The Road from National LiDAR mapping program to Zonation of the Geohazards in Taiwan

Li-Yuan FEI(1), Yu-Chung HSIEH(1)

(1)Environmental and Engineering Division, Central Geological Survey, Taiwan
E-mail:feily@moeacgs.gov.tw

Abstract

On August 8, 2009, when typhoon Morakot swept through Taiwan, the island nation suffered a devastating disaster, the scope of which it had never seen before. Typhoon Morakot in two days brought 211cm of heavy rain, and in some southern Taiwan areas as much as 300cm of rain was measured. The resulting landslides amounted to 40,594 separate incidents. Responding to the Morakot disaster, our government enacted an emergency measure, entitled "Special Statute for Reconstruction of Post-typhoon Morokot Disaster", which prodded Central Geological Survey to initiate a dedicated project aimed at the preservation of land in zones sensitive to geohazards, due to geomorphological and geological conditions.

As part of this project, airborne LiDAR was deployed to establish a new nationwide DEM (Digital elevation model) with grid size of 1 m, and to obtain digital aerial photograph, with grid size of 50 cm, simultaneously. The first National LiDAR mapping program was conducted by four survey teams and one quality assurance team. Survey teams operated a variety of laser sensor systems. Weather, terrain relief, and dense vegetation conditions were the three most challenging issues, limiting the performance of this project. After overcoming all the difficulties, we completed the project and achieved our goal, which is, establishing the first National LiDAR map of Taiwan.

In addition, the application of high resolution DEM database to investigate and analyze geologically sensitive areas, geological and topographical characteristics, river system analysis were all part of this project. The key work was to identify and analyze large-scale landslides. We concluded that there were about 600 high-susceptible, large-scale landslide areas in central, southern and eastern Taiwan.

At present we are planning a second phase of National LiDAR program in the near future to further study different issues of large-scale landslides to prevent the Shiaolin Village disaster from ever occurring again.

Keywords: national LiDAR mapping program, large-scale landslides, geologically Sensitive Area

1. Introduction

Nearly three-quarters of the territory of Taiwan and 95% of its population are exposed to multiple, frequent natural hazards. Typhoon Morakot hit Southern Taiwan on August 8 and 9, 2009. It inflicted an area of ten thousand square kilometers with massive landslides, debris flows and flooding. Among the victims, Shiaolin Village suffered the most with 681 casualties, 18 people still unaccounted for, and the destruction of over 100 houses. Our government realized that the country was lacking in detailed, accurate and current terrain data, as well as aerial imagery. In response, a national LiDAR mapping and zonation of the geohazards program, employing state-of-the-art technology of integrated airborne LiDAR and digital photography, was launched by Central Geological Survey (CGS) in 2010 and continued to this date. To confer and grant under conditions laid down in the "Special Statute for Reconstruction of Post-typhoon Morakot Disaster", a project of "Investigation and Analysis for Geologically Sensitive Areas under the Program of National Land Preservation" was initiated. It was the first national mapping program with the aim of simultaneously capturing the territory (36,000km^2) terrain data by airborne LiDAR and digital imagery in Taiwan. The terrain data would include very detailed DEM and DSM (Digital surface model) of 1-meter grid and digital aerial photograph of 50-centimeter grid.

LiDAR provides high resolution topographic data with notable advantages over traditional surveying techniques (Slatton et al., 2007). With LiDAR techniques, it is possible to generate a bare-earth elevation model, and this fast and preliminary data could meet the requirements for geological harzard identification and suitable for analyzing many major hydro-geomorphic processes. For CGS, using this datasets to establish a new landslide inventory and estimate landslide activity in areas partially or completely covered by dense vegetation, was thought to be a new powerful innovative method, especially for large-scale landslide research.

Applications with those high resolution datasets of terrain are many folds: (a) geological structures and stratum identification, (b) landform change of river beds, river terraces, and river channels, (c) high landslide susceptible zones evaluation, (d) large-scale landslides detection, and (e) detailed geological mapping and safety assessment for selected areas near mountainous settlements are the other objectives of this project.

Both the establishment of high resolution terrain datasets and the identification of the locations with geohazards were some of the many challenges we faced. In this paper, the status of the national LiDAR mapping program will be summarized. In addition, some examples of studying active geomorphology and geohazards on a regional scale are offered to demonstrate the unique capability of these terrain datasets, especially for the potential large-scale landslides associated with settlements in the mountainous areas.

2. Airborne LiDAR survey

In the last ten years techniques of Airborne LiDAR have been developed and experimentally applied in land surveying and mapping since they provide notable advantages over traditional survey techniques in Taiwan. Establishing a national spatial database of high resolution DEM and DSM is very important for all phases of disaster management cycle, from preparedness to response, to recovery, and is a foundation for national land preservation policy.

From the beginning of the project, there have been multitudes of difficulties to overcome, such as: (a) 4 different survey teams with different airborne LiDAR scanning sensors with unequal experience level, (b) chronic shortage of aircrafts, (c) flight plans requiring immediate approval, (d) frequent heavy clouds unsuitable for executing aerial survey, (e) densely developed urban and heavy forest coverage, (f) establishing surveying protocols and a strict, nearly automatic review process, (g) complicated terrain relief conditions, (h) matching of margins of survey blocks of DEM,DSM and digital aerial photograph, (i) scheduling constraints for carrying out the project.

Here, I shall focus on the survey plan, specifications, and the major challenges we are still facing.

2.1 The survey plan

Map tiles of survey plan are the basis of the frames of a large-scaled national map of scale 1:5,000 series. As shown in Fig. 1, the small rectangles on the map are the tiles of a 1:5,000 map-sheet with an area of around 7 square kilometers. In total, 5,519 tiles with 37,603 square kilometers (including parts of sea area) are to be completed in six years. The typhoon Morakot disaster area was divided into 10 survey blocks and the remaining area sub-divided into 12 survey blocks; surveys would be conducted by four local companies. Each year a survey team had to complete from 2,500(in Morakot disaster area) to 1,000(remaining area) square kilometers. In addition, another 1,600 square kilometers would still need to be surveyed in the events of typhoon, severe rainfall, or earthquake.

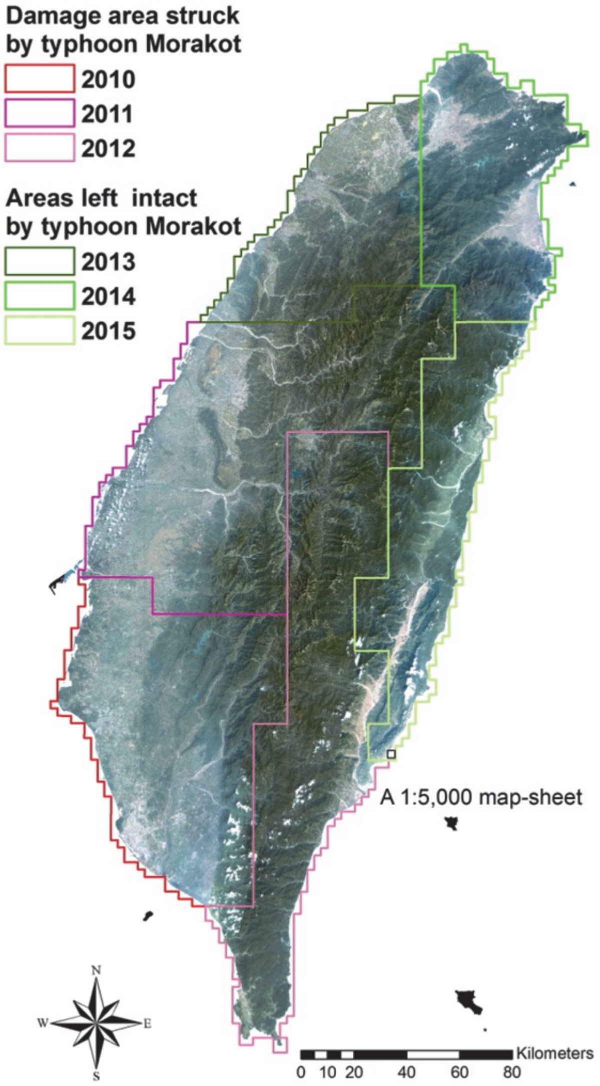

Fig. 1 LiDAR survey plan in 2010-2015 of Taiwan .

For this project, the LiDAR scanning sensors including Leica ALS70-HP, Riegl LMS-Q680i, ALTM Pegasus, and Leica ALS60, belonged to 4 different companies. For digital aerial photograph, they used DMC, AIC pro P65+, IGI DigiCAM, Dimac Ultralight 60MP+, Trimble Aerial Camera P65+cameras for this national survey project.

Quality assurance was assigned to a team organized by a survey professor. Team members were put in charge of maintaining the quality of LiDAR and digital aerial photograph results, monitoring the whole process and verifying the results of each survey team. Also, quality assurance team assisted the survey teams in resolving unexpected events, completing quality checkup manuals, providing instructions and updates of the inspection procedures. Lastly, it designed at least 20 check-list tables for different processed results; some of them were checked automatically by computer programs. The supervision and examination of the case for the LiDAR measurement system, included in the high resolution LiDAR DEM Generation QA/QC in Taiwan for the first time, has been very successful. We believe that this is the key procedure for the completion of the survey plan.

2.2 Specifications

Although airborne LiDAR have been developed at least ten years in Taiwan, many issues still remain for further discussions when applied to the entire island. Deliverables, flight parameters, and the major challenges, included in the specifications of this LiDAR survey will be discussed here.

2.2.1 Deliverables

In addition to interim and final reports, three major deliverables are required for this LiDAR survey: (a) LiDAR point clouds, (b) Synchronous colour aerial photographs, (c) Digital Terrain Models.

For LiDAR point clouds, classified point clouds were the main issue to be considered. An area of small block representing a map unit of 1:5,000 map-sheet was used for point cloud editing. One of the four classes should be assigned to each point, namely outlier, water, ground, and others. Outliers including low points, high points, and other possible noises should be identified and filtered before going further for other point editing. Water points should be assigned to all points that fell on water-bodies as interpreted by ancillary information such as colour aerial photographs. Intensive manual editing was required to further distinguish ground points and others. Classified point clouds should be delivered by data files of map-sheet with nomenclature of 1:5,000 national map series.

Synchronous medium format colour aerial photographs were required with the laser scanning. Exterior orientation parameters of each frame of aerial photographs had to be estimated by direct geo-referencing and control points as applied to raw LiDAR strips. Orthophotos with a GSD of 0.5m should be generated and delivered along with the medium format aerial photographs. Because colour aerial photographs and airborne LiDAR needed different sky conditions to fly, the results were solved by increasing new flight strips for survey team. Different colour or tone of the aerial photographs could be confusing, until the quality control team could define a standard sampling.

One meter grid of DEM and DSM were the two most important products to be delivered in this project because they would be used by geologists for geohazard interpretations. Both DEM and DSM were measured at 1m grid resolution. DEMs at 1m grid was interpolated from ground points whereas DSM from all points was filtered out of all outliers and water points.

2.2.2 Flight parameters

Flight plans would be checked by the quality control team and approved by the authorities (to avoid flying over military base). The technical parameters for flight plan included: (a) Point density should be at least 2 points per m^2 in an above-mean-sea-level elevation below 800m and at least 1.5 points per m^2 above 800m. (b) Point density should be more than 2 points per m^2 in an mountainous areas with settlements for geoharzds analysis, using more denser flight strips or full-wave form technique to increase ground points if needed, (c) Normal flight lines should be parallel with at least 40% overlap, (d) Cross flights perpendicular to normal flights were required every 20km, (e) The FOV scanning angle should not exceed 40 degrees, (f) Two ground control GPS stations should be installed in a distance less than 20km to the airplane for a flight mission. The GPS receivers should be dual-frequency.

2.3 The major challenges

Weather and terrain relief conditions were the two fateful issues limiting the execution of the project. Other problems were of lesser consequences, compared with these two natural issues.

2.3.1 Weather conditions

Air sortie for data collection was dependent entirely on weather conditions. Survey areas were located at latitude from 21 to 25 degrees in tropical and subtropical zones. The sky was cloudy most of the time all year long, which made data acquisition difficult and imposed additional requirements for re-flight to fill the cloud gaps. Fig. 2 shows the statistics of de-facto flight hours of a survey plane for aerial photography in the second half from years 2007 to 2009. Normally there were at least 240 hours of day-light time in a month. But, we were only able to log 68 hours of flight time in August of 2008. In overall average, there are only 30 hours of flight for a month, and only 200 hours for a year. Some specific southern mountainous areas of Taiwan have clouds over the sky over the years, according to the past ten-years aerial photograph records. The 4 survey teams installed some CCTV stations in the key locations of the surveying areas to observe the increment weather patterns in real-time in these unfavorable conditions.

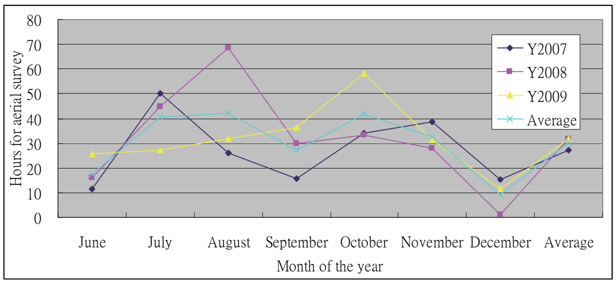

Fig. 2 Statistics of flight hours of a survey plane from 2007 to 2009, showing that most of the time the sky is not suitable for aerial photography.

2.3.2 Terrain relief conditions

Terrain relief herein with is defined as the altitude difference within one kilometer grid, which is approximated by a swath of LiDAR scans. Taiwan is a mountainous island with its highest point of Central range, Yushan, at 3,952 meters above sea level. Mountains account for 30% of its total area, hills and plateaus for 40%, and plains for the remaining 30%, and there are more than 100 mountains higher than 3,000 meters. The valleys are very narrow, steep and deep, in mountainous areas, that increases the difficulties of airborne LiDAR and aerial photography. In this high relief area, MPiA(Multi-Pulse in Air) mode cannot be applied to give a higher density and the spacing of flight lines has to be closely distributed. Using the multi-angle laser scanners or increasing flight strips from different incident angle may raise the airborne LiDAR penetration rate and add effective ground points.

In addition, human factors such as limitations due to national security, air traffic clearance, and military training all increase the difficulties of execution. Military facilities or establishments are always forbidden to be mapped by high resolution aerial sensors operated by civilians. In the beginning, it would take two to three months to obtain a survey permit before any aerial operation could be conducted. The limitation due to national security requirement was necessary. As shown in Fig. 1, the widest distance stretching east to west of Taiwan is only 144km. Therefore, the sky is too crowded to allow many airplanes in the air at the same time. In addition, military training has the top priority. In some areas, only weekends are available for civilian aerial survey. On Aug 30, 2012, an airplane crashed while executing the project in the eastern, mountainous areas, causing three crew members to lose their lives, the saddest event for this project.

The key for success of the project may be attributed to the monthly meetings. Four LiDAR survey teams and one team for quality check were invited to attend the meeting. CGS hosted monthly meetings to monitor the progress of all parties. Flaws found by the third party team and issues encountered by all four survey teams were raised for discussion. Experiences were shared. Some experiences were translated into survey parameters as for renewed regulation. Finally, all the participants cooperated to make it a success of such a challenging project.

3. Applications in geological Aspects

The understanding of a country's geomorphological and geological conditions is essential for combating and responding to natural disaster. In the years 2005 to 2011, CGS mapped active faults, volcanic and other geological features of northern Taiwan by using DEM extracted from airborne LiDAR point-clouds. Although this mapping project was very successful, only 5,400 square kilometers DEM mapping was completed in seven years. To establish the datasets of DEM, DSM and digital orthoimages of the whole island were very important, and applications with these high resolution data of terrain to mitigate future natural disaster were urgent for the authorities in the aftermath of the Morakot disaster in 2009. As Professor Paolo Tarolli(2014) pointed out: the limits of using high-resolution DEM, did not directly represent geology, and applications to geologically complex areas might be difficult. We believe only agency such as CGS, has the capability and responsibility for both air surveying and geological interpretation missions.

3.1 Large-scale landslide

Shiaolin Village became the focal point, nationally and internationally, immediately after Typhoon Morakot stuck. The press media wanted to know why we couldn’t have predicted or prevented this kind of disaster. The public wanted to know who should be held responsible for this tragedy. The experts and scholars wanted to research the mechanisms of this gigantic and devastating landslide. In the mean time, we learned that the Japanese government had published a map of “deep-seated landslides in Japan” in recent years. To our regret, we could not even identify this kind of landslide at the time. In the past, we at CGS focused our attention mostly on the shallow landslide, slow moving landslide, and rock fall etc. The main reason was attributed to the lacking of high resolution datasets of terrain. So the first priority of the application with the datasets was to identify the large-scale landslide by the results of new nationwide DEM from year to year.

Definition and a universal scientific name were the first issue to be decided. Although there had not been any consensus until now, we recommended 10,000 cubic meters in volume and 10 meters in depth as a definition for reference. Considering human life, the safety of inhabitants in the disaster-prone areas would be the only exception to the above-mentioned definition. For the official disaster reduction agency, NCDR(National Science and Technology Center for

Disaster Reduction) has a different definition, it would only consider the critical human infrastructure, disaster-prone areas, and the landslide disaster magnitude etc. affected by large-scale landslide and other triggered disasters.

Because recognition of areas where large-scale landslides may occur has become a critical issue for landslide hazard mitigation for the government and for the people living in mountainous areas of Taiwan, zonation of large-scale landslide potential areas as soon as possible became our agency's duty. Geologists have adequate knowledge of geomorphology and geology to identify large-scale landslide both in the lab and in the field. So, compiling a detailed and constantly updated inventory map of large-scale landslide was the first step of this strategy.

For large-scale landslides, detection and characterization are the most important task before any mitigation measure can be taken or any inference of landslide kinematics and mechanics can be made. After Shiaolin Village disaster and similar landslides occurred in other countries recently, many researchers have paid more attention to this issue from different aspects such as identification, investigation, characterization, monitoring, simulation, hazard assessment, risk evaluation, warning etc. Only the issues of identification, investigation, monitoring will be presented and discussed in this paper.

Although automatic and objective method has been developed, based on the use of thresholds obtained by the statistical analysis of variability of landform curvature (Lin et al., 2013). For example, introducing simple topographic indexes of surface roughness enables the automatic mapping of landslide morphology and estimation of landslide activity, providing a preliminary landslide inventory map (Paolo Tarolli, 2014). But traditional expert-based method is mainly used for the detection of large-scale landslides in this national program. Surface topography indicative of past large bedrock landslides is very common in certain landscapes. In some areas large-scale landslides have transformed steep, high relief topography into lower-relief and lower-gradient topography, thereby reducing the occurrence of shallow failures in the affected areas. Unlike incipient shallow landslides in bedrock hollows, large-scale landslides often show signs of instability such as crown cracks, scarps, tension cracks, transverse ridges and tipped trees. Because most of the large-scale landslides are either latent or located under forest cover, only a few of them which are in creeping or newly-happened in a catastrophe can be identified in the past, but from DEM-derived shading map and aerial photography are much easier to recognize. The merit of this new technology is obvious. Glenn et al. (2006) demonstrates that high-resolution topographic data have the potential to differentiate morphological components within a landslide, and they can support the analysis of the material type and landslide activity.

Together with the identification results, landslide inventory and the geological map, checking in the field is the second step. Excepting for discontinuities, such as bedding plane, foliation plane, faulting structure, folding structure, and joint sets, creeping and buckling are the two kinds of important deformation phenomena associated with potential large-scale landslide in the argillite, slate formation, and also sedimentary rocks easily observed in the field. For example, Shiaolin landslide has very typical buckling deformation observed by Tsou et al.(2010). The most difficulty is differentiating the fissure, fracture, uplift, bulging, depression, opening all observed in the hillslopes, roads, retaining walls etc. as a result of large-scale landslide or shallow landslide. We presume that high-potential shallow landslide will trigger large-scale landslide as a key block in the future and a large-scale landslide consists of many shallow landslides in a delineated area. For the time being, we mark all the signs in the map as the preliminary results and will collect more information from further investigation activities.

Traditionally, there are many commercial monitoring devices installed in the field, such as rain-gauge, observation wells with piezometer, inclinometer, extensometer both in the ground surface and borehole are very common for landslide monitoring. And innovative new adequate devices such as "Multiple-borehole extensometer" , "wireless extensometer" and "SAA(Shape Acceleration Array)" , utilized for the observation of large-scale landslide activity are necessary. Also we have constructed a network of single-frequency GPS for measuring a single large-scale landslide for surface displacement.

The above-mentioned innovated monitoring techniques are still in prospective state, needing more time and data to verify its valuation.

For this six-year project, we selected an area covering 100 map-sheets of scale 1:5,000 with total area of around 700 square kilometers for detailed field investigation each year. These selected areas may take into account already existing protective structures, such as houses, public buildings, villages or traffic constructions etc. which located in the low-relief slopeland or high-relief mountainous areas, all considered highly geologically sensitive for natural hazards. The safety assessment of the first three years, in the severe damaged areas caused by typhoon Morakot, included 403 villages in the area 2,100 square kilometers. 469 large-scale landslides with total area of 3,155 hectre acres were identified (Fig. 3), and about 56 of them close to 42 villages. Within 42 villages, 45% of them were evaluated as dangerous and threatened by nearby large-scale landslides, 38% of villages were ranked as safe in specific conditions, and the remaining 17% considered safe. But when we delineated the potential large-scale landslide areas without consideration of the villages and the traffic constructions factors, we estimated about 1,607 large-scale landslides with total area of 532.42 square kilometers which covered an area about 4,980 square kilometers. Roughly speaking, that was about 10% of the assessed areas with large-scale landslide susceptibility in the slopeland or mountainous areas in Taiwan. The above mentioned results would be used to evaluate the geological susceptibility of the whole island and to mitigate reoccurrence secondary hazards in the future.

3.2 Active fault

Taiwan is situated on an active orogenic belt and possesses high seismicity and frequent active fault hazards. More than 9 severe inland earthquakes have been recorded since last century. The morphotectonic analysis provides not only the precise location and the activity of the faults, but also the fundamental information for geological hazard assessment in some cases. To better constrain the potential threat brought by fault movements, the active faults morphotectonic study has thus been analyzed by using the Airborne LiDAR data. In 4 years (2011-2014), we analyzed the morphtectonic features of 33 active faults in total, read more tectonic deformation information from topography, defined the fault zone more precisely, and understood better the characteristics of each fault. At the end, we reached the following objectives, results and conclusions: (a) generation of 3D anaglyph images, (b) analysis of detail structural characteristics, (c) digitization of the fault traces of active faults and their associated structures, (d) evaluation and modification of the strip geological map (2 kilometers wide of each fault) within the study area, and (e) generation nearfault 3D geological anaglyph images. The results might suggest some possible sites for field investigation and provide GIS dataset for other further applications

3.3 Geohazard analysis after typhoon Morakot disaster

CGS has completed a series of environmental geological map of scale 1:25,000, the maps included: (a) Lithological assemblage map, (b) Rockmass strength map, (c) Environmental geological map, (d) Landslide susceptibility map, a nine-year project (2002-2010) before typhoon Morakot. The information provided with fundamental dataset for experts to analyze the environmental potential geological risks for a site and also provided recommendations to the authorities to minimize and/or mitigate secondary natural disaster impacts.

After typhoon Morakot, we established a new landslide inventory map and will continue to renew the geohazard datasets by the interpretation of new LiDAR images and other ancillary information. The results of geohazard mapping should include: (a) geological structures, (b) landform change of river beds, river terraces, and river channels, (c) landslide features, (d) high landslide vulnerable zones, and (e) detailed mapping and assessment for selected areas near mountainous settlements. One result of this part is map-sheet of scale 1:25,000 to include: (a) Geologically Sensitive Area Map, (b) Geohazards and Susceptibility Map, and (c) Geohazard Map of Key Area Survey.

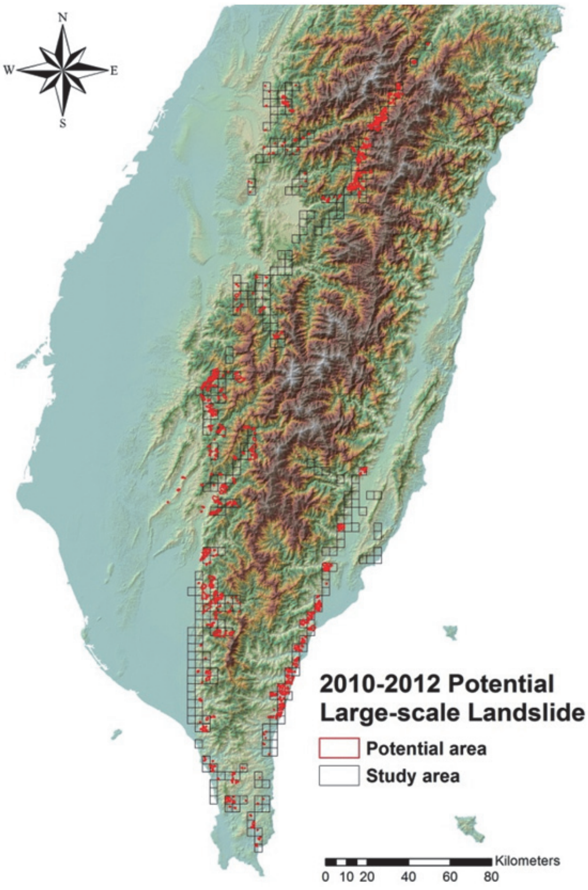

Fig. 3 The distribution of potential large-scale landslides in middle and southern Taiwan.

On Dec. 1, 2011, Taiwan enacted the Geology Act, it might be the first law to govern the geology investigation in the world. The purpose of this Act is to improve the geological survey system, to effectively manage geological data of national land, and to establish basic geological information related to changes in the nation's environment and to enact land resources management. According to the Act, the authority shall publicly announce areas with special geological scenery, special geological environments, or potential geological hazards to be geologically sensitive areas. One kind of the geologically sensitive areas is Landslide-Landslip Geologically Sensitive Area, which means the areas with landslide history or high susceptible sliding conditions. The identification of potential large-scale landslide, sliding-affected area, and dip-slope were evaluated from LiDAR-DEM data, combined with other geological database to delineate the Landslide-Landslip Geologically Sensitive Area. To date, delineation and publicly announcement of Landslide-Landslip Geologically Sensitive Area is 13,693 square kilometers, close to 38% of Taiwan territory. Almost 50% of population shall incorporate data pertaining to geologically sensitive areas for reference in land utilization plans, land development reviews, hazard prevention and mitigation, environmental protection, and resource development in the future.

4. Summary

Thus far, we have applied the high-resolution LiDAR topographic datasets only in small portions of earth science applications, mainly in large-scale landslide detection and active fault analysis. Although it has its limits of applications, it has the potential to solve the research problems especially in densely forested areas and also in densely-populated urban areas. As Paolo Tarolli (2014) pointed out: such analysis would help in scheduling appropriate environmental planning for sustainable development, to mitigate the consequences of anthropogenic alteration and, of course, to better understand the evolution of our Planet. So we are looking forward to opening more avenues for researches relating to earth surface processes based on geomorphic signatures. Also we are planning a second phase of National LiDAR program in the near future to establish the renewed dataset in terrain information for sustainable land preservation purpose.

References

Glenn, N.F., Streutker, D.R., Chadwick, D.J., Thackray, G.D., Dorsch, S.J. (2006): Analysis of lidar-derived topographic information for characterizing and differentiating landslide morphology and activity, Geomorphology, Vol. 73, pp. 131–148.

Lin, C.W., Tseng, C. M., Tseng, Y. H., Fei, L. Y., Hsieh, Y. C., Tarolli, P. (2013): Recognition of large scale deep-seated landslides in forest areas of Taiwan using high resolution topography, J. Asian Earth Sci. Vol. 62, pp. 389–400.

Slatton, K.C., Carter, W.E., Shrestha, R.L., Dietrich, W.E. (2007): Airborne laser swath mapping:achieving the resolution and accuracy required for geosurficial research. Geophys. Res. Lett. 34, L23S10. http://dx.doi.org/10.1029/2007GL031939.

Tarolli , P. (2014): High-resolution topography for understanding Earth surface processes: Opportunities and challenges, Geomorphology, Vol. 216, pp. 295–312.

Tsou ,C. Y., Feng, Z. Y., Chigira, M. (2011): Catastrophic landslide induced by Typhoon Morakot, Shiaolin, Taiwan, Geomorphology, Vol. 127, pp.166–178.