ADVANCING THE USE OF LIDAR IN GEOTECHNICAL APPLICATIONS IN HONG KONG – A 10-YEAR OVERVIEW

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ABSTRACT: Hong Kong has been facing chronic hazard of landslides on both man-made slopes and natural terrain. Many landslides have occurred on natural terrain which is rugged, steep, not easily accessible and very often covered by dense vegetation. Acquisition of geospatial information for studying these landslides by conventional surveying methods could be difficult. Over the last decade, the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) of the Government of the Hong Kong Special Administrative Region has been employing various remote sensing techniques including Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR) and photogrammetry to collect useful geospatial data to support geotechnical studies on landslide hazard. Among various techniques, LiDAR is considered the most effective for the unique terrain setting of Hong Kong. We have conducted LiDAR surveys by using different equipment including terrestrial, airborne, mobile, backpack and handheld devices. The first territory-wide airborne LiDAR survey was conducted in 2010 and we just completed the second one in 2020. With the availability of the LiDAR datasets, we are able to establish more accurate terrain models to support a wide range of geotechnical assessments. Detailed landform information can be obtained by combining the LiDAR data with other sources of data. This can help identify important ground features such as drainage lines, relict landslides, boulders and rock outcrop. Moreover, landslide occurrence can be identified by applying change detection of landform in different time domains. Recently, we have successfully developed a new method for measuring orientations of rock joints from point clouds. The technological advancements have significantly changed our practice of handling problems and have brought about improvements in the efficiency, cost-effectiveness and safety of our work. This paper consolidates our ten-year experience in leveraging the use of LiDAR across various geotechnical applications in Hong Kong.

1. INTRODUCTION

Hong Kong has long been facing landslide hazard on man-made slopes and natural terrain. With the continual increase in population, there has been growing number of developments encroaching on the steep natural hillsides, thereby resulting in a consequential increase in exposure to landslide risk. Natural terrain hazard models include rock falls, boulder falls, open hillside failures, deep-seated slides and channelized debris flows (Ng et al, 2003; Ho & Roberts, 2016). To evaluate natural terrain hazard, it often involves assessment of large, remote and inaccessible hilly areas (Figure 1). Owing to such site conditions, acquisition of geospatial information by using conventional surveying methods is of great difficulty. Hence, the GEO of the CEDD of the Government of the Hong Kong Special Administrative Region, over the last decade, has been employing various remote sensing techniques including Light Detection and Ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR) and photogrammetry to collect geospatial data to support landslide hazard studies, particularly for natural terrain areas.

Figure 1: Landslides on Natural Terrain in Lantau Island in 2008

2. HISTORY OF LIDAR IN GEOTECHNICAL APPLICATIONS

2.1 Terrestrial LiDAR (TLS)

TLS was the first LiDAR technique employed in Hong Kong. It was applied in some of the geotechnical studies in Hong Kong (Figure 2). Since the TLS is relatively immobile, it may not be suitable for capturing geospatial data in remote locations.

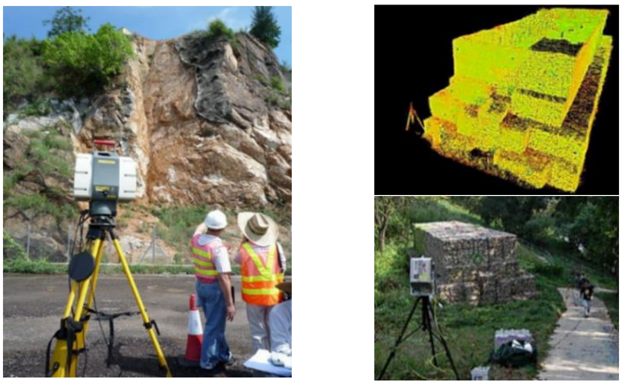


Figure 2: TLS for Geotechnical Studies in Hong Kong

2.2 Airborne LiDAR (ALS)

In 2006, the GEO conducted a pilot study to evaluate the usefulness of the ALS technology in geotechnical studies for the Hong Kong environment. The study demonstrated that the ALS has the capability to survey a large area at high accuracy within a short period of time, and to effectively obtain the ‘bare-earth’ ground profile by virtual deforestation in Hong Kong conditions (AAM, 2006). In 2010, the GEO conducted the first territory-wide ALS survey through which a set of high-resolution geospatial data was acquired (Figure 3). The multi-returned LiDAR data were collected up to 4 returned signals and at maximum point spacing of 0.5 m, with horizontal and vertical accuracies of 0.3 m and 0.1 m respectively (Lai, et al 2012). The flying heights were between 1,000 m to about 1,200 m for staying clear of the mountains.

In the second territory-wide ALS survey conducted in 2020, a helicopter was employed with much lower flying heights, mostly around 600 m. This enabled us to get better penetration of laser pulses to obtain more ground points for generating more accurate terrain models. Given the advancements in the technology, the data point density was significantly increased (up to 100 points/m^2 for some areas) and a maximum of 8 returned signals were collected for any single laser pulse, giving a higher chance to reach the ground level in vegetated areas.

With the rapid development of unmanned aerial vehicles (UAV), the GEO has also used such devices to conduct LiDAR surveys to supplement other remote sensing techniques, especially for obtaining geospatial information after occurrence of landslides.

Fixed-wing aircraft used in the 2006 pilot study and 2010 territory-wide survey

Helicopter used in the second territory-wide survey in 2020

Drone LiDAR

Figure 3: ALS Surveys

2.3 Mobile LiDAR (MLS)

Following the success of the territory-wide ALS in 2010 (Lai et al., 2012), the GEO continued to explore different remote sensing techniques to obtain high resolution geospatial information for landform mapping and slope investigation in order to enhance the efficiency of natural terrain landslide risk management. The study of the MLS was conducted in 2013 and 2014 (Lai & So, 2014). In the study, the MLS had been proven to be capable of recording high resolution multi-return signals along busy roads, narrow footpaths, underground space and seas cliffs (Figure 4). This study demonstrated that the MLS data could be integrated with the airborne LiDAR results to enhance the quality of ground information, thereby improving mapping of landform features for natural terrain hazard studies.

Figure 4: The MLS System Mounted on Different Mobile Platforms for Different Site Conditions

Survey of a cut slope

Tunnel survey

Figure 5: Backpack LiDAR

Recently, we have also adopted backpack LiDAR which is a very flexible device to obtain geospatial data of man-made slopes and underground space (Figure 5).

2.4 Handheld LiDAR (HLS)

There has been rapid development of various handheld LiDAR technology. HLS is extremely mobile and flexible with the capability of acquiring 3D measurement of physical objects. It provides the right balance between accuracy, range, field of view, operating conditions and cost (Figure 6). The GEO conducted the first trial on the applications of HLS in 2014 (So et al., 2015). The recent studies by applying more advanced HLS devices in 2018 and 2019 have demonstrated that HLS is capable of acquiring high resolution and accurate geospatial data at various site settings including difficult terrains and under adverse weather, which cannot be done by most of other remote sensing techniques (Leung & Ho, 2020). The use of simultaneous localization and mapping (SLAM) algorithm for data acquisition without the need of global navigation satellite system (GNSS) for positioning means that it can be used for surveying indoors and outdoors, even without GNSS. Hence, HLS offers a versatile means for a wide range of geotechnical applications.

Figure 6: Handheld LiDAR Surveys

3. APPLICATIONS OF LIDAR

3.1 Geotechnical Applications

Digital Terrain Models and 3-D Model Visualization: In the natural terrain hazard assessments carried out in the past, aerial photographs were used to identify geomorphological features such as landslide scars or debris trails. However, these features are sometimes obscured by dense vegetation and cannot readily be seen in aerial photographs. The 3-D terrain model derived from the LiDAR ground points overcomes the limitations of the conventional approach and facilitates identification of geomorphological features in vegetated areas (Figure 7).

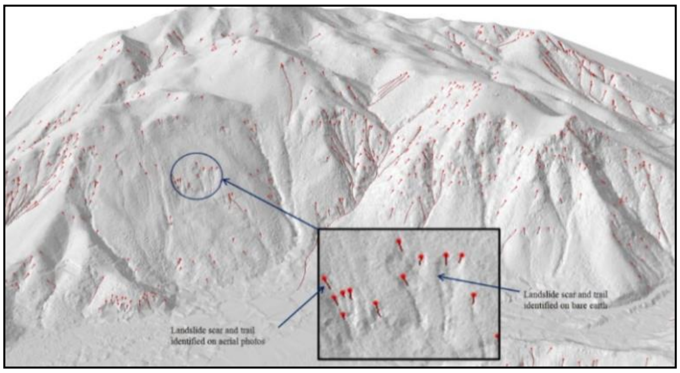
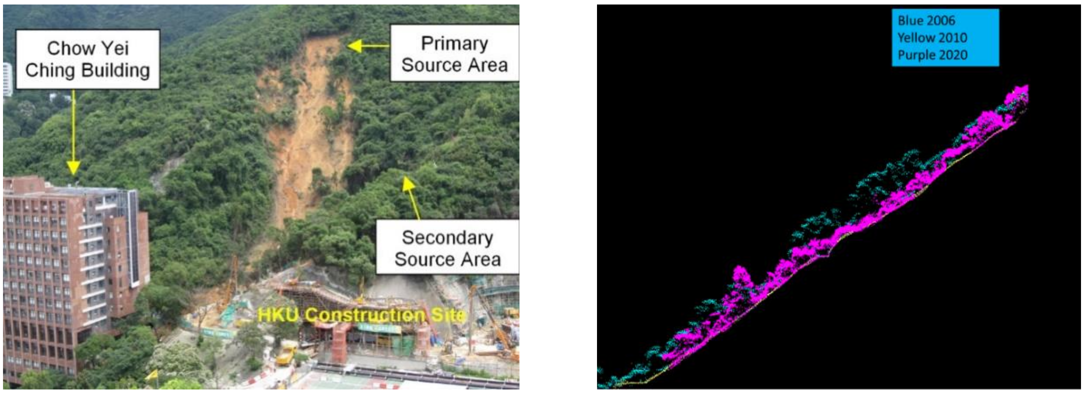


Figure 7: Landslide Scars and Trails Clearly Seen on Bare Earth Surface Model

Change Detection: LiDAR technology can also be used to detect changes in landform if the surveys of the same area are done in successive time periods. It is particularly useful for studying changes in topography after landsliding. For example, a landslide occurred on the hillside behind The University of Hong Kong in 2008 was studied by using the LiDAR data obtained in the 2006, 2010 and 2020 surveys. The slope surface derived from the LiDAR surveys were compared to assess the change of ground profile before and after the landslide (Figure 8).



2008 Landslide behind HKU

LiDAR data obtained in different surveys

Figure 8: Terrain Profile before and after the 2008 Landslide behind the University of Hong Kong

Boulder Study Integrated LiDAR with Image Processing Techniques: In 2015, we developed an approach which combined image processing and LiDAR data analysis technologies to detect boulders. The results are more accurate than those achieved by using image processing alone (Shi et al., 2015). This approach can also improve the estimation of shape and dimension of the boulders (Figure 9).

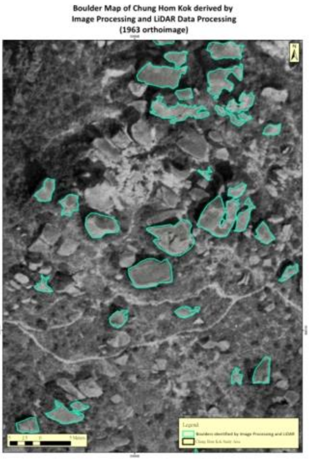
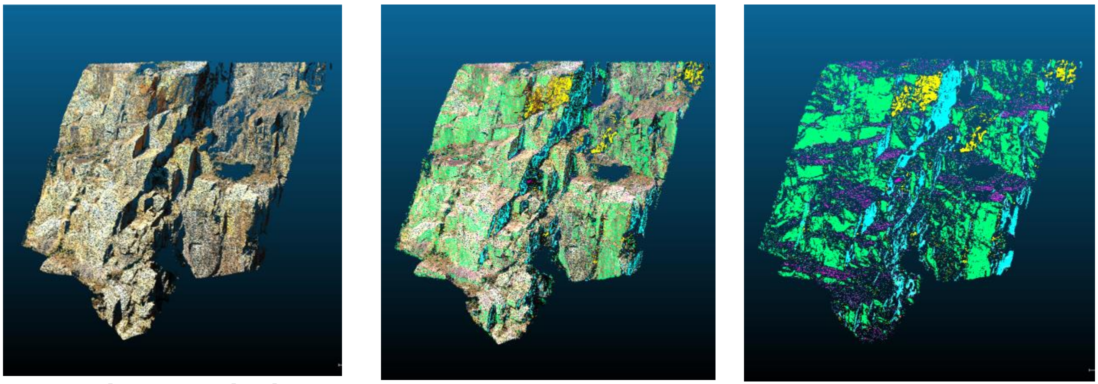


Figure 9: Results of Boulder Identification by Combining Image Processing and LiDAR Data Analysis (Shi et al., 2015)

Underground Space Study: LiDAR technology applies equally well to underground environment. It is therefore suitable for surveying tunneling/cavern works, underground facilities and disused tunnels, etc. to provide records of site progress and as-built conditions. Recent trials on the use of backpack LiDAR and HLS in tunnels demonstrated that the state-of-the-art SLAM algorithm can generate reliable tunnel alignment and geometry.

Rock Joint Mapping: Accurate mapping of discontinuities including dip angle, dip direction and persistence, etc., is of paramount importance in rock slope stability analysis. Conventional manual mapping method to measure joint orientations is time-consuming and very often limited to areas that are accessible to geologists unless scaffold/ladder is provided. LiDAR offers as a quick means to scan a large rock slope surface with a wealth of geospatial data acquired over the entire rock surface. We have recently developed a new Facet Amalgamation Approach (FAA) to derive major rock joints from the LiDAR data. In addition to identifying and taking measurements of joint planes, this approach can assist in conducting stability analyses of rock slopes with promising results produced (Figure 10).



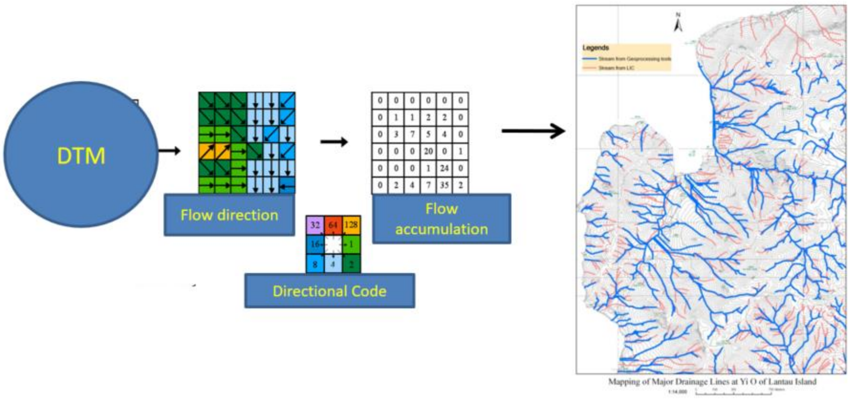
Colour point cloud

Colour point cloud and the major joint planes identified using FAA

Major joint planes identified using FAA

Figure 10: Major Joint Planes Identified from Point Cloud using FAA

Delineations of Drainage Lines: The high resolution topographical information derived from LiDAR ground points is valuable for a variety of analyses pertaining to natural terrain hazard assessment. These include debris mobility analysis, extraction of basic terrain parameters and drainage network analysis (Figure 11).



0	0	0	0	0	0
0	1	1	2	2	0
0	3	7	5	4	0
0	0	0	20	0	1
0	0	0	1	24	0
0	2	4	7	35	2

32	64	128
16		1
8	4	2

Figure 11: Drainages Delineated from LiDAR Generated Digital Terrain Model (DTM)

Landslide Studies: As mentioned earlier, HLS is extremely flexible and can be mobilized quickly to acquire geospatial information for landslide studies (Figure 12). It is always important to obtain landslide information as soon as possible after the occurrence of landslide incidents so that original details of landslides can be captured before any remedial works are done. Considering the urgency of the landslide studies, we have developed a workflow for getting geospatial data rapidly and conducting real-time processing of such data to provide valuable information of the landslides such as position, geometry and volume of debris (Figure 13).

Figure 12: Landslide Study by Using HLS

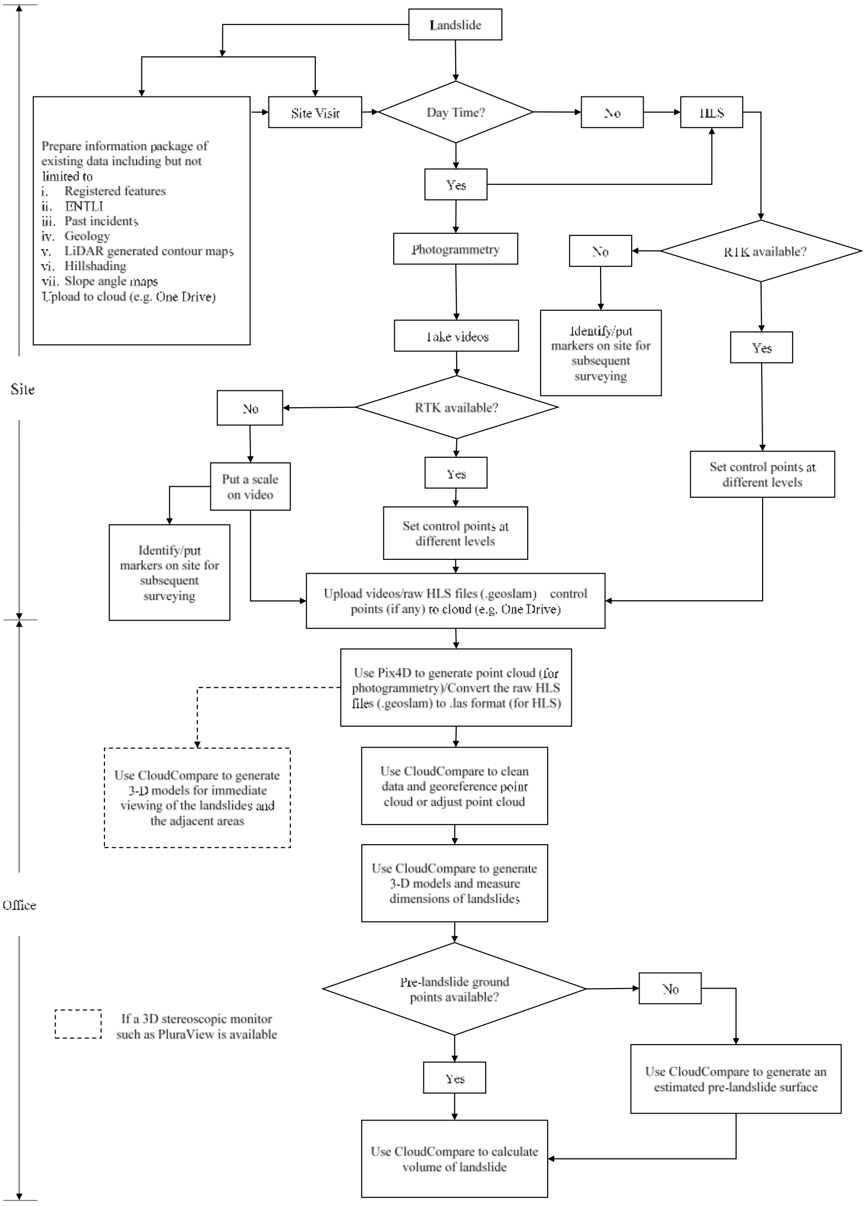


Figure 13: Flowchart for Acquisition of Landslide Information by Remote Sensing Techniques

Data-Information-Knowledge Framework for LiDAR Data Applications: To use LiDAR data effectively, we have formulated a systematic data-information-knowledge framework to handle LiDAR data (Lai & So, 2013) (Figure 14). At the lowest level of the framework, LiDAR data may come from primary or secondary sources. The primary data refer to those obtained directly from the LIDAR surveys, e.g. ground data points such as coordinates, elevations, intensity and number of returns. The secondary data are those generated after processing of the primary data. Examples are DTMs, digital surface models (DSMs) and contours. In combination with other data, useful information such as landform features can be obtained which in turn can assist with other geotechnical studies such as landslides hazard assessment and feature extraction.

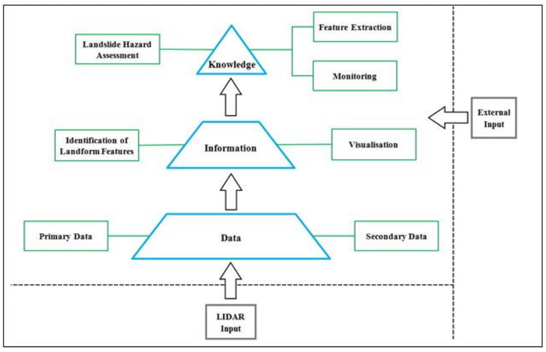
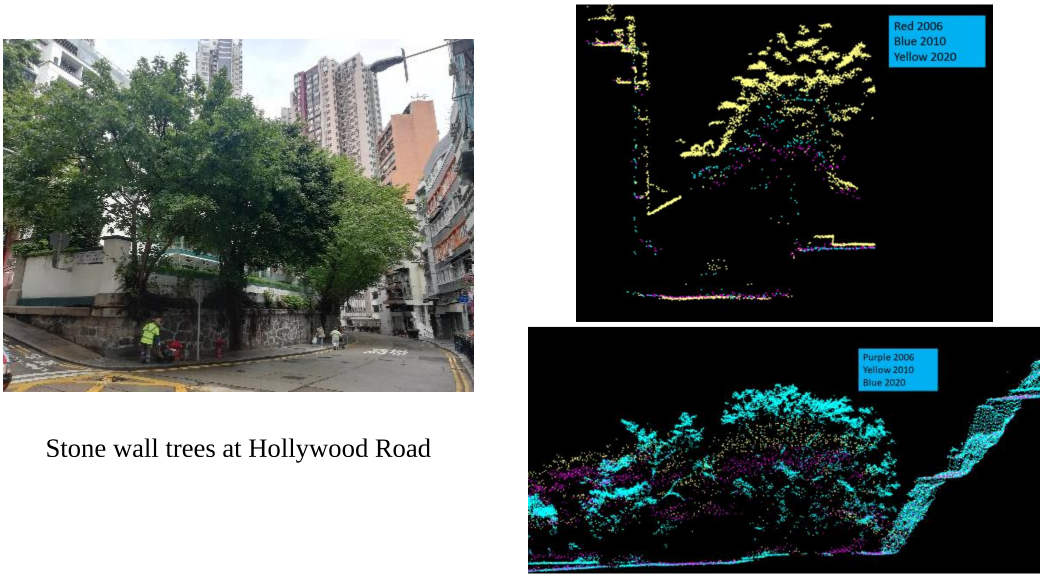


Figure 14: Overall Framework of LiDAR Data Applications

3.2 Other Applications

Besides geotechnical applications, LiDAR survey can be used for urban planning, tree risk assessment (Figure 15), flood analysis, aviation controls, identification of historical structures and monitoring the progress of construction works, just to mention a few.



Stone wall trees at Hollywood Road

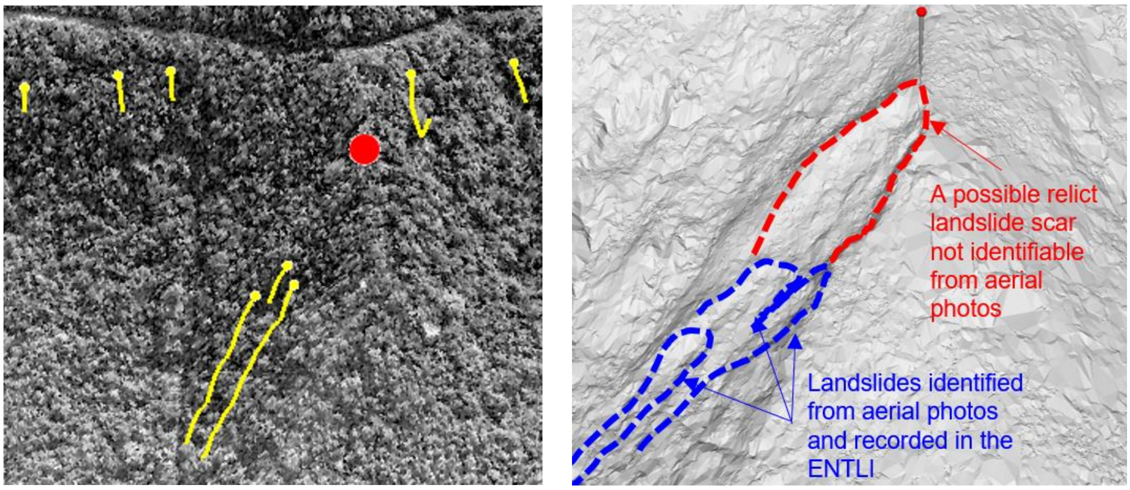
Figure 15: Changes in Tree Canopy in LiDAR Surveys Conducted in Different Years

4. WAY FORWARD AND CHALLENGES

4.1 Way Forward

Although LiDAR has been extensively used in geotechnical field, there are many applications yet to be developed.

Integration with Aerial Photograph Interpretation to Enhance Natural Landslide Inventory: In Hong Kong, the GEO is maintaining a database called the Enhanced Natural Terrain Landslide Inventory (ENTLI) which uses aerial photographs to delineate recent and relict landslides to assist with the landslide risk assessment. Landslide scars or debris trails are sometimes obscured by dense vegetation and cannot readily be seen in aerial photographs. Ground points in the LiDAR dataset are therefore considered to be useful to delineate those features covered by vegetation. A study is currently underway to interpret the terrain models generated from the LiDAR ground points of selected study areas for comparison with the landslide records in the ENTLI. Preliminary results show that the LiDAR can significantly identify more relict landslides and provide better positional information of landslides such as locations, geometry and volume. It is believed that LiDAR data can be integrated with aerial photographs to provide a powerful tool for landslide risk assessment (Figure 16).



1963 aerial photograph with ENTLI records

LiDAR derived DTM – no ENTLI record detected for the possible scar (red)

Figure 16: Landslide Scars and Trails Identified in Terrain Model Generated from LiDAR

After gaining more experience in identifying natural terrain landslides from the terrain model generated from LiDAR data, we expect that we would be able to develop objective tools to identify landslides using landform curvatures or other quantitative parameters/indexes. This would allow semi-automatic and consistent delineation of geomorphological features, especially relict natural terrain landslides, in a territory-wide scale. The application of machine learning in such study can also be explored.

Integration of LiDAR Data with Other Remote Sensing Data: Although LiDAR can provide valuable geospatial information for geotechnical studies, the properties of the slope forming materials such as seepages, soils and rocks may not be easily identified in LiDAR. We are currently undertaking a study to explore the feasibility of integrating LiDAR with thermal infrared imaging for geotechnical studies and the experimental results are promising (Figure 17).

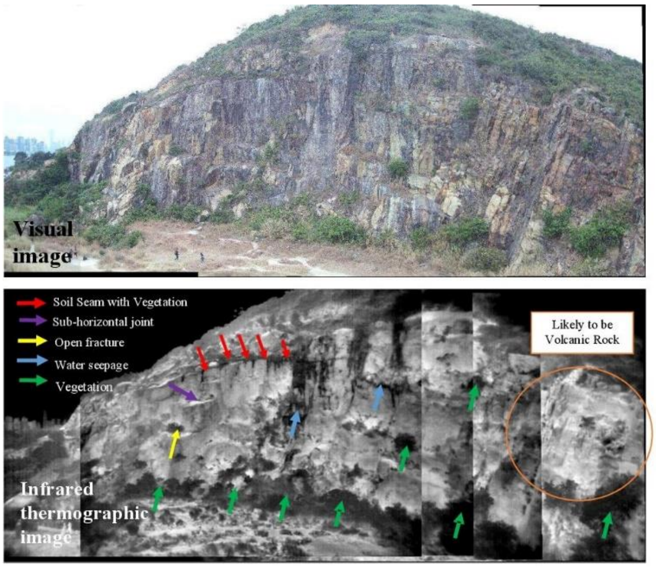


Figure 17: Results of Integration of LiDAR Data with Thermal Infrared Imaging

Assessment of Stability of Underground Space: Apart from rock slope mapping, we may apply different LiDAR equipment to capture the geometry of the faces of active tunnel/cavern projects right after blasting. Rock joint data, for example, orientation, spacing and persistence can then be semi-automatically extracted from the point cloud data for assessment of the stability of rock faces. With further advancement in other remote sensing techniques, we may be able to obtain more rock joint properties like nature of infillings and seepage conditions in the near future for a more comprehensive analysis of stability and design of supporting work.

4.2 Challenges

Flying Restrictions: Owing to the busy air traffic, hilly terrains and abundant high-rise buildings in Hong Kong, data acquisition of ALS is subject to flying restrictions. Close liaison with Civil Aviation Department on the flight height and flight time was required for the territory-wide airborne LiDAR surveys. The use of UAV for capturing LiDAR data of local areas is also subject to relevant regulations.

Areas with Dense Vegetation: The ability of LiDAR signals penetrating vegetation to collect ground information depends on the density of vegetation. For areas with gaps between tree canopies, there would be reasonable data points reflected from the ground. However, for areas with very dense vegetation, for example, ground covered by dense shrubs or grasses, there may be little points reflecting from the actual ground for accurate terrain modelling (Figure 18).

Tree canopy – Reasonable returned signals

Shrub or grass – Poor or no returned signals

Figure 18: Amount of Returned Signals Depends on Vegetation Density.

Size and Volume of Digital Data: With the improvement in LiDAR equipment, much higher data point density and more accurate measurement can be collected. However, this would inevitably increase the size and volume of digital data. For example, in the 2020 territory-wide airborne LiDAR survey, the total size of raw and processed data is over 20TB. More powerful workstations may be required to process the increased amount of data.

Problem of Poor Signal Return, in Particular, in Locations Close to Tall Buildings: Line-of-sight issue may happen for some LiDAR acquisition methods, for example, TLS and ALS. Despite having overlapping flight swathes, there were inevitably areas with poor signal return due to blockage by features like tall buildings (Figure 19) in ALS. The application of more mobile data capturing methods, for example, MLS and HLS, may supplement the data gaps.

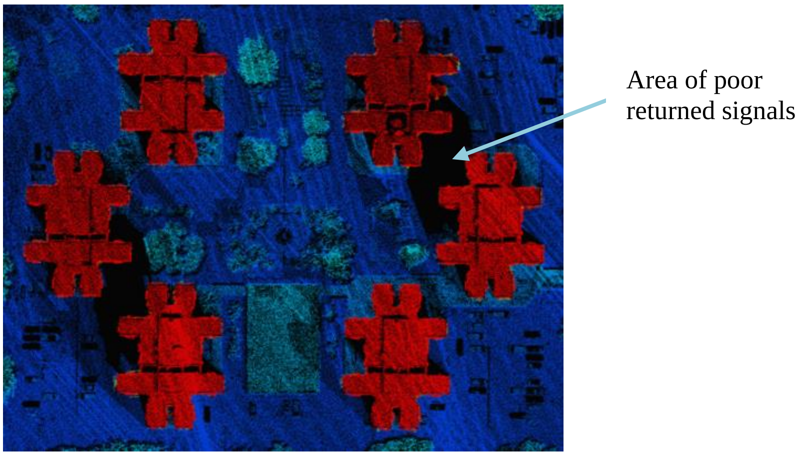


Figure 19 : Poor Returned Signals Adjacent to Tall Buildings

5. CONCLUSION

The GEO has been applying different types of LiDAR technology for geotechnical studies, especially landslide risk assessment in Hong Kong. Based on the past 10-year experience, it demonstrates that various kinds of LiDAR capturing techniques do provide reliable geospatial information for different types of studies and site settings. The applicability of LiDAR has been further enhanced by applying new analytical methods (e.g. FAA) that have been developed recently. Moving ahead, new applications, especially in combination with other latest technologies such as AI and machine learning, are worth exploring and are expected to bring the capability of the LiDAR technique to a higher level.

6. ACKNOWLEDGMENTS

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