Application of GIS to landslide risk management in Hong Kong

K.C. Ng, K.M. Chiu, K.K.S. Ho & V.M.C. Chan
Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong SAR Government

ABSTRACT
Since the early 1990s, the Geotechnical Engineering Office (GEO) has paid considerable effort in compiling slope-related GIS data layers to enhance the capability and efficiency of landslide risk management. The GEO operates a GIS platform, namely the Geological Modelling System (GMS), not just for geospatial data management but also for a wide range of engineering analyses and landslide modelling. Remote sensing techniques and the corresponding spatial data, together with advances in information and telecommunication technology, also play an increasingly important role in slope engineering practice, particularly in remote areas and/or on terrain with difficult access. These spatial data are integrated with the GMS.

RÉSUMÉ
Depuis le début des années 1990, le Bureau d'ingénierie géotechnique (GEO) a payé des efforts considérables dans la compilation de pente les données SIG de couches pour accroître la capacité et l'efficacité de la gestion des risques de glissement de terrain. Le GEO exploite une plate-forme SIG, à savoir le système de modélisation géologique (GMS), non seulement pour la gestion des données géospatiales, mais aussi pour une large gamme de l'ingénierie des analyses de modélisation et les glissements de terrain. Les techniques de télédétection et les données spatiales, ainsi que les progrès en matière d'information et les télécommunications, jouent également un rôle de plus en plus important dans l'art de pente, en particulier dans les zones reculées et / ou sur un terrain d'accès difficile. Ces données spatiales sont intégrées avec les GMS.

1 INTRODUCTION

With a land area of about 1,100 km^2 and a population of about 7 million, Hong Kong is one of the most densely populated cities in the world. As over 60% of the land comprises hilly terrain, a substantial portion of Hong Kong's dense urban development is located on or near steep hillsides.

Following a number of disastrous landslides which resulted in some 150 fatalities in the 1970s, the Geotechnical Control Office (renamed Geotechnical Engineering Office, GEO, in 1991) was set up in 1977 to regulate the investigation, design and construction of geotechnical works in Hong Kong. Since then, the GEO has developed a comprehensive slope safety system for managing landslide risk (Chan 2000).

The GEO has been taking advantages of advances in information and digital technologies over the years (Wong 2004). Geospatial and other relevant datasets are compiled in formats that can be accessed and managed by Geographic Information System (GIS). The data are disseminated through GIS platforms and/or tailor-made applications for the general public and the geotechnical profession. Geospatial analyses and modelling provide valuable input for decision-making with respect to landslide risk management.

This paper presents an overview of the use of GIS in slope engineering practice in Hong Kong, including the application of key geospatial datasets and GIS to landslide risk management by the GEO.

2 KEY GEOTECHNICAL-RELATED DATASETS

The GIS datasets in the GEO cover both geotechnical and non-geotechnical data. The non-geotechnical datasets are compiled and managed by other Government departments and include territory-wide base maps of different scales, land-use and vegetation classification map, land-use zoning plan, slope maintenance responsibility, water-carrying utilities, etc. Geotechnical-related GIS datasets include slope and landslide data, geological information, ground investigation data, topographical modelling data and rainfall data. These datasets are discussed below.

2.1 Slope Data

The GEO launched a project in 1994 to systematically identify, catalogue and register all sizeable man-made slopes including retaining walls. There are about 57,000 registered man-made slopes and the information is stored in the Government's Slope Catalogue. Each slope is represented by a GIS polygon showing its extent and linked to the corresponding slope data. The dataset, which is regularly maintained and updated, forms an important inventory of information on man-made slopes and is disseminated through different channels to the general public and geotechnical practitioners.

2.2 Landslide Records

2.2.1 Reported Landslides

Reported landslide incidents attended to by the GEO are recorded systematically since 1984. These landslide records, including ad hoc landslide records before 1984, have been digitised and converted into GIS format. The dataset provides information on the location, time, scale, dimensions, consequences of landslides, etc.

2.2.2 Landslide Inventories

For natural hillsides, the GEO has compiled two landslide inventories, namely the Natural Terrain Landslide Inventory (NTLI) and the Enhanced Natural Terrain Landslide Inventory (ENTLI). NTLI was first compiled in 1995 from interpretation of high-flight aerial photographs taken at about 2,400 m or above. The location of each identified natural terrain landslide crown and the centre-line of the debris trail were recorded. Up to the year 2003, the NTLI contained some 30,000 landslides.

Between 2004 and 2007, the GEO undertook a comprehensive aerial photograph interpretation (API) using both high- and low-flight aerial photographs (viz. <2,400 m) taken between 1924 and 2006. This new dataset, referred to as the Enhanced Natural Terrain Landslide Inventory (ENTLI), contains information on about 105,000 landslides that occurred on natural terrain (Figure 1). Information recorded for each landslide record includes the dates of the aerial photographs when the landslide was first observed, width and length of the landslide scar, slope gradient and nature of vegetation cover across the landslide source area. The relict landslides are further classified with respect to the degree of certainty of interpretation, based on specific terrain characteristics. Some of the landslide features in the NTLI were found to be non-landslides, e.g. graves, small footpaths. This new dataset, which essentially replaces the NTLI, provides invaluable information for establishing rainfall-landslide correlations, hillside susceptibility analyses, etc.

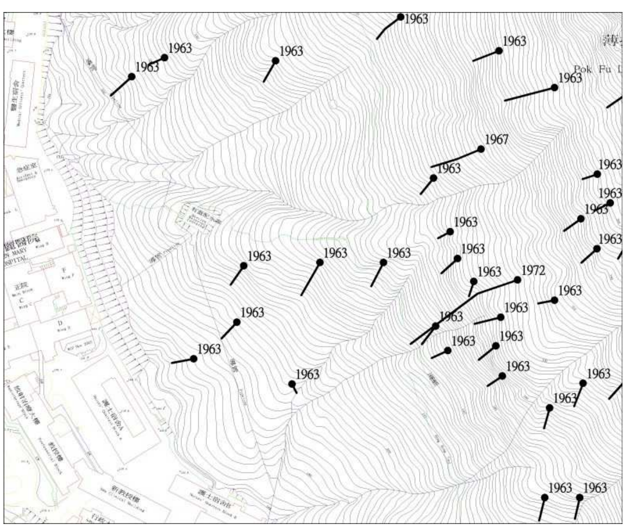

Figure 1. Enhanced Natural Terrain Landslide Inventory overlaid on 1:1,000 scale base map

2.3 Geological Information

2.3.1 Geological Maps

The GEO conducts detailed geological mapping since 1982 and produces territory-wide geological maps at 1:100,000 and 1:20,000 scales, as well as maps at 1:5,000 scale for selected areas with more complex geological conditions. The maps and details of the associated geophysical surveys (e.g. gravity, seismic and magnetic surveys) are digitised and form part of the geospatial datasets.

2.3.2 Ground Investigation Records

The GEO manages a Geotechnical Information Unit (GIU), which contains a comprehensive collection of data and reports of ground investigations (GI) including laboratory testing. The GIU now holds about 56,000 reports containing the records of some 300,000 GI stations.

The details of the GI stations, including locations, elevations, GI type, etc. are stored in a geospatial dataset. Users of the GIU can search for the required GI information via a GIS spatial query application.

2.4 Topographical Modelling Data

2.4.1 Ortho-rectified Images

By application of digital photogrammetric techniques, conventional aerial photographs can be converted into ortho-rectified images. Such images are true to scale and position accurate, which can supplement conventional survey plans. The geo-referenced ortho-rectified images are integrated into GIS environment for a range of GIS and remote-sensing applications.

2.4.2 Digital Elevation Model

A digital elevation model (DEM) is compiled using the elevation data, such as contour lines and spot levels. The GEO has constructed two sets of territory-wide DEM. The 5-m grid DEM was compiled in 2001 using 1:5,000 base map data and ground control points (e.g. GI stations). The higher resolution 2-m grid DEM was constructed in 2004 using 1:1,000 scale base maps with the use of a new algorithm to eliminate flat polygons and 'dead' areas. Improvement has also been made in the provision for break lines, such as drainage lines, roads and slopes to remove artifacts and enhance the accuracy of the DEM in modelling ground features (Figure 2). Related GIS datasets that have been derived from the DEM include shaded relief maps, slope gradient maps, etc.

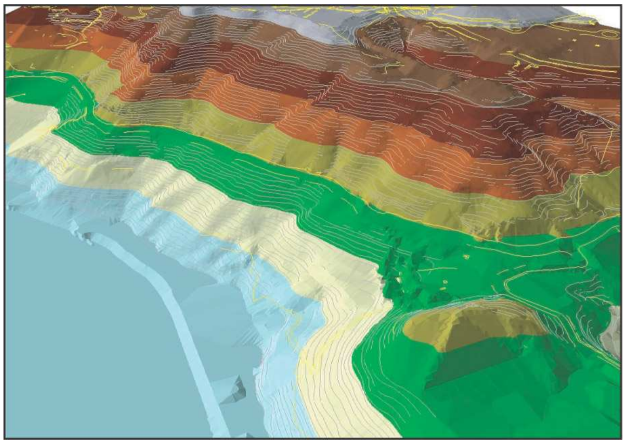

Figure 2. 2-m grid DEM

2.4.3 Airborne Light Detection And Ranging (LiDAR) Data

The GEO launched a pilot airborne LiDAR survey in December 2006 for the Hong Kong Island using multi-return LiDAR technology. A complete dataset of about 768 million survey data points were provided in LAS format. Separate datasets comprising point cloud classified as ground, and point cloud for digital surface model were provided in ASCII format. The DEM generated using these datasets are of high resolution and accuracy that can reveal the morphology of landslide scars and other ground features in vegetated hillsides (Figure 3) that cannot be otherwise obtained from conventional means such as digital photogrammetry. It provides useful information for engineering geological and geomorphological interpretation in natural terrain hazard studies (Ng et al. 2008).

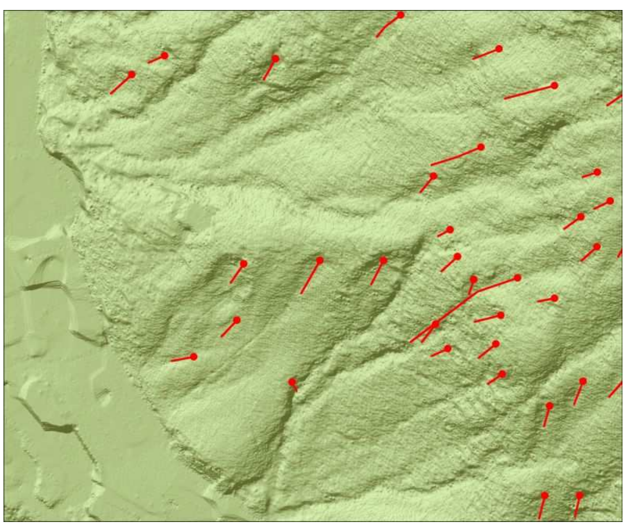

Figure 3. DEM generated using LiDAR Data overlain with ENTLI records

2.5 Rainfall Data

In collaboration with the Hong Kong Observatory (HKO), the GEO has been operating an extensive network of 110 automatic raingauges that record real-time rainfall data since the early 1980s and form part of Government's Landslip Warning System. The rainfall data are transmitted via wireless technology (viz. GPRS) at 5-minute intervals to the GEO, where the data are downloaded, analysed and disseminated (Figure 4).

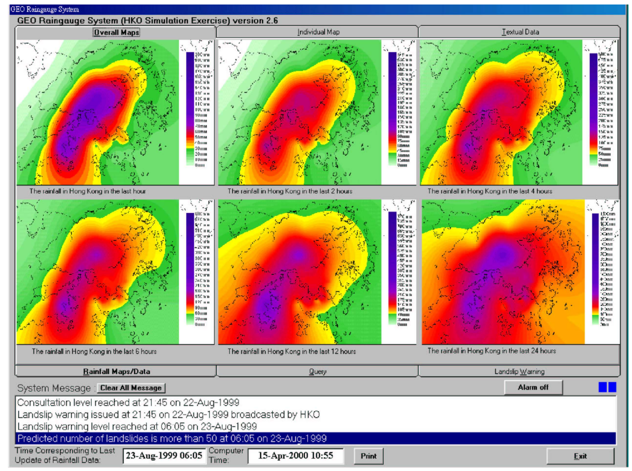

Figure 4. Display of real-time rainfall data

3 GEOGRAPHIC INFORMATION SYSTEMS IN GEO

In order to cater for the needs and expectations of different users, three different modes of management and dissemination of the GIS datasets are operated in the GEO.

3.1 Slope Information System

The GEO operates the Slope Information System (SIS) to disseminate the Slope Catalogue (see Section 2.1) and other slope-related information to the general public and geotechnical practitioners. Pertinent information on all registered man-made slopes is linked by the unique slope registration number to a textual database with site photographs depicting the slope condition and configuration. Other relevant information, such as slope location, physical dimensions, drainage provisions, history of development and maintenance records are stored in an Oracle database. The SIS also serves as the in-house platform for managing project-related information.

Besides serving the information via a Local Area Network through the Government's Intranet system, the SIS also disseminates the data to the general public through the Internet via the Hong Kong Slope Safety Website 〈http://hkss.cedd.gov.hk〉 (Figure 5). The GIS graphical search interface, including the web-service

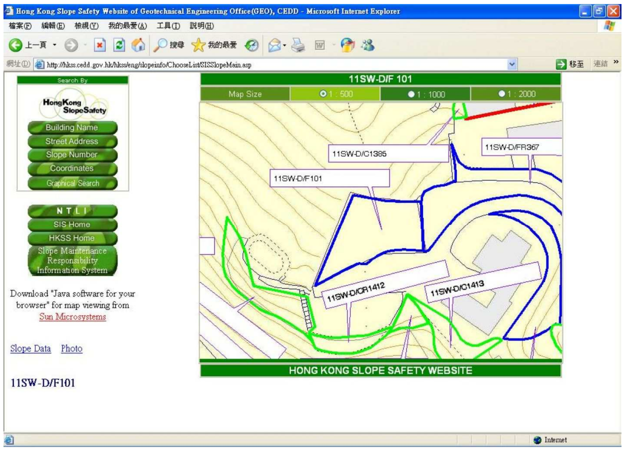

Figure 5. Slope Information System

functionality, is powered by GeoMedia. The launching of the SIS in 1999 marked a milestone in the application of GIS, which succeeded in integrating a wide range of spatial and textual datasets, and efficiently disseminating a vast amount of slope-related information via the Internet (Mak et al. 2001).

3.2 Geological Modelling System

The GEO also operates a high-end GIS, namely the Geological Modelling System (GMS), for the management and manipulation of spatial geotechnical data. Since its set up in the early 1990s, the GIS datasets that are accessible to the GMS and its GIS functionalities have expanded considerably. The system has become a core GIS in the GEO for professional applications that cover the full range of information service, analysis and modelling.

The system architect of the GMS comprises a suite of ESRI software as the GIS and graphic engine, and Oracle as the relational database. Its hardware components include high-powered servers, workstations and digital photogrammetric facilities. GMS workstations are connected to dedicated GIS servers via different configurations, including Local Area Network, Internet and mobile connection, for enterprise GIS application powered by Spatial Database Engine (ArcSDE) and Internet Map Server (ArcIMS) (Figure 6).

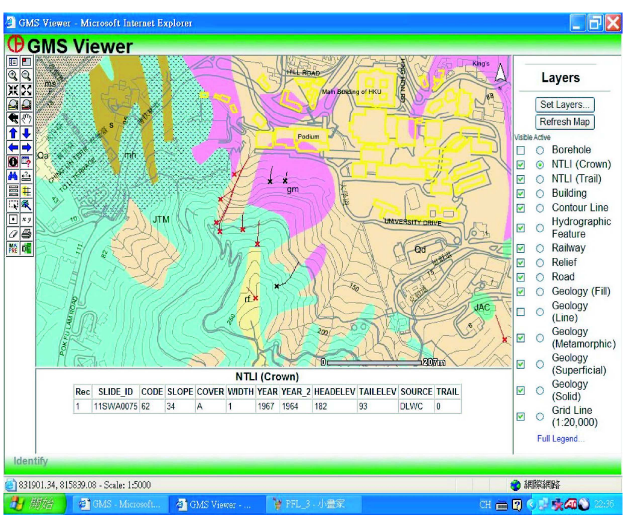

Figure 6. Geological Modelling System

3.3 Tailor-made Systems

Tailor-made systems have been developed in-house to meet specific needs on the use of the GIS datasets. Two selected platforms operating in the GEO are described below to illustrate the arrangement.

3.3.1 Digital Geotechnical Information Unit (DGIU)

The GI reports kept in the GIU (see Section 2.3.2) are open to the public and practitioners. In the past, a catalogue system was developed for manual searching of GI information. The catalogue consisted of cards each representing a base map sheet of 1:5,000 or 1:20,000 scale and contained a list of GI reports with GI stations that fall within the corresponding base map. The user could then find the reports from the shelves. As the base map normally covered an area that was much larger than the area of concern, some reports listed on the card were irrelevant and a lot of time was wasted in the review of the reports.

In 2004, the Geotechnical Information Library System (GILS) introduced GIS query functions for more effective and efficient searching of GI information. It runs on ArcView 3.2 platform with the GI dataset. GILS substantially reduces the time for identifying the required GI information.

As an enhancement to GILS, an application called the Digital Geotechnical Information Unit (DGIU) has been developed in 2007 on an ArcIMS platform. In addition to improved searching functions, the DGIU allows users to view the digitised GI records directly on screen (Figure 7). The capability of simultaneous access to the same GI record assures the availability of the records and reduces the demand for hardcopies of the GI reports.

3.3.2 Aerial Photograph Library Management System (APLMS)

The GEO operates an Aerial Photograph Library, which currently holds more than 160,000 historical aerial photographs. The library is open to all government staff and consultants working on government projects, and about 9,000 aerial photographs are loaned out each month. In the past, the search of relevant aerial photographs covering a site was done manually by going through a set of flight plans. As the number of photographs held in the library continues to grow, the manual search becomes laborious and time-consuming.

The APLMS enables spatial search of the relevant aerial photographs and provides library management functions, thereby assisting the users to identify the photographs and their availability in a highly efficient manner. The APLMS runs on an ArcView 3.2 platform

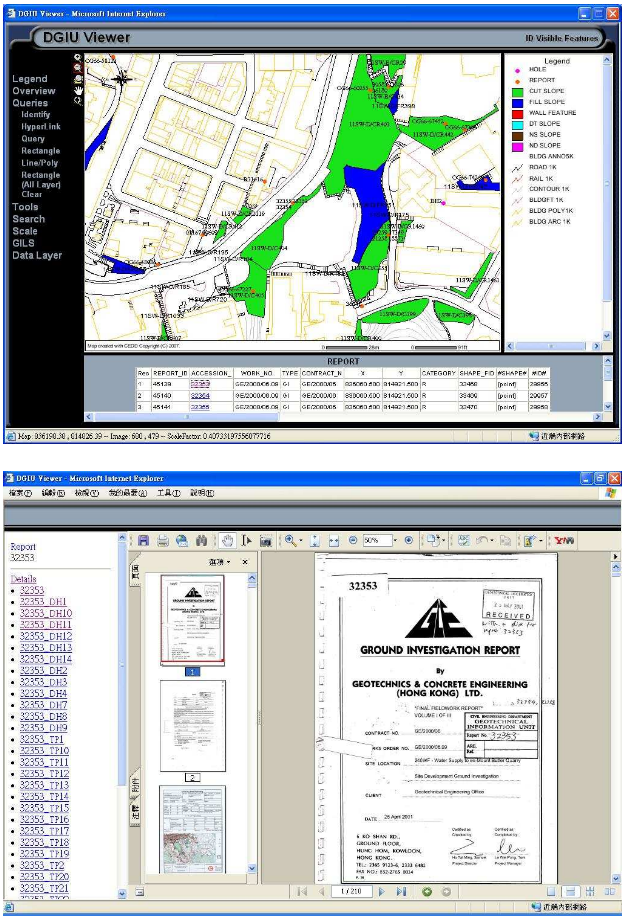

Figure 7. Digital Geotechnical Information Unit: (upper) user interface showing the search results; (lower) GI report

that is connected to the data server via a Local Area Network. It has also been incorporated into the Internet module of the GMS, which allows access to the APLMS functionalities using an ordinary web-browser through the Internet. A new version is currently being developed on an ArcIMS platform.

4 GIS APPLICATIONS

In recent years, more advanced GIS functionalities are implemented to address geotechnical problems in Hong Kong. This is partly the result of the gradual build-up of GIS capability amongst the geotechnical profession, and more importantly the increasing demand and recognition of the use of GIS in problem solving and assisting decision-making. Some notable applications are described below.

4.1 Desk Studies

A geotechnical desk study normally involves examination of the available geotechnical data, review of the site history and assimilation of the key information for presentation. In the past, the information was available mainly in hardcopies and assemblage of all the available information requires further cartographic input.

Advanced GIS searches enable users to access multiple datasets, and perform queries and retrieve data that meet certain prescribed criteria or geographical relationship. Examples of such application include delineation of area of deep rock weathering using ground investigation data, identification of man-made slope features requiring further stability assessment, and identification of sites affected by historical natural terrain landslides.

Data manipulation and assemblage can be carried out using appropriate GIS software both for presentation purposes and analysis purposes. For example, recent landslides and new developments can be identified from overlays to ortho-rectified images of different vintages (Figure 8).

4.2 Spatial Analyses of Geotechnical Data

4.2.1 Natural Terrain Landslide Susceptibility

A territory-wide landslide susceptibility map was prepared

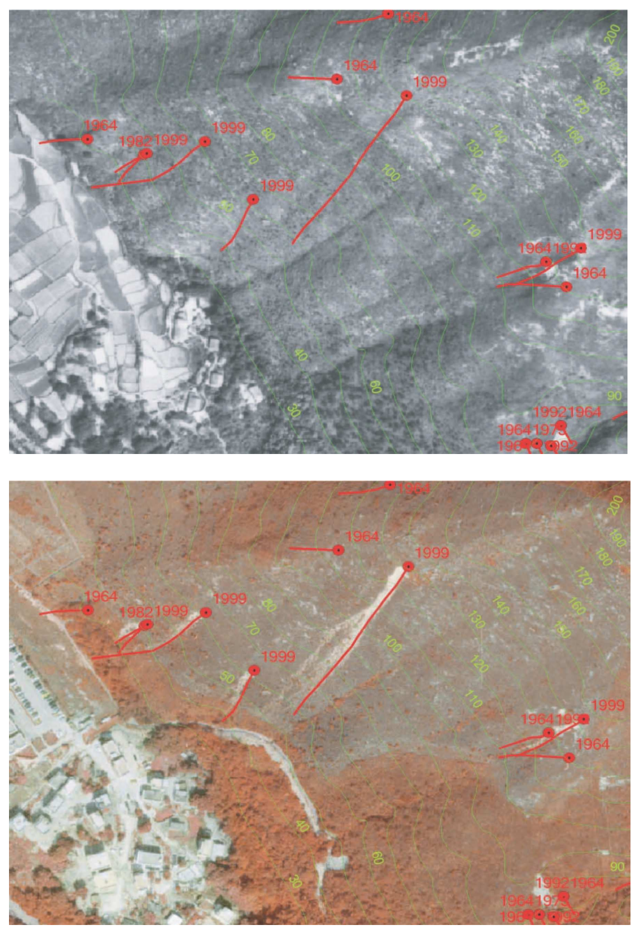

Figure 8. NTLI records overlaid to ortho-rectified images in 1963 (upper) and in 2000 (lower)

by the GEO in 1998, based on correlation of past landslides with slope gradient and solid geology (Evans and King 1998). The natural terrain landslide data were taken from the NTLI up to the year 1994. The analysis used a DEM compiled from the 1:20,000-scale topographical plans converted initially into a Triangulated Irregular Network (TIN) model and then into a grid model. Five susceptibility classes were defined: very low, low, moderate, high and very high with densities varying from <10 to >100 landslides per km^2 corresponding to frequencies varying from 0.1 to >1 landslide/yr per km^2.

4.2.2 Correlation of Natural Terrain Landslide Intensity and Rainfall Intensity

GIS analysis is an efficient means to examine the relationship and correlation among different spatial data, which are difficult to analyse using conventional means. It offers a unique capability in geotechnical research and development work involving spatial analysis of geotechnical data. Figure 9 shows an example of correlating natural terrain landslide density and rainfall intensity in Hong Kong using GIS analysis, together with GIS-based geostatistics (Ko 2003).

4.2.3 Landslip Warning System

The GEO and the HKO (see Section 2.5) operate a Landslip Warning System at times of intense rainfall since 1978, to alert the general public to reduce their exposure to possible danger from landslides, and to trigger the operation of Government's emergency system that mobilises staff and resources to deal with landslide incidents. A simplified GIS approach was used to derive territory-wide correlation between slope failure rate, maximum rolling 24-hour rainfall and slope characteristics for soil cut slopes (Yu et al. 2004). The correlation has been adopted since 2004 to predict the number of landslides. Landslip Warning will be issued when the threshold level (i.e. when the estimated number of landslide is 15 or more) is expected to be reached shortly, coupled with the short-term nowcasting of rainfall.

4.3 Modelling

Performing GIS-based geotechnical analysis and numerical modelling based on application of engineering principles and governing physical laws has become increasingly important. Such application integrates engineering analysis with a GIS platform, and provides a powerful modelling tool, particularly for the analysis of a large amount of spatial geographical and engineering attributes. Examples of such application in modelling the runout of landslide debris (Kwan et al. 2007) and quantitative risk assessment of natural terrain landslides (Wong 2005) are shown in Figures 10 and 11, respectively. In the latter, landslide hazard and consequence models are incorporated into the GIS calculation of landslide risk using the relevant spatial data of the hillside catchments and facilities (buildings, roads, etc.) at risk.

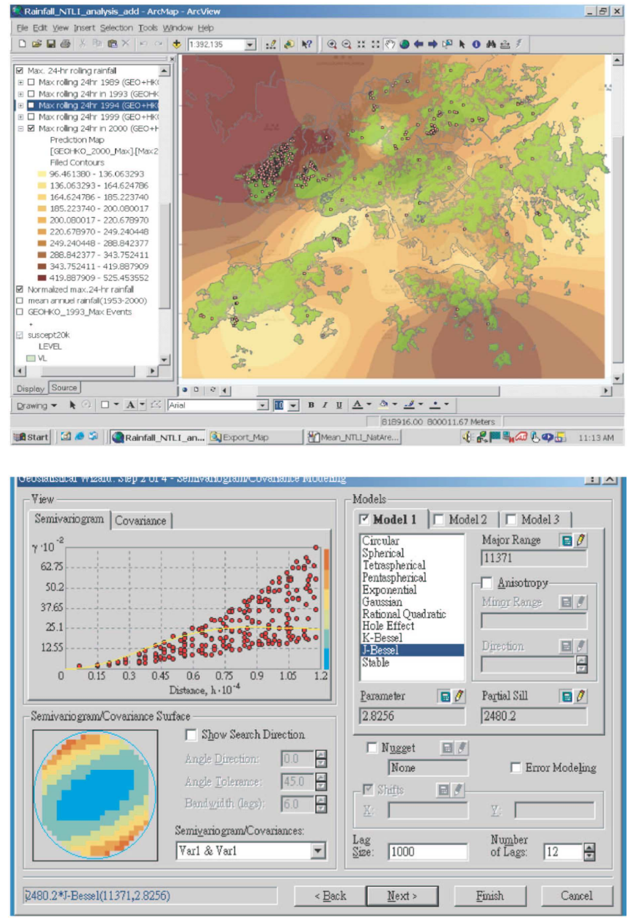

Figure 9. GIS analysis of natural terrain landslide-rainfall correlation: (upper) year 2000 maximum rolling 24-hr rainfall and natural terrain landslide locations; (lower) GIS-based geostatistical analysis

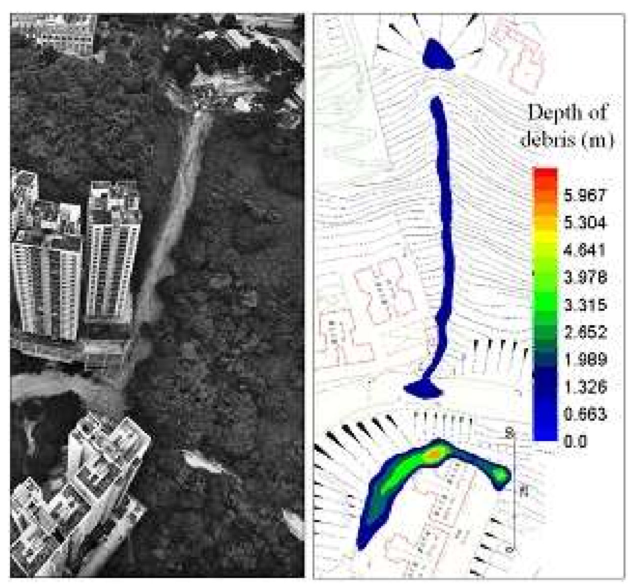

Figure 10. 3-D debris runout modelling

Figure 11. GIS-based landslide quantitative risk assessment

4.4 Image Processing for Boulder Mapping

Image processing techniques have been used in parallel with digital photogrammetry for feature identification, extraction and change detection. An example of such application in the mapping of boulders on natural hillsides is depicted in Figure 12. Shi et al. (2004) show that by integrating digital photogrammetry with human-machine interaction, image analysis data can be used to map boulder distribution and extract boulder properties (e.g. size and shape) in an efficient manner. The output, with the necessary selective field verification, can assist the assessment of boulder fall hazards.

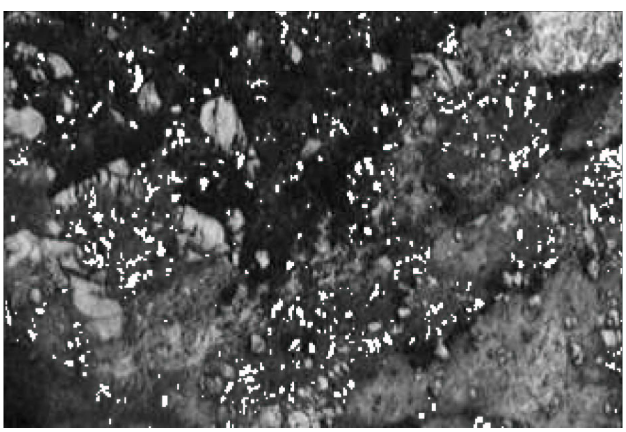
Figure 12. Boulders (white specks) extracted by image processing techniques

4.5 Mobile Location-based Applications

GIS can play an important role in field mapping by employing a pocket computer installed with a mobile GIS platform connected to a Global Positioning System (GPS). Relevant datasets can be uploaded to the pocket computer and brought to site. The GIS-GPS system can guide on-site navigation to the point of interest as previously identified in the office from the available information and can precisely and conveniently record the location of features noted on site. In addition, the available spatial data relevant to the site can be retrieved for location-based applications.

The GEO has pioneered the development of a state-of-the-art GIS-GPS mobile mapping system that also incorporates the use of ortho-rectified images (Ng et al. 2004). The system is equipped with wireless telecommunication via the Internet with GEO's GIS Internet Map Server, for GIS data transfer to facilitate use in geotechnical fieldwork and field mapping.

4.6 3-D Visualisation

3-D virtual reality (VR) models can be generated by combining the DEM and other elevation data with ortho-rectified images. They are useful in visualisation of the landform and urban development, together with identification of geotechnical features such as past landslides, boulders, tension cracks and man-made slope features (Figure 13). This capability enhances the quality of landslide studies, e.g. in reviewing historical landslides and terrain evaluation (Wong 2004). VR animation and computer 'fly-through' can also be produced for presentation and evaluation purposes.

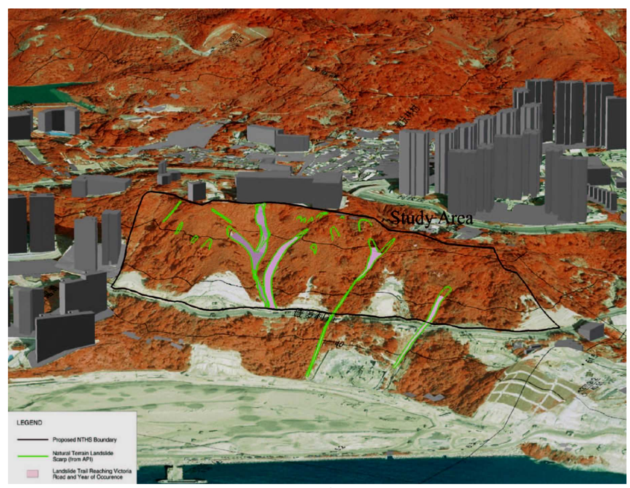

Figure 13. 3-D Visualisation of historical landslides

5 CONCLUSION

The GEO has compiled a comprehensive collection of geospatial datasets, and suitable arrangements and applications are in place for the management and dissemination of the data. The development and application of GIS functionalities have led to improved capability and efficiency in undertaking geotechnical work. The successful integration of GIS into routine slope-engineering practice, including data management, analyses and modelling, has helped capitalise on the benefits and advances of GIS technology.

ACKNOWLEDGEMENTS

The paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of the Civil Engineering and Development Department, Government of the Hong Kong Special Administrative Region.

REFERENCES

Chan, R.K.S. 2000. Hong Kong slope safety management system (Keynote Paper). *Proc., Symposium on Slope Hazards and Their Prevention*, Hong Kong, 1-16.

Evans, N.C. and King, J.P. 1998. The Natural Terrain Landslide Study: Debris Avalanche Susceptibility. Technical Note No. TN 1/98, Geotechnical Engineering Office, Hong Kong.

Ko, F.W.Y. 2003. Correlation between rainfall and natural terrain landslide occurrence in Hong Kong. GEO Report No. 168. Geotechnical Engineering Office, Hong Kong, 77 p.

Kwan, J.S.H., Wong, T.K.C. and Ko, F.W.Y. 2007. Development and applications of debris mobility modeling in assessment of natural terrain landslide hazards. *Proc., Geotechnical Advancements in Hong Kong since 1970s*, Hong Kong Institution of Engineers, Geotechnical Division, 241-247.

Mak, S.H., Ma, T.M., Chan, T.P. and Chan, D.C. 2001. Slope Information System - an indispensable tool for Hong Kong slope safety management. *Proc., Fourteenth Southeast Asian Geotechnical Conference*, Ho, K.K.S. and Li, K.S., Editors, Geotechnical Engineering Meeting Society's Needs, Hong Kong, Vol. 1, 855-861.

Ng, K.C., Fung, K.S. and Shum, W.L. 2004. Applying mobile GIS technology to geotechnical fieldwork. *Proc., Recent Advances in Geotechnical Engineering*, Hong Kong Institution of Engineers, Geotechnical Division, 113-121.

Ng, K.C. and Chiu, K.M. 2008. Pilot Airborne LiDAR Survey in Hong Kong – Application to Natural Terrain Hazard Study. *Proc. Applications of Innovative Technologies in Geotechnical Works*, Hong Kong Institution of Engineers, Geotechnical Division, Hong Kong, 219-224.

Shi, W.Z., Ng, K.C., Huang, C.Q. and Li, X.C. 2004. Applying image processing technology to boulder mapping. *Proc., Recent Advances in Geotechnical Engineering*, Hong Kong Institution of Engineers, Geotechnical Division, 177-184.

Wong, H.N. 2004. New capability and opportunities for using digital technology in geotechnical engineering (Theme Report). *Proc., Recent Advances in Geotechnical Engineering*, Hong Kong Institution of Engineers, Geotechnical Division, 77-94.

Wong, H.N. 2005. Landslide risk assessment for individual facilities. *Proc., International Conference on Landslide Risk Management*, Vancouver, Canada, 237-297.

Yu Y.F., Lam J.S., Siu C.K. and Pun W.K. 2004. Recent Advances in Landslip Warning. *Proc. Recent Advances in Geotechnical Engineering*, Hong Kong Institution of Engineers, Geotechnical Division, Hong Kong, 139-147.