June 5, 2016. The landslide inventory was largely developed based on high resolution airborne LiDAR data coupled with field investigation.

Multi-scale LiDAR data have revolutionized the analysis and assessment of hillslope-, and tectonic geomorphology in a tropical environment. An intensive 3D point cloud- and image processing with stringent analysis routine made the LiDAR technology and massive geospatial data worth to invest and obtain. Landslide diagnostic feature is one of the indicators to landslide identification but interpretation still depends on the study area, geology, and topography. Field observation becomes easier with the help of LiDAR because it directs the field investigators into the accurate location with relatively detailed characteristics of mapped landslides and their precursors at different working scales. A combination of the aforementioned methods produce the first reported landslide inventory after the 5th June earthquake by taken several considerations, which are the map utilized the best resolution for LiDAR, recorded landslide causal factor, and the level of hazard, as indicated in the field is very high because of the existing debris and rock boulders. The possibility of constructing new roads, bridges and other infrastructures is very challenging as all the infrastructures, e.g. disconnected roads should be carefully investigated and monitored. Landuse planning for the surrounding area along Sungai Mesilou also should be taken into consideration. These mitigation actions show the usefulness of landslide inventory map helps hazard and risk assessment.

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