Research on LiDAR technology in early identification of geo-hazards in alpine loess areas

L C Wang1,*, M Wang2, X C Hung2 and Z Feng1
1 China Institute of Geo-Environment Monitoring (Technical Guidance Centre for Geo-Hazard Mitigation, the Ministry of Natural Resources of People’s Republic of China), 20 Dahuisi Road, Haidian, Beijing, 100081, PRC
2 Sichuan Geological Survey, 25 Renminbei Road, Jinniu, Chengdu, 610081, PRC
*Corresponding author: wanglc@cigem

Abstract: The early identification is a key topic in geo-hazards science in China. Methods including engineering geological analysis, optical RS, InSAR, field survey verification, have been used for early identification of geo-hazards. This paper presents the application of airborne LiDAR to data collection and landslide identification in alpine areas. High-resolution images and point clouds of several landslides were obtained. And the characteristics of landslides have been interpreted. The study of relationship between point clouds and vegetation removal model (VRM) showed that the density of point cloud had a great influence on VRM. The lusher the vegetation, the less point cloud could be collected, resulting in much less point cloud density and lower resolution of VRM. When the density of point cloud is greater than 15 points/m², the hillshade map generated after vegetation removal was usable for landslide characteristics recognition. The boundaries, shape, zoning, and some micro-topography, such as cracks with a certain length and width, could be effectively identified. The hillshade map with different azimuth angles were able to visually display the micro-topography features from different orientations. The slope image and surface roughness image from airborne LiDAR provided quantitative topographic parameters for geo-hazards identification, boundaries delineation and volume assessment. In the end, this paper proposes a guidance of early identification of geo-hazards in alpine areas by using LiDAR Technology.

Keywords: Airborne LiDAR, Early identification, Geological hazard, Point cloud, Steep slope

1. Introduction
Due to the Qinghai-Tibet Plateau uplift, the mountainous areas of west China are characterized by dense and active faults, intense neotectonic movements, deep valleys, and large relative relief. The near-surface rock and soil affected by active fault belts have resulted in poor integrity and loose structure. In recent years, under the combined impacts from extreme climate phenomena and growing engineering activities, landslides initiated from the top of high and steep slopes have occurred from time to time. High-located landslides have high potential energy, and the moving process is accompanied by disintegration, entrainment, enlargement, causing catastrophic losses. Taking the Sanxi Landslide for example, it occurred in 2013 in Sichuan, China. The landslide ran downwards from 1130m at the slope top to 755m in the toe. It turned into avalanche and traveled 1260m, burying 11 houses and causing 161 death. There are similar catastrophes, such as the Xinmo Landslide in...
Sichuan Province and the Leyte Landslide in the Philippines. The sources of high-located landslides are usually out of sight. And because of the steep terrain and lush vegetation, they are difficult to be detected by traditional field surveys. Therefore, early identification of geo-hazards with high-concealment has become a focus in geo-hazards prevention and control (YIN et al., 2016, 2017, WANG et al., 2019).

Integrated RS is a method that has been widely employed in early identification, investigation, monitoring, and early warning of geo-hazards. This method helps to change the conventional, time-consuming and strenuous field works in landslide survey and monitoring (GE et al., 2019). Optical RS imagery is a multi-temporal and multi-spectral technique characterized by wide coverage, multiple data sources, and low cost (FANG et al., 2015). It can effectively identify potential geo-hazards with complete characteristic elements and obvious signs of deformation (XIE et al., 2011; ZHANG et al., 2017). InSAR technology was first used in landslide monitoring in 1996 and it has become one of the most common geodetic surveying technologies by virtue of high precision, high resolution, high efficiency, all-time, all-weather, and large-scale coverage (Fruneau et al., 1997; Gabriel et al., 1989, ZHANG et al., 2018, MIAO et al., 2018). With better penetration, the airborne LiDAR system has much higher resolution, velocity, efficiency, comparing to optical RS and InSAR. The point clouds from LiDAR could be used to build high-resolution DEM and DOM. This technology has huge advantages for microtopography detection, geometric shape extraction, and high-resolution modeling (JIANG et al., 2018, FAN et al., 2018, LI et al., 2018). It is now being extensively applied for landslide recognition and investigation (KANG et al., 2017, SHE et al., 2018).

The loess plateau in northwest China has sparse vegetation which is favorable for the use of laser scanning. Landslide microtopography and hidden cracks could be identified because of less interference from vegetation and more effective irradiation points on the ground. Through fully utilizing the advantages of airborne LiDAR technology, several loess landslides in Min County, Gansu, northwest China, have been chosen. The object is to explore technical parameters (such as landslide boundary, crack width and ductility, and slope scarp gradient and height) for landslide identification under different flight heights and sampling frequencies, aiming to propose an integrated method for early identifying of geo-hazards in alpine loess area.

2 Geological Background of the Study Area
The study area is in the convergence zone of the Gannan Plateau, the Longnan Mountainous Region, the Longxi Loess Plateau. Under the combined influence of the complex tectonic faults and structures, this area has experienced intense geological tectonic movements, which makes the geological environment very vulnerable.
The study area has a mean altitude of 2,500 m, a minimum altitude of 2,040 m, and a maximum altitude of 3,872 m. Its general topography inclines from southeast to northwest. Its topographic types include tectonic erosional middle mountains, tectonic denuded middle and lower mountains, tectonic karstic planation surfaces, and eroded deposited river valleys. Outcroppings of various strata can be observed in the study area, from late Palaeozoic Devonian strata to Cenozoic Quaternary strata, although Mesozoic Cretaceous strata are missing. Neotectonic movements in the study area are mainly manifested as vertical movements, and there is a large relative relief between terraces. Falling within a region of intense seismic activity, the study area has a seismic intensity of grade VII according to the Chinese seismic intensity scale.

3 Working Principle and Processing Flow

3.1 Working principle
A LiDAR system is composed of four parts: (1) a laser scanner (the core of the system), used to measure the distance from the laser emitting point to the ground laser foot point; (2) a dynamic differential GPS (DGPS), used to record the instant of laser irradiation and the pulse activation time taken by the digital camera and acquire the 3D coordinates; (3) a laser measuring unit (IMU), used to determine the space attitude parameters of the principal optic axis of the laser scanner; and (4) a digital camera, used to capture the true color or infrared digital image information from ground objects and topography. Depending on the loading platform, LiDAR systems can be classified into ground, vehicle-mounted, airborne, or satellite-borne systems. Airborne LiDAR systems are usually carried by aircrafts or helicopters, and include common systems such as the LeicaALS series, Optech ALTM series, Falcon series, and Litter Maper series, with cm-m-level spatial resolution.
The laser range finder in LiDAR systems consists of a single-beam narrow-band laser and a receiving system. When the laser emits a beam of discrete laser pulse onto a ground object, the reflection is received by the receiving system which can accurately record the duration from laser pulse emission to reception. Given that the laser pulse travels at the speed of light, the distance between the laser and the ground object can be calculated by the following formula:

$$R = \frac{C \cdot t}{2}$$

where, R denotes the distance between the sensor and the target object; C denotes the speed of light; and t denotes the duration from laser pulse emission to reception.

First, the position coordinates of the laser can be obtained from DGPS data and the attitude parameters of the aircraft can be acquired by IMU. Next, these measurements can be combined with laser height, laser scanning angle, and other relevant data to accurately calculate the 3D coordinates of each ground laser foot point. Figures 2 and figure 3 show the schematic diagram and basic principles of an airborne LiDAR system, respectively.

3.2 Work flow

The work flow consists of airborne LiDAR data acquisition and processing. The data acquisition procedure includes flight route planning, flight preparation, flight calibration, airborne magnetic data collection, field data check, supplementary photography, and rephotography (Figure 4). The data processing includes point cloud data preprocessing (Figure 5), digital surface model (DSM) processing (Figure 6), DEM processing (Figure 7), and DOM processing (Figure 8).
4 LiDAR Technology-based Identification of Potential geo-hazards

LiDAR technology-based identification of potential geo-hazards uses the high-resolution point cloud data of the study area from airborne LiDAR, then obtains landslide form and deformation characteristics through building a point cloud data model for the surface vegetation and performing vegetation removal. Finally, airborne LiDAR technology is combined with optical RS and field survey verification to discover potential geo-hazards. After a general survey of geo-hazards development in the study area, this paper mainly targeted steep alpine areas, densely populated areas (such as major towns), important traffic arteries, and other major areas for study. Seven typical landslide events were selected for analysis on the basis of field survey results that considered the deformation characteristics.
of landslides, the development of trailing-edge tension cracks, the scale of slope disasters, and the objects threatened by disasters. The events included the Lengdi Village Landslide of Xizhai Town, the Wangjiagou Village Landslide of Qingshui Town, the Zhifang Village Repair Factory Landslide of Minyang Town, the S306 Roadside Landslide of Minyang Town, the G212 Roadside Landslide of Chabu Town, the Landslide behind the Qinxu Township People’s Government, and the Landslide behind the Wendou School of Meichuan Town (Figure 9).

Figure 19. Distribution map of the seven typical landslide areas surveyed by LiDAR

4.1 Point cloud data and the vegetation removal model
In investigating point cloud data and the vegetation removal model (VRM), the point cloud data were obtained using the multiple-echo technique solved by different distance filtering methods and followed by de-noising and removal of useless point clouds. Through analyzing the relationship between point cloud data and vegetation height, this paper built a point cloud data model for surface vegetation and removed that data using software, thus obtaining the ground surface model.

In this paper, seven LiDAR surveying areas were selected in the study area for data collection and processing. Due to the differences in vegetation coverage and vegetation height in the area (grassland is equal to 10-30 cm, shrubland is equal to 30-100 cm, forest land is equal to 300-1,500 cm), there were differences in the quantity of points in the clouds. In particular, the point cloud density was relatively low in the Lengdi Village Landslide of Xizhai Town due to the presence of earth magnetic field jamming. Table 1 shows the point cloud densities before and after vegetation removal in various LiDAR flight zones. Figures 10 and 11 show the hillshade maps of the Landside behind the Qinxu Township People’s Government before and after vegetation removal produced by DSM and DEM.

Table 1. Statistics of point cloud data collected in the LiDAR flight zone and after vegetation removal

| No | Flight zone name          | Vegetation type    | Point cloud density collected (points/ m²) | Point cloud density after vegetation removal (points/ m²) |
|----|--------------------------|--------------------|-------------------------------------------|----------------------------------------------------------|
| 1  | Wendou School Landslide  | Grassland, shrubland | 23                                        | 1.3                                                      |
| 2  | G212 Roadside Landslide  | Grassland, shrubland, bare land | 25                                        | 5                                                        |
Clearly, different densities of point cloud data significantly affected the analysis of VRM. Under different vegetation coverage types, the resolution of VRM differed as well, as manifested in the following aspects:

(1) In the same area, the more point cloud data that was collected, the more effective the data after vegetation removal and the higher the resolution of VRM. Taking the S306 Roadside landslide and G212 Roadside landslide as examples, data with different density of point cloud had been obtained. By comparing the VRMs, it was found that the higher density of point cloud, the higher resolution the model got. When the density exceeds 20 points/m², the resolution of VRM tends toward stable (Figure 12).

(2) Under same conditions, the resolution of VRM is determined by vegetation type: bare land >
grassland > shrub > woodland. For example, by analyzing the Qinxu landslide and Zhifang landslide, it showed that the lusher the vegetation, the less the effective the data after vegetation removal and the lower the resolution of VRM (Figure 13).

![Figure 13](image)

**Figure 13.** The point cloud densities before and after vegetation removal

### 4.2 Identification of landslide form characteristics

Relying on the ground surface model after vegetation removal, airborne LiDAR technology was used to obtain high-resolution 3D ground data of the landslide area. A high-resolution DEM hillshade map was then adopted to acquire Side scarp, landslide scarp, landslide body, and other landslide form characteristics, establishing the identification marks of landslides in steep alpine areas. Examples of deformation characteristics include Side scarps (Figure 14a), tension cracks (Figure 14b), Scars (Figure 14c), and sliding deformation bodies (Figure 14d). In addition, identifying marks of landslides in steep alpine areas can be comparatively analyzed through high-resolution DOM, using deformation features such as Side scarps (Figure 15a), tension cracks (Figure 15b), Scars (Figure 15c), and sliding deformation bodies (Figure 15d).

![Figure 14](image)

**Figure 14.** Identifying marks of landslide forms based on LiDAR DEM
On the basis of the results from landslide identification mark analysis, this paper sorted the plane forms of landslides in the study area and established LiDAR technology-based RS interpretation marks for the early identification of landslide hazards in steep alpine areas. There are many landslide forms such as dustpan, armchair, pear, and tongue shapes (Figure 16-Figure 19).

**Figure 15.** Identifying marks of landslide forms based on LiDAR DOM

**Figure 16.** Dustpan-shaped landslide

**Figure 17.** Armchair-shaped landslide
Through the above analysis, this paper summarizes a LiDAR technology-based method for the early identification of landslide hazards. On the basis of the classification and vegetation removal processing of laser point cloud data, the generated LiDAR data images and DEM can reproduce real terrain and topography, thus facilitating the RS interpretation of geo-hazards. The specific steps were as follows: airborne LiDAR data collection→ airborne LiDAR data processing→ airborne LiDAR data classification→ vegetation removal processing→ generation of DOM, DEM, DSM, and DEM hillshade maps→ identification of landslide elements→ field survey verification→ detailed interpretation→ comprehensive analysis.

On the whole, the application of LiDAR technology in the early identification of geo-hazards is based on its clear description of microscopic terrain. This technology can acquire ground surface information by penetrating vegetation coverage to some extent. Relative to aerial photographs, the way in which data is collected can largely reduce the influence of terrain cutting. Thus, LiDAR technology can improve the resolution of the early identification of landslides as embodied in the following two aspects:

1) The overall change characteristics of the slope can be used to identify slope depressions and abrupt changes using the DEM and DEM hillshade maps generated by LiDAR;

2) On the basis of the DEM and DEM hillshade maps generated by LiDAR, changes in ground roughness can be employed to identify some landslide deformation characteristics such as tension cracks, pull-apart scarps, and slope surface collapses.

4.3 Quantity of point clouds and identification of hidden cracks

Through establishing the DEM for tension crack identification based on different quantities of point clouds, this paper analyzed the relationship between different quantities of point clouds and the identified tension crack length and width. This information was used to create minimum-scale identification indices for identifying tension cracks and other deformation characteristics based on the quantity of point clouds and establishing the identifying marks of hidden cracks.

Taking the Qinxu landslide as an example, hidden tension cracks were identified using the optical image, DEM hillshade map before vegetation removal, and DEM hillshade map after vegetation removal (Figure 20-Figure 22). The interpretation of the DOM image and the DSM hillshade map revealed that there was a clear boundary between forested and farmland. However, it was impossible to recognize whether tension cracks exist or not. In contrast, the DEM hillshade map directly indicated that an obvious tension crack had developed and evolved into a long and large main scarp. Meanwhile, the DEM hillshade map also clearly showed the boundary of the landslide.
More landslides with point cloud density higher than 20 points/m² have been studied using the same method and the identification results are presented in table 2.

| Landslide Name       | Vegetation type | Minimum Length of Tension Cracks (m) | Minimum Length of Scarps (m) |
|----------------------|-----------------|--------------------------------------|------------------------------|
| Wendou School Landslide | Grassland       | 10.19                                | 11.1                         |
|                       | Shrubland       | 13.56                                | 14.54                        |
|                       | Bareland        | 6.03                                 | 7.43                         |
| G212 Roadside Landslide | Grassland       | 7.05                                 | 9.38                         |
|                       | Shrubland       | 8.59                                 | 10.34                        |
|                       | Grassland       | 5.77                                 | 10.06                        |
| S306 Roadside Landslide | Shrubland       | 8.96                                 | 11.8                         |
|                       | Forest          | 10.34                                | 12.25                        |
| Wangjiagou Landslide | Grassland       | 8.22                                 | 9.59                         |
|                       | Bareland        | 3.63                                 | 4.19                         |
|                       | Grassland       | 5.86                                 | 5.03                         |
| Qinxu Landside        | Shrubland       | 6.61                                 | 7.33                         |
|                       | Forest          | 7.36                                 | 7.7                          |
|                       | Bareland        | 5.75                                 | 7.39                         |
|                       | Grassland       | 7.86                                 | 9.77                         |
|                       | Shrubland       | 8.46                                 | 10.64                        |
|                       | Forest          | 9.68                                 | 12.71                        |
| Zhifang Landslide     | Grassland       | 7.86                                 | 9.77                         |
|                       | Shrubland       | 8.46                                 | 10.64                        |
|                       | Forest          | 9.68                                 | 12.71                        |

The results show that the scarps and tension cracks are unable to be identified unless their length exceeds 4.19m and 3.63m in bareland, 5.03m and 5.77m in grassland, 7.33m and 6.61m in shrubland, 7.7m and 7.36m in forest, respectively.

In summary, by observing the DEM hillshade map after vegetation removal, one can observe the length, width, trend, and other basic parameters of hidden cracks, thus offering marks to aid in the early identification of geo-hazards in steep alpine areas.

### 4.4 Integrated identification of potential geo-hazards

The early identification of potential geo-hazards in steep alpine areas is a comprehensive research process that requires the integrated application of multiple methods and means. For this purpose, it is necessary to give full play to the unique advantages of optical RS technology, InSAR technology, and LiDAR technology, and adopt SAR satellite data as the RS data source of InSAR, providing basic RS data for the early identification of geo-hazards using airborne LiDAR technology. After collecting LiDAR data, high-resolution DEM, DSM, DOM, and DSM and DEM hillshade maps should be generated for integrated identification and interpretation, and field survey verification should also be performed so as to realize the early identification of potential landslide hazards in steep alpine areas by multiple methods and means.

### 5 Conclusions
Airborne LiDAR can penetrate vegetation to acquire high-resolution elevation models, which can can precisely express microtopography. Taking several landslide in loess plateau in northwestern China as experimental subjects, the airborne LiDAR technology were used to conduct high-precision survey for landslide identification. Some results have been concluded as follows.

Different densities of point cloud significantly affected the resolution of the VRM. In the same area, when more point cloud data was collected, the VRM was more precise. Under same conditions, lusher vegetation resulted in less effective data after vegetation removal and a less precise model. In the loess plateau, areas with Different vegetation types can be ranked as follows in descending order of the resolution of the VRM: bare land>grassland>shrubland>forest land.

VRM from Airborne LiDAR data can be used to accurately extract side scarps, tension cracks, tension scarps, displaced area, and other landslide elements. Airborne LiDAR data are significantly superior to both optical RS data or UAV image. But vegetation type significantly affects the identification of hidden cracks. For airborne LiDAR data with a mean point cloud density of more than 20 points/m², the minimum identifiable lengths of scarp and tension cracks were 4.19 m and 3.63 m for bare land, 5.03 m and 5.77 m in grassland, 7.33 m and 6.61 m in shrubland, 7.70 m and 7.36 m in forested land, respectively.

6 Discussion
Compared with RS or UAV tilt photography, airborne LiDAR mountain shadow maps have obvious advantages in depicting the micro-topography of landslides. Steep scarps and tension cracks are important signs for landslide identification. It is expected to use airborne LiDAR hillshade to reach high resolution in identifying steep scarps and cracks. However, the field verification shows that the current method can only achieve accuracy above the meter level, which is far from the expectation, especially in lush area. As a high-resolution and -mobility method, it is still worth exploring the LiDAR technology in landslide early identification from the flight parameter control system and identification technology etc, aiming to obtain higher resolution and more reliable results.

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