The application of information technology in managing landslide risk

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Abstract

The Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department has been using Geographic Information System (GIS) since the early 1990s, to collate the vast amount of geospatial datasets and manage landslide risk in Hong Kong. Conventional GIS functionality have focused on correlating geospatial datasets and data mining for hidden patterns. Over the years, GEO has developed applications based on such conventional GIS functionality, including dissemination of geospatial data (e.g. the Slope Information System and the Geological Modelling System), production of cartographic maps, management of geospatial datasets and emergency preparedness. In recent years, there are several novel advances in information technology, which will bring new capabilities to GIS and have potential applications for managing landslide risk. These include location-based applications equipped with Global Positioning System, objects recognition and change detection based on remote sensing techniques and three-dimensional virtual reality simulation. Besides adapting to these new technologies, GEO is also actively developing applications that integrate GIS with physical laws and engineering principles. This paper presents GEO's efforts and experience in using information technology in managing landslide risk in Hong Kong and the way forward in promoting GIS applications to geotechnical practitioners.

Keyword: information technology, landslide risk, geographic information system.

Introduction

Hong Kong, a vibrant city and a leading economy in the region, has a population of more than seven millions. It is not difficult to imagine the extremely high demand on developable land. Unfortunately, Hong Kong does not have abundance of flat land and more than 70% of the land in the territories is on hilly terrains. Reclamation on the coastal front and land formation on the hillsides (Figure 1) have been the conventional methods in finding suitable land to meet the rapid economic and population growth. As a result, a substantial amount of building developments and infrastructures is located close to or near man-made slopes and natural hillsides. Hong Kong has a subtropical climate and the average annual rainfall exceeds 2000 mm. Majority of them is falling in the summer, which comes along with tropical typhoons and low-pressure troughs. On a wetter year, the annual rainfall record could reach 3000 mm. These, together with the tropically weathered ground conditions, lead to a high occurrence of landslide events and pose a significant landslide risk to the community and geotechnical constraint to developments.

Figure 1 – Reclamation and land formation in hillsides

The Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) is entrusted with the responsibility of regulating the investigation, design and construction of geotechnical works in Hong Kong. The GEO implements a comprehensive Slope Safety System (Chan, 2000) to meet these obligations. As part of the works, a lot of data relating to the ground conditions and slopes are collected, analysed and correlated. Examples of these include the compilation of geological maps, slope catalogue, landslide locations, terrain model, rainfall records, etc. The collection of some datasets relies on the use of information technology, such as remote sensing and digital photogrammetry, real-time monitoring system. These data have one common attribute, which is their spatial position. On the other hand, these geospatial datasets are usually colossal in volume. These have made Geographic Information System (GIS) particularly suitable and attractive to the GEO in managing, manipulating and correlating these geospatial datasets, in order to find hidden patterns and give a better understanding of slope safety problems.

The GEO has been using GIS since 1990. The Fill Management Information System was among the first GIS developed to manage the marine fill resources and disposal pits within the territories (Selwood & Whiteside, 1992). Since then, a number of GIS-based information systems have been developed to provide services to the community. The Slope Information System (SIS) supports the management of more than 57,000 man-made features registered in the Catalogue of Slopes. Part of the information in the SIS can be accessed by the public through the Hong Kong Slope Safety website, which serves as a focal point to promote public awareness on the maintenance of man-made slopes. The Geological Modelling System consolidates the datasets on geology, boreholes and terrain elevation models. This information system is restricted to internal users and consultants working on government projects.

There have been significant advances in information technologies that are applicable to geotechnical works. Technological developments in digital photogrammetry, remote sensing, wireless transmission, location-based services and the continuous evolution of geographic information science have already made some positive impacts on the approaches in managing landslide risk. However, this will not be possible without a substantial reduction in the cost of owning such capabilities. The computational power of a workstation has greatly increased amid a reduction in price. There is also a significant drop in the cost of the software, such as satellite images and software analysing them. These advancements have made information technologies more readily accessible to geotechnical practitioners. Some examples of using information technologies in geotechnical application in GEO are illustrated in the following systems and applications.

Landslip Warning Systems

The GEO operates the landslip warning system in collaboration with the Hong Kong Observatory (HKO). The warning system is a major component of the Slope Safety System, which is to warn the public the landslide risk at times of heavy rainstorms. The public is advised to take precautionary measures when such a signal is in effect, e.g. staying at home and away from dangerous slopes. It is evident and well established that landslides in Hong Kong are closely related to rainfall intensity (Brand et al, 1984; Pun el at, 2001; Yu et al, 2003). An effective warning system is therefore dependent upon a representative correlation between landslides and rainfall intensity and the capability of predicting when the prescribed rainfall intensity is reached. This requires monitoring the rainfall on a real-time basis and predicting the rainfall ahead, so as to give adequate lead-time for preparing emergency responses.

A network of 110 raingauge stations is installed throughout Hong Kong, of which 86 raingauge stations are operated by the GEO. The HKO and the Drainage Services Department are responsible for the remaining 24 stations. The GEO raingauges are fully automatic and record in a data logger the rainfall magnitude at every five-minute interval. Each raingauge station comprises a tipping bucket, a data logger and solar panel with a rechargeable battery (Figure 3). When fully charged, the battery can power the data logger for about 18 consecutive days without sunlight. For security consideration, the five-minute rainfall data from all raingauge stations are transmitted to a centralised server operated by the network service provider for integrity checks. This is then forward to the GEO raingauge control centre. The rainfall data are simultaneously shared between the HKO and Drainage Services Department.

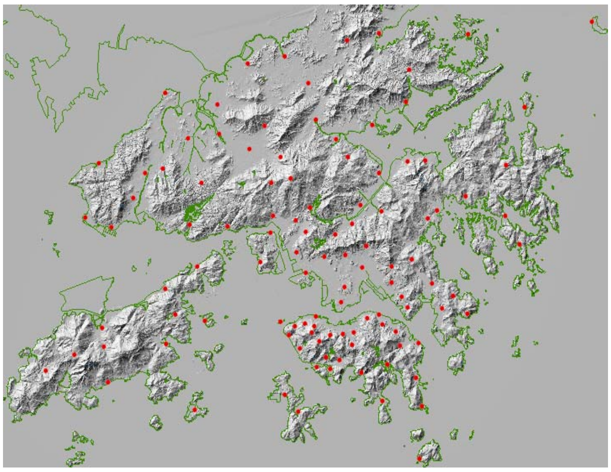

Figure 2 – Location of automatic raingauge stations in Hong Kong

Figure 3 – Typical set up of a raingauge station

Last year, the GEO has switched the connection of 65 raingauge stations from dedicated fixed data lines to a wireless mobile network based on general packet radio services (GPRS). The GPRS mobile network provides a connectivity solution based on Internet Protocol and transmits data in packets. The data logger and the network are always connected. In case of disruption, the GPRS modem will automatically scan for available channels and re-establish the connection. Such high immediacy of data transmission makes GPRS suitable for this time-critical application.

The wireless technology eliminates the need for cabling works and reduces the cost of the installation. This is particularly suitable for installing raingauge in a remote site, provided that there is network coverage in the area. The GPRS system is more cost-effective than dedicated data lines, possibly due to strong competition amongst service providers. In general, a saving of about 60% in monthly subscription fee has been achieved after switching 65 raingauge stations to GPRS. The reliability of data transmission using GPRS connection is very good. The rainstorm in August 2005 was the first major rainstorm after using GPRS. The success rate of acquiring the rainfall data in real-time was close to 99%. When real-time rainfall data is uploaded to the GEO control centre, the data are analysed and disseminated in designated workstations.

Another groundwork for the landslip warning system is to establish the correlations between landslide frequency and the rainfall intensity. GIS had been used to determine the spatial distributions of maximum rainfall and landslides at various durations for major rainstorm events since 1984. In this correlation model, the spatial relationship between landslide frequency and rainfall intensity is established for different types of slope features, e.g. cut slopes, retaining walls and rock slopes (Figure 4).

In the landslip warning system, the territories are partitioned into 1600 cells. The number and types of slope features in each cell are determined using GIS analysis. The real-time rainfall data for the past rolling 21-hour period and the predicted rainfall in the next three hours are summed before being discretized into 1600 cells (Figure 5). These values, together with the landslide frequency for each type of slope features and the number of slope features in each cell, are multiplied together to give the predicted number of landslides. This predicted number is a key factor that GEO and HKO will take into consideration when deciding the issue of landslip warning signal.

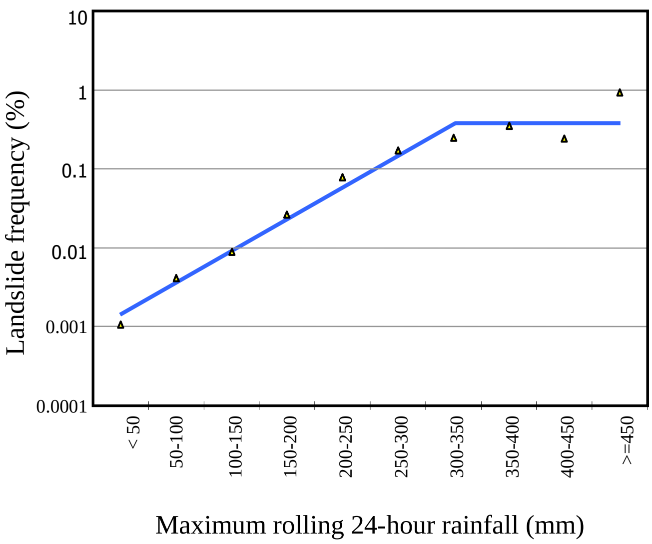

Figure 4 – Landslide frequency for soil and rock cut slopes

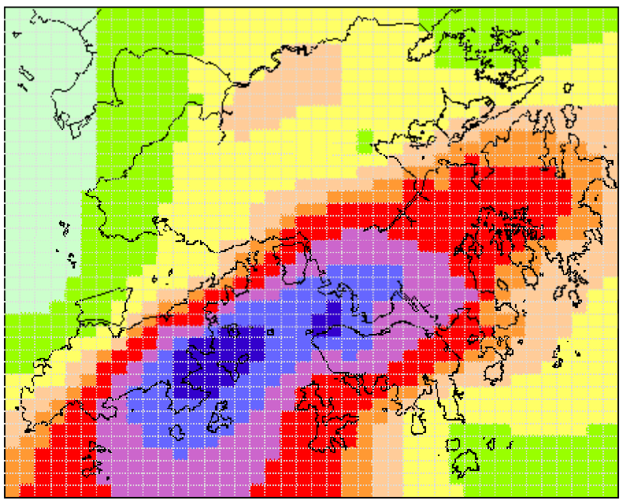

Figure 5 – Real-time rainfall data and predicted rainfall in a rolling 24-hour period are discretized into 1600 cells

When establishing the correlation between landslides and rainfall intensity, GIS modelling offers a unique capability for data mining hidden patterns between landslides and rainfall intensity. The GEO also exploits the GIS technology in improving the correlation between landslides and rainfall intensity. Ko (2003) used GIS modelling and statistical analysis in establishing a correlation between landslides in natural terrain and rainfall (Figures 6 & 7). The results of GIS modelling and analysis had revealed the importance of other attributes, such as terrain characteristics and susceptibility, and orographic effects in the landslide and rainfall correlation. Such relationship cannot be easily examined using conventional method.

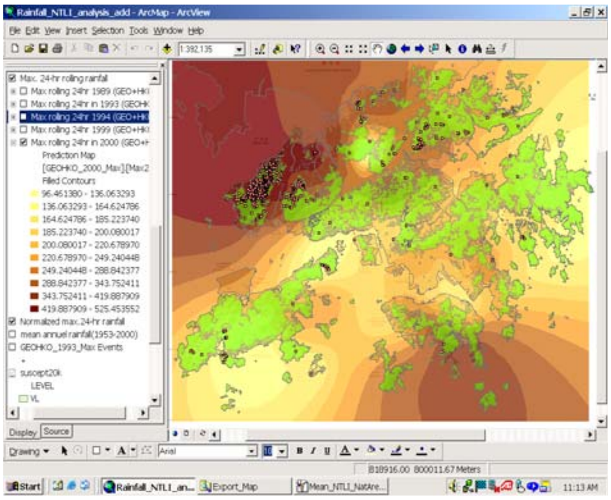

Figure 6 – Spatial analysis of rolling 24-hour rainfall and landslides in natural terrain

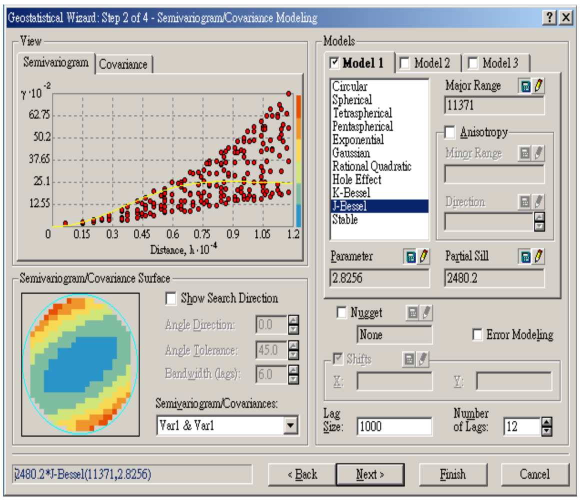

Figure 7 – Correlation of spatial distribution of rainfall based on statistical analysis

Surface Profiling by Light Detection and Ranging (LIDAR)

Light detection and ranging (LIDAR) is a remote sensing technique for determining a surface profile. The method relies on measuring the direction and time of sending and receiving coherent laser beams to the objects surveyed. The LIDAR can produce a high-resolution image of the surface surveyed with a very high accuracy. Its applications in slope engineering include the construction of a digital terrain model, movement monitoring for slopes and structures and mapping of rock joints. This technique has applications in other fields, such as environmental and meteorological monitoring. The Hong Kong Observatory has installed a LIDAR-based radar in the Chek Lap Kok Airport to detect and alert pilot of low-level wind shear in the runway.

The CEDD has acquired two high-accuracy LIDAR laser scanners. The laser scanner can measure the surfaces of an object within about 150 m with a positional accuracy of 6 mm in 50 m range. It has been used in topographic survey and is particularly suitable for sites where physical access is difficult or dangerous, e.g. a rock slope or a landslide scar (Figures 8 & 9). The laser scanner sends out thousands of laser pulses in a second and the reflected signals are processed and assembled as an array of point clouds in the three-dimensional space. The point clouds can be further transformed to a three-dimensional object. Such technique has been used in the monitoring of a gabion debris barrier (Figure 10) constructed in Tuen Mun. The gabion debris barrier was surveyed by the laser scanner and its shape and position is represented by millions of cloud points (Figure 11). However, it would not be practicable to monitor the movement of these cloud points. The skeletal frame of the gabion barrier was extracted and the key points in the frame were chosen as the reference points for movement monitoring.

Figure 8 – Topographic survey of a rock slope with difficult access

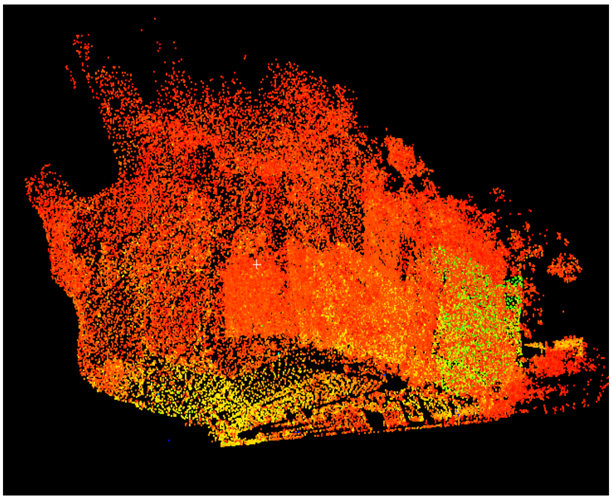

Figure 9 – Surveyed rock surface shown in three-dimensional point clouds

Figure 10 – Gabion debris barrier

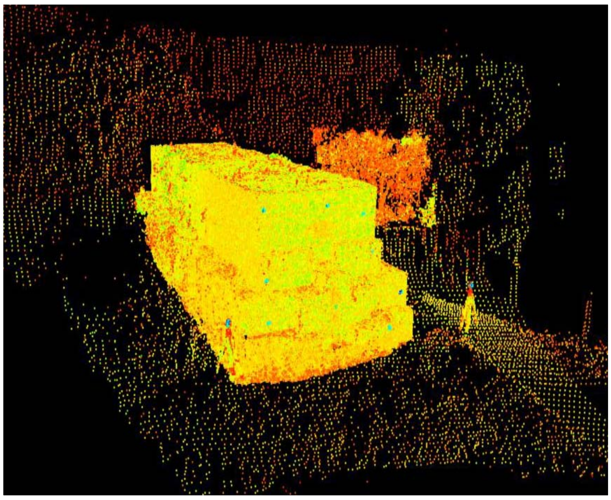

Figure 11 – Gabion debris barrier shown in three-dimensional point clouds

Airborne LIDAR mapping can provide more comprehensive and precise topographic features than other conventional methods, such as aerial photographs interpretation and digital photogrammetry. The LIDAR scanning device is mounted at the bottom or sides of an aircraft flying along selected parallel flight paths (Figure 12). The instrument is bundled with an onboard differential global positioning system and an inertial navigation system to locate accurately the position of the aircraft. The information, together with the orientation of the scanning mirror for firing the laser, can compute the geodetic reference of the objects scanned. The digital elevation model can typically be constructed with an accuracy of ±0.15 m in vertical height.

Modern airborne LIDAR scanner measures multiple returns for each laser pulse. A typical laser pulse covers several feet in diameter. Part of the laser pulse will bounce off from tree branches or foliage at several levels and the remainder from the ground (Figure 13). Sophisticated algorithms can filter the multiple returns and determine the time for the last return of laser pulse. The last signal return is more likely bounced off the ground surface.

This capability is important when trying to map the ground topography beneath heavy vegetation and identify salient features in the ground, e.g. ground disruption and displacement. Significant ground movements in hillsides had been discovered and reported to the GEO in past rainstorm events. However, these salient features may not be easily identified from aerial photographs (Figures 14 and 15). The GEO is arranging a pilot study of mapping the southern part of the Hong Kong Island using airborne LIDAR technology. The digital terrain model compiled from the LIDAR mapping could reveal presence of ground displacement in hillsides. This study also provides an opportunity to examine the potential application of airborne LIDAR in assessing landslide risks in hillsides.

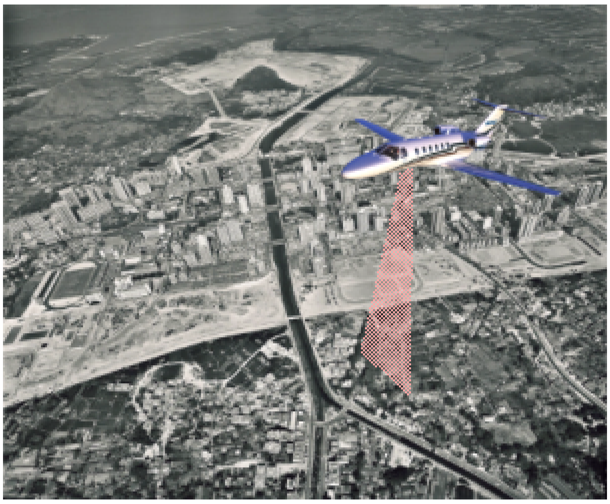

Figure 12 – Airborne LIDAR mapping of topography

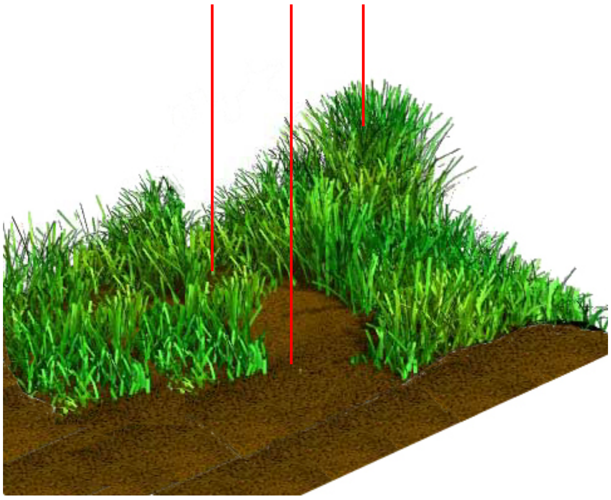

Figure 13 – Multiple reflections of a laser pulse from foliage and ground surface

Figure 14 – Aerial photograph taken above a displaced landmass in hillside

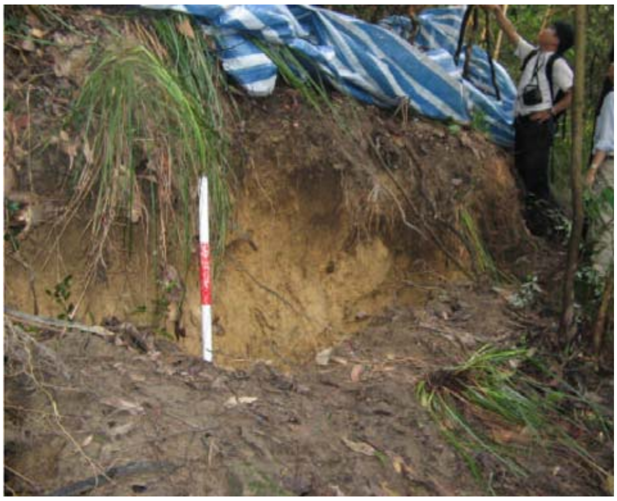

Figure 15 – Displaced landmass revealed in site inspection

Interferometric Synthetic Aperture Radar

Synthetic Aperture Radar Interferometry (InSAR) is a remote sensing technology that could measure the surface elevation and ground displacements. The radar satellite (e.g. ERS-2, RadarSat, EnviSat, etc) shoots the earth with electromagnetic radiations, which are propagating transverse oscillating sine waves of electric and magnetic field. The satellite records the strength, the phase and time delay of the reflected signals to produce a synthetic aperture radar (SAR) image of the ground (Figure 16). In principle, the phase of the returned signal depends on the travel distance of the electromagnetic radiation. By subtracting the phase difference between pairs of SAR images of an area, the surface elevation can be evaluated and an interferogram image produced. The surface elevation is represented by fringes of differing grey level intensities. Adjoining fringes with the same grey level can be visualized as contour lines of same elevation. In principle, the phase difference should remain constant every time the satellite revisits the same location if there is no ground movement occurred during the observation period. The differential interferometry technique uses SAR images obtained over an observation period and subtracts the phase difference between images. The fringes that relate to common topography will be eliminated so that the remaining fringes represent only the difference in the topography, which is the displacement of the ground.

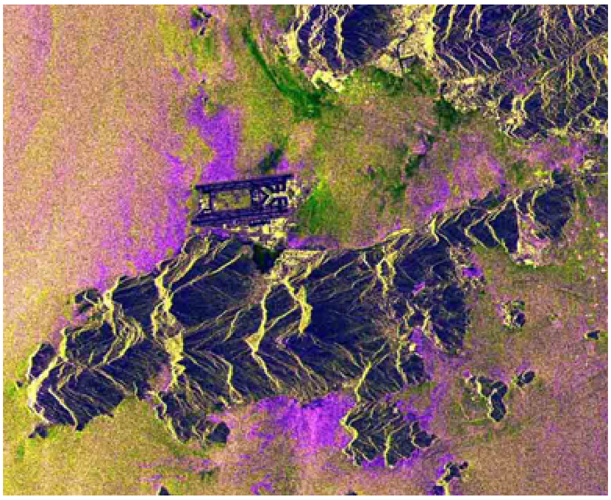

Figure 16 – SAR image of the Lantau Island in 2004 (Image: ESA/EnviSat)

The InSAR technique has been successfully used in monitoring crustal movement induced by earthquake, volcanic activities and ground subsidence (Massonnet et al 1993; Lu et al, 2002; Fielding et al, 1998). Applications on monitoring slope movement and landslides by InSAR have also been reported (e.g. Strozzi et al, 2001; Singhroy et al, 2005). In collaboration with the Hong Kong Polytechnic University, the GEO had completed a trial application of InSAR for detecting slope movement and ground deformation at four sites in Hong Kong (Ding, 2004). The trial study noted the current constraints of applying InSAR in the urban setting of Hong Kong. These include the availability of InSAR images with low Doppler centriod frequency shift and good coherence, the low-resolution of the SAR images. InSAR results can also be seriously affected by geometric distortion, atmospheric effects and temporal decoration of the ground surface, e.g. variation of vegetation covers in different seasons (Wong, 2004).

As InSAR technology continues to improve and evolve, some of these constraints will be resolved. The quality and availability of SAR images will be enhanced with the launch of modern and advance satellites (e.g. EnviSat). Filtering technique has also been improved and has the potential to use earlier SAR images with lower coherence as baseline images for comparison. In collaboration with the Hong Kong Polytechnic University, the GEO has installed corner reflectors (Figure 17) at three sites over the territories. These reflectors will be strongly illuminated in a SAR image and are useful in calibrating future SAR images of

Hong Kong. The GEO is acquiring latest SAR images and will examine further the potential application of InSAR in Hong Kong with these improvements.

Figure 17 – Corner reflector in Tseung Kwan O

GIS Modelling

Conventional GIS applications have focussed on asset management, data manipulation and information dissemination. The GEO has developed a number of information systems for these purposes (e.g. Fill Management Information System, Slope Information System and Geological Modelling System). These systems provide simple GIS searching and browsing functionality to interact with the geospatial data available in GEO. The system can be launched in a web service framework or in a desktop client-server platform. Besides these conventional applications, the GEO has been using GIS to carry out sophisticated spatial analysis to examine the relationship and correlations between various geospatial data, so as to identify any hidden patterns and important factors that will influence the occurrence of landslides events. Such a technique has been commonly used in landslide susceptibility analysis in hillsides (Figures 18 & 19) as part of the natural terrain hazard study (e.g. Dai & Lee, 2002; OAP, 2003).

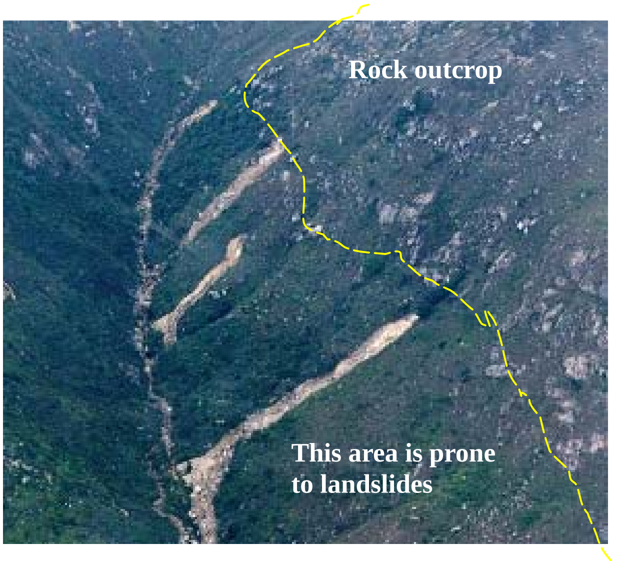

Figure 18 – Correlation of landslides with terrain of different characteristic and mapping of susceptibility map

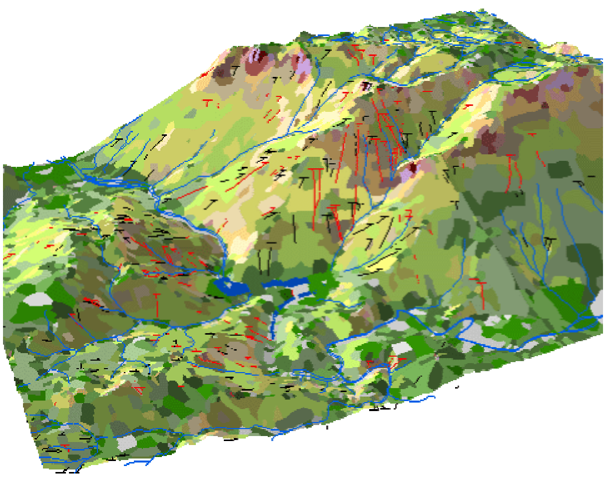

Figure 19 – Visualization of historical landslides and terrain with different susceptibility

In recent years, GIS software developers have expanded the capability of customising applications by integrating standard programming languages into the GIS software, e.g. Visual Basic and object-oriented programming. This opens the opportunity for more advance and sophisticated customisation be made. The GEO has developed a number of modelling tools that have integrated engineering analysis with GIS analysis, e.g. the debris mobility modeller and quantitative risk assessment model (Figures 20 & 21). These powerful tools interrogate a large amount of geospatial data and apply physical laws to solve complicated engineering problems. They have been enhanced to provide solutions in a three-dimensional space. The analytical results, when combined with 3D virtual reality modelling, can produce clear visualization for evaluation and planning of measures to mitigate landslide risk (Figure 22).

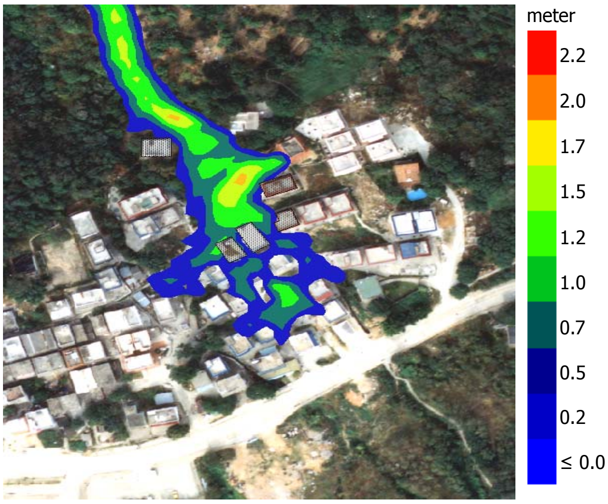

Figure 20 – Debris flow model for predicting the depth of debris deposited if a landslide occurs in hillside (Ko & Kwan, 2006)

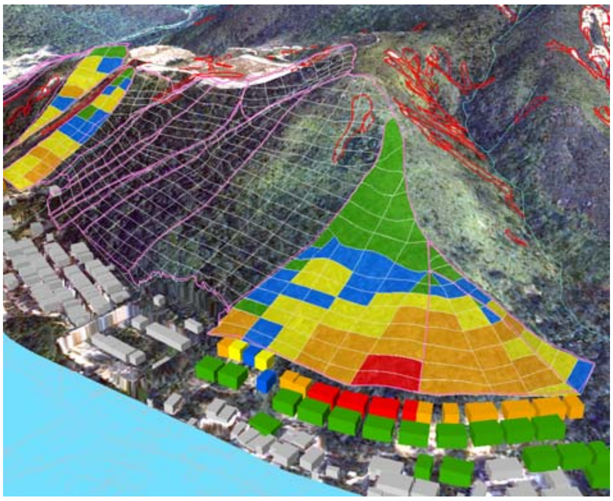

Figure 21 – Quantitative risk assessment model for predicting areas where developments would be subject to unacceptable risks

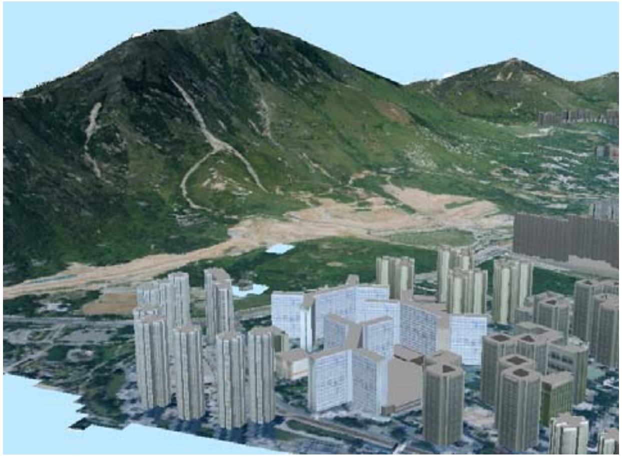

Figure 22 – Virtual reality model of Tsing Shan foothills

Way Forward

Information technology has been a key component of the GEO strategies in implementing the Slope Safety System. The GEO has developed an information system for the public to access slope-related information in the Internet. There are also many database and information systems developed to improve the design process or works management within the GEO. In the process of developing different systems and applications, the GEO has a comprehensive set of geospatial data collected or compiled over the years. These datasets are essential in many geotechnical applications and are demanded by many practitioners. The GEO sees the need to standardize the quality of the geospatial data and consolidate them in a spatial data infrastructure, such that they are more readily accessible. These should become important assets to the geotechnical engineering community.

There is a trend of developing advance GIS applications that integrate engineering principle with GIS analysis. Novel technologies, such as remote sensing technology based on LIDAR and InSAR, will be improved. The GEO has been actively pursuing the GIS developments and applications of the novel technologies in geotechnical engineering practice. These, together with the easier access of the geospatial data, should lay the groundwork for the geotechnical professions to take the benefits of using information technology. The GEO will continue to partner with industry practitioners and academics in these areas, such that the geotechnical engineering community, as a whole, will improve their capability and efficiency to meet the challenges of keeping our slopes safe.

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