DETECTION AND INTERPRETATION OF LANDSLIDES USING SATELLITE IMAGES

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Received 30 January 2004; Revised 18 June 2004; Accepted 8 July 2004

ABSTRACT

The severity of the landslide hazard in Hong Kong has resulted in the establishment of a comprehensive landslide database, the Natural Terrain Landslide Inventory (NTLI). It is derived mainly from the interpretation of medium to large-scale aerial photographs, and describes the location of all landslides. In view of the labour-intensive nature of air photo interpretation, as well as the lack of regular aerial photo cover in many countries, satellite images were examined for their ability to monitor landslides at a similarly detailed level, using the NTLI database as a reference. Using automated change detection with SPOT XS® images it was possible to identify 70% of landslides, the main omissions being due to those less than 10 m in width, and many of those identified were of sub-pixel width. The study also examined different techniques of image fusion for the enhancement of IKONOS images, and demonstrated that landslides on fused images are of similar detail to those on air photos. A methodology for regional scale monitoring is proposed which combines the efficiency of automated techniques for large area monitoring using SPOT® with the qualitative detail obtained from Pan-sharpened IKONOS images. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: landslides; remote sensing; air photo interpretation; image fusion; change detection; SPOT®; IKONOS; Hong Kong

INTRODUCTION

In spite of some of the highest urban population densities in the world, 40 per cent of the land area of the Hong Kong Special Administrative Region (HKSAR) is designated as country parks. The seeming incongruity is explained by the fact that the mountainous terrain is subject to landslide hazard, with urban development confined to 10 per cent of the land area: a narrow coastal strip backed by steep convex slopes. A rainfall event affecting 20–50 per cent of Hong Kong with the potential to trigger a high density (>10 km$^{-2}$) of natural terrain landslides in susceptible areas can be expected on average every two years (Evans et al., 1997). This fact, combined with some of the highest land prices in the world, makes landslide hazard assessment an important factor in any development project and the government spends $25 million annually for landslide studies and remedial work over a mere 1090 km$^2$ of land area.

Landslide-prone areas are thus subject to severe planning restrictions. In order to designate and enforce these, the Geotechnical Engineering Office (GEO) of the Hong Kong Government has created a database of past landslides and their characteristics. Established in 1945, the Natural Terrain Landslide Inventory (NTLI) is based mainly on the study of medium scale (1:20 000) aerial photographs and documents a total of over 26 000
landslides. Accuracy assessments using larger scale air photos indicate that 80 per cent of landslides are identified (Evans et al., 1997), but this constitutes almost all, if those with multiple scarps are considered as one. Since the early-1990s larger scale (1:10 000) colour air photos have been used, giving identification accuracies approaching 100 per cent. These are produced annually by the Lands Department, and provided free of charge as prints, or softcopy orthorectified mosaics, to different government departments for a variety of uses.

Although the method of landslide monitoring in Hong Kong appears to be satisfactory, it is labour-intensive, with over 400 air photos required for stereo cover of the territory. The tasks of manual interpretation and the creation of orthophoto mosaics are both considerable, and colour inconsistencies may occur across the mosaics. Thus, a cheaper and faster methodology based on satellite imagery would be useful to supplement air photo-based methods, if the results were of comparable accuracy. Additionally, most neighbouring Asian countries are undergoing rapid development, much of it in mountainous landscapes similar to those in the HKSAR, but they do not have the resources, and are too large, to obtain regular air photo cover. The basic requirement is to detect the locations of past landslides and to use these, as well as other qualitative indicators of slope failure such as step-like morphology and differential vegetation and drainage conditions (Soeters and Cornelis, 1996) to identify landslide-prone areas.

OBJECTIVES

The high quality of landslide data available in the Hong Kong NTLI database recommends its use as a reference for the testing of other more cost- and time-effective methods. Thus, the present study aims to provide a satellite-based methodology for regional scale landslide monitoring at a level of detail similar to that obtainable from air photos at 1:10 000 scale. This will be demonstrated using image-processing techniques as follows:

1. automated change detection with medium resolution SPOT® images to identify past landslides; and
2. enhancement of high resolution IKONOS satellite images using techniques of image fusion to preserve both the spatial and spectral qualities of the imagery.

The NTLI digital database, which contains the location of the crowns and trails of past landslides derived from high resolution air photos was used to verify the accuracy of landslides detected in (1). The second objective demonstrates the ability to identify details associated with slope movement, and to interpret their significance to slope instability processes.

MODELS FOR LANDSLIDE HAZARD ZONATION

Simple Inventories

Many landslide prediction studies utilize the basic concept that an area in which a landslide has occurred is in a landslide-prone area, and such environments have a high probability of new landslides occurring (Odajima et al., 1998). The Hong Kong NTLI database shows that of a total of 6638 landslides, which occurred in Lantau Island, Hong Kong between 1945 and 2000, 984 reoccurred along the same track: a repeatability of 15 per cent. In a study of Lantau Island, Wong et al. (1998) observed that landslides are two to three times more likely to occur in places where they have occurred previously. Thus landslide inventories are the basis for most hazard zoning techniques (Evans et al., 1997). Inventory maps can be used by themselves as a form of elementary hazard map because they show the locations of past landslides.

Multivariate Models

Simple inventories can be combined with other data if available. For example, Odajima et al. (1998) produced a weighted landslide hazard map of a part of Indonesia, where the weightings for environmental parameters such as slope, land cover and geology were derived from the known frequency of past landslides associated with those parameters. A similar approach was adopted by Saha et al. (2002) in the Himalayas. Such approaches, using statistical analysis with environmental parameters, could be referred to as multivariate models. However their application over large areas, and in developing countries, is limited by the availability of environmental data.
simple inventories can be derived from satellite-based sensors, this may be a more feasible approach for regional scale studies. The simple inventory approach was adopted in this study since it can be used alone to predict where landslides may occur, or as an input to multivariate models.

STUDY AREA AND IMAGES

The study area was a mountainous volcanic region on Lantau Island, Hong Kong. The area comprises 36 km$^2$ and is extremely rugged, with a relative relief of over 800 m (Figure 1). Lowland forest occupies the valleys, giving way to grassland at the higher levels and on ridges and summits. Since summits, steep slopes and rock outcrops are only sparsely vegetated, there are many areas spectrally similar to landslides, making it impossible to identify landslides spectrally on a single-date image.

For this area, two wintertime SPOT$^\text{®}$ images, of 1991 and 1995 were obtained (Table I). The images pre- and post-date a serious rainstorm-induced landslide event in November 1993, during which 551 landslides occurred. Experience from Hong Kong (Evans et al., 1997) suggests that the landslides would not have been significantly re-vegetated by the date of the second image 15 months later, since, on average, landslide tracks are only 70 per cent revegetated after five years.

For the second part of the study on image fusion, an IKONOS image of January 2003 was obtained. Since IKONOS is a new sensor it was not operating at the time of the landslide event studied on the SPOT$^\text{®}$ images, therefore its evaluation was based on more recent landslides in the study area. Colour aerial photographs were available at dates close to both sets of satellite images to verify and compare the capabilities of the satellite data (Table I).

RATIONALE FOR IMAGE IDENTIFICATION OF LANDSLIDES

Air Photo Interpretation

Traditionally, landslide inventories are based on air photo interpretation. This is a cognitive process involving the inherent characteristics of the landslide, such as tonal, contrast, size, shape, and shadow, as well as contextual indicators such as position, and direction (Liu et al., 2002) (Table II). For these contextual indicators many ground resolution cells (GRCs) are required, and small-scale air photos, or remote sensing systems with large pixel sizes are thus unable to identify small landslides.

Soeters and Cornelis (1996) suggest 1:15 000 as an optimal scale for air photo interpretation of landslides. However, the air photo scale of 1:10 000 has been used in recent years for landslide monitoring in Hong Kong, therefore this scale was selected in the present study for accuracy comparison with the SPOT$^\text{®}$ change images. At this scale 1 mm on the air photo represents 10 m on the ground. Since the resolution of aerial photographic systems is in the order of 40 line pairs mm$^{-1}$ (Soeters and Cornelis, 1996) this would correspond to a ground resolution of 0-25 m.

Thus, if the smallest landslides were 1 m wide they would occupy four air photo pixels and, if highly contrasted against their background (i.e. recent landslides) they can be detected using 1:10 000 scale air photos, as illustrated in Figure 2. However, although the feature in Figure 2 can be detected, it may not be identified as a landslide without additional information obtained from the interpretation of surrounding contextual features. The example suggests that if the context is known, small features that are detected may sometimes be identified, even if their size is so small as to approximate the resolution of the sensing system.

A further requirement in landslide monitoring is the qualitative interpretation of ground features associated with slope failure such as ground cracks, slopes, depressions and discontinuities in vegetation and soil moisture. Sissakian et al. (1983) state that for clear recognition of such processes, an air photo scale of 1:5000 is necessary.

Automated Change Detection

Since the present study area is a natural area, 80 per cent of it within protected country parks, the environmental context is already known. In this situation the parameters required for visual air photo interpretation (Table II) are not necessary, and only detection, using the change in image tone between two different image dates is required: thus even a single GRC representing change from vegetation into rock or bare soil, may be identified as a type of...
Figure 1. Location of study area in Lantau Island, Hong Kong, showing the distribution of landslides during the study period, 1992–1995, and terrain elevations.
Table I. Image details

<table>
<thead>
<tr>
<th>Image details</th>
<th>SPOT [(\mu m)]</th>
<th>IKONOS [(\mu m)]</th>
<th>Hardcopy aerial photographs</th>
<th>Digital orthophoto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavebands</td>
<td>Green 0.43–0.47</td>
<td>Blue 0.45–0.52</td>
<td>True colour</td>
<td>Blue</td>
</tr>
<tr>
<td></td>
<td>Red 0.50–0.59</td>
<td>Green 0.55–0.60</td>
<td></td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>NIR 0.61–0.68</td>
<td>Red 0.63–0.69</td>
<td></td>
<td>Red</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NIR 0.76–0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Panchromatic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>20 m</td>
<td>Panchromatic: 1 m</td>
<td>0.25 m</td>
<td>0.35 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multispectral: 4 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>05 February 1995</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table II. Parameters for air photo interpretation of landslides (adapted from Liu et al., 2002)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Likely characteristics</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Colour</td>
<td>Brown, dark brown, greenish brown, light brown</td>
<td>Inherent</td>
</tr>
<tr>
<td>2 Shape</td>
<td>Lenticular, spoon-like, tree-like pattern, triangular</td>
<td>Inherent</td>
</tr>
<tr>
<td>3 Shadow</td>
<td>Indicates positions of valleys and ridges</td>
<td>Inherent</td>
</tr>
<tr>
<td>4 Position</td>
<td>Near ridge, cut-off slope of riverbank, road cut</td>
<td>Contextual</td>
</tr>
<tr>
<td>5 Direction</td>
<td>Long axis along direction of gravity</td>
<td>Contextual</td>
</tr>
</tbody>
</table>

Figure 2. Greatly enlarged air photo of 1:10,000 scale showing a landslide in the study area, with crown 10 m, and trail 1 m wide.
natural earth movement including landslides and landslips (see Appendix for definitions of ‘detection’, ‘identification’ and ‘interpretation’). In order to avoid errors of commission, or ‘false alarms’, whereby change due to human activities such as building and road construction are identified as landslides, planning data available in a GIS was used.

**Satellite-based Landslide Studies**

There is currently no research suggesting that the new generation of fine resolution satellite sensors is able to replace air photos for interpreting landslides at a detailed level. For example, Marcelino *et al.* (2003) were only able to identify landslides ‘a few pixels wide’ (i.e. a few tens of metres wide) using SPOT® and Landsat® images. Petley *et al.* (2002) using Landsat® ETM+ images in the Himalayas were only able to identify 25 per cent of the total number of landslides, i.e. those over 50 m wide, even when the multispectral bands with 30 m resolution were pan-sharpened to a resolution of 15 m. Furthermore, although the authors state that satellite sensors having sub-metre resolution show the potential for delineation of small landslides, they are only able visually to identify landslides over 10 m wide using IKONOS panchromatic images with 1 m spatial resolution. Additionally there is no research on automated approaches to landslide mapping based on change detection of multi-temporal images, although Rössner *et al.* (2002) emphasise the importance of developing this approach for regional scale assessments.

The body of evidence would therefore suggest that satellite images, even those with 1 m spatial resolution such as IKONOS are not suitable for landslide mapping in a region such as Hong Kong where 80 per cent of landslides are less than 10 m wide (Evans *et al.*, 1997). However, such landslides may be as long as 200 m and can be very destructive, and they are equally indicative of a landslide-prone environment. Thus, there is a need for a technique or data source that can be applied at regional scale to enable such small landslides and their associated features to be identified.

**METHODS FOR CHANGE DETECTION**

In order to permit direct comparison of the two image dates and for overlay with the NTLI landslide records, the 1991 and 1995 SPOT® images were orthorectified to the Hong Kong 1980 Grid Coordinate System using 330 and 440 GCPs respectively, giving an RMS error of 0.66 pixels. Since for change detection relative accuracy of the two images is more important than overall accuracy, 20 additional points were selected in upland and lowland areas to verify accurate co-registration. The RMS error of co-registration was approximately 0.5 pixels.

Several methods of automated change detection were tested for this study, including image band subtraction, and post-classification comparison. Overall, the post-classification comparison approach using the Maximum Likelihood classifier (MLC) was found to be the most accurate and objective when the results were compared with the landslides recorded in the NTLI database over the same time period. The method involves classifying each image separately by designating all significant land cover types in the image as classes. Because shadow was a significant component of the images, due to the steepness of the terrain combined with the low sun angle in winter, it was also included as a class. This reduced the classification confusion between dark shadowed areas and forest and water, which had similar spectral characteristics. The overall classification accuracy was assessed by comparison of 100 sample points with the orthorectified air photos and the overall classification accuracy was 85 per cent. The classified images for each date were combined into one file and two change images were created representing pixels which changed from grassland to soil, and those which changed from woodland to soil over the time period. This was done using a conditional formula in ER Mapper.

The NTLI data showing the positions of landslides were then overlaid onto each change image and the landslides whose crowns and/or trails were seen to be overlapping by more than 60 per cent with change pixels were flagged as successfully detected.

**RESULTS OF CHANGE DETECTION**

Of the 551 landslides occurring in the study area between the two image dates, 75 were in grassland and 59 in bare soil areas on the upper slopes. The remaining 417 occurred in woodland on mid-slopes, which tend to be the steepest (Table III).
The detection rate was high: 67 per cent of landslides in grassland areas and 71 per cent in woodland areas were detected, including landslide scars as small as 7–10 m wide. For example, the 10 m wide crown (but not the 1 m wide trail) of the landslide illustrated in Figure 2 could be detected on the SPOT image. Figure 3 indicates the appearance of landslides with crowns and trails of different widths on the same 1:10000 scale air photos. These were matched visually with the SPOT change pixels and their detectability is stated on the figure. Thus the upper portions of Figures 3a, and 3b show landslides having trails 1 m wide that were not detected on the SPOT image. However, the 10 m wide crown and 7 m wide trail in Figure 3a were detected, as were two of the three 10 m wide crowns, and the multiple trail in the lower portion of Figure 3b. This ability to detect landslides of sub-pixel size can be explained by the very high contrast between landslides and their background, especially in the SPOT green and red bands, such that the overall reflectance value of a 20 m pixel is ‘contaminated’ by the small bright feature within it. Additionally it is due to the Point Spread Function (Mather, 1999) whereby light from a very

<table>
<thead>
<tr>
<th>Land cover in 1991 by ML classifier</th>
<th>Landslides by land-cover type (by overlay of classified image with NTLI data)</th>
<th>Change detection image</th>
<th>Landslides detected by MLC n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland</td>
<td>75</td>
<td>Grassland to Soil</td>
<td>50 (67)</td>
</tr>
<tr>
<td>Woodward</td>
<td>417</td>
<td>Woodland to Soil</td>
<td>296 (71)</td>
</tr>
<tr>
<td>Soil/rock</td>
<td>59</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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bright ground object may diffuse into surrounding areas of an image, and appear to emanate from them. The above examples demonstrate the relationship between image contrast and system resolution and explain the detectability of sub-pixel-sized landslides on the SPOT® images.

The main errors of omission (those not detected) are due to small landslides under 10 m in width, e.g. features measuring 1–3 m in width on Figures 3a and 3b. Other cases of omission were landslides in shadow areas and those which reoccurred on the same track, and thus were classed as bare soil on both image dates. Classification errors, especially confusion between grassland and soil on these wintertime images when grass is spectrally similar to soil, may also account for some omissions from the change images.

The requirement that a pixel or group of pixels should be overlapping by at least 60 per cent with an NTLI landslide in order to be identified, actually excludes some correctly identified pixels, which could not be exactly matched, given the unavoidable errors of orthorectification due to the large (20 m) pixel size of SPOT®.

Since the NTLI landslides are represented as single lines not areas, the 0·6 pixel RMS error of image rectification means that some pixels representing landslides displaced by up to 12 m from the line representing the true position were not counted. Visual inspection shows that some of these omitted are clearly matched with landslides but do not meet the criteria, and if they were included the detection rate would increase to 80 per cent for grassland and 82 per cent for woodland.

Errors of commission (i.e. change pixels that were actually not landslides) were mainly due to human-induced terrain disturbance during the study period. Figure 4 shows an area with road and building development, containing as change pixels, and they represent ‘false alarms’ in the data.

Overall the result, showing approximately 70 per cent of landslides detected by SPOT® was surprisingly good, given the constraints of the spatial resolution and the relatively small size of landslides in the study area.

![Figure 4. Change pixels not due to landslides but due to building and road development during the study period.](image-url)
ENHANCEMENT OF IKONOS IMAGES BY IMAGE FUSION

Rationale
Traditionally, landslides are visually interpreted in their environmental context using a variety of parameters, which are listed in Table II. This requires higher spatial and spectral resolution than for automated change detection, and generally twice as many GRCs are required for interpretation than for mere identification (Strandberg, 1967). This second part of the study showed that the additional qualitative information, similar to that on air photos can be obtained by Pan-sharpening of IKONOS multispectral images.

Images Used
IKONOS by Space Imaging is one of the new generation of high resolution satellite sensors. It has a 1 × 1 m panchromatic band and four multispectral visible and near infra-red bands at 4 m spatial resolution. The non-nadir look angle of the system makes revisit in a matter of days possible: less than 3 days with 1 m spatial resolution at look angles less than 26°, and 1.5 days at 4 m resolution. Its currently high cost precludes its use for short-term monitoring but the high revisit rate means that images may be available if required, e.g. following major rainstorm-induced landslide events. The Quickbird sensor by Digital Globe has similar spatial, spectral and temporal capability.

A digital orthophoto dated less than three months earlier than the IKONOS image, having spatial resolution of 0.35 m in true colour, was created. It was used for visual, qualitative comparison with the original, and processed IKONOS images.

Fusion Methods
The objective of image fusion is to take advantage of the synergy between multispectral images, which are of lower spatial resolution, and a single broad (panchromatic) band covering the whole of the visible spectrum, which has higher spatial resolution. In the case of IKONOS if the 1 m resolution panchromatic band can be combined with the four 4 m multispectral bands, the spatial and spectral qualities of both images will be preserved. In this study four methods of combining the IKONOS wavebands were tested: they were IHS, Brovey Transform, SFIM, and Pan-sharpening by PCI Geomatica. These are briefly described below.

IHS method (Foley et al., 1990). The IHS method involves the transformation of a three-band combination of a multispectral image to an intensity, hue, and saturation color space image. The intensity component of this transformation is replaced with the PAN image, and a transformation back into an RGB image is performed. However, some colour distortion may result.

Brovey Transform method (Gillespie et al., 1987). The Brovey Transform is a formula-based process that works by dividing each colour band by the sum of three colour layers (for example, red, green, and blue) then multiplying this by the intensity layer (e.g. IKONOS panchromatic layer). A disadvantage is that, like the IHS method, it is limited to three-band composites.

Smoothing filter-based modulation (SFIM) method (Liu, 2000). SFIM can be performed on any number of multispectral bands, and maintains more of the spectral qualities than the IHS and Brovey methods. This method uses a smoothing convolution filter on the panchromatic image, which theoretically corresponds to the spectral qualities, not including the edge information. A ratio is taken where the smoothed image’s placement in the denominator will serve to cancel out the spectral qualities of the original PAN image in the numerator, while leaving intact the edge information left out of the smoothed image. Therefore the resulting image should maintain the spectral properties of the data, while gaining the edge information from the higher-resolution panchromatic data.

Pan-sharpening (PCI Geomatica) (Zhang, 2002). Like the SFIM method, this can operate on more than three bands, and also maintains the 11-bit data range. It is more suitable for use with IKONOS images than other methods, which assume that the panchromatic band covers only the visible spectrum. In fact, the IKONOS panchromatic band is additionally sensitive to near infra-red energy. Thus the method uses least squares to retain
the true greyscale value relationship between the IKONOS panchromatic and multispectral bands. It thus preserves almost the same colour as the original multispectral images and the same spatial detail as the original panchromatic image.

Visual Quality of Fused Images

Plate I shows the visual results of image fusion, by comparing them with the digital orthophoto (Plate Ib). The area is a partially forested slope with grassland at the upper levels (top of image) having two landslides of width 32 m and 19 m respectively. There is an obvious difference in image quality between the original IKONOS multispectral (Plate Ic) and panchromatic images (Plate Id), and both individually are inferior to the digital orthophoto. However, all of the fused images compare favourably in both tonal contrast and spatial definition (sharpness of boundaries) with the digital orthophoto. The spectral information content differs between the four fused images however. The IHS (Plate Ie) and Brovey methods (Plate If) were unable to preserve the spectral information (true colour) of the scene. The SFIM method (Plate Ig) was able to preserve the spectral (colour) information but it resulted in an overall smoothing of the image thus losing some spatial detail.

Overall the Pan-sharpened image (Plate Ih) using PCI Geomatica software was judged to be most satisfactory visually, and compared well with the orthophoto. In some respects this IKONOS Pan-sharpened image was superior to the orthophoto. This can be seen more clearly in Plate IIa and b, which show an area with several small landslides. On the Pan-sharpened IKONOS image (Plate IIb) the boundaries between landslides and their vegetated background are sharper and the image texture is enhanced, e.g. individual tree crowns are clearer, and other small disturbed ground features have a higher contrast and are more interpretable. Furthermore, the fused IKONOS image is less subject to shadow: the shadowed area covering the upper right portion of the orthophoto is absent on the IKONOS image. Additionally the colour spectrum is continuous over the whole IKONOS image area whereas the mosaics of the orthophoto create colour discontinuities.

For a more objective evaluation of the spectral information content, each fused band was correlated with its raw, unfused equivalent, for each fusion method. The Pan-sharpening method obtained the highest correlation coefficient, based on the total of three bands, with 2.83, and the IHS method had the lowest, with 2.52. Thus the Pan-sharpened image appears to be the least degraded spectrally by the fusion processing and retains more of the original information than the other methods.

DISCUSSION

Whereas, many ground resolution cells are usually required for successful air photo interpretation of features, as discussed earlier, the change detection analysis in this study has shown that small landslides, even those of 7–10 m (i.e. sub-pixel size) can be detected using SPOT® multispectral satellite images with 20 m spatial resolution. Specifically, Soeters and Cornelis (1996) state that 20–30 GRCs are required for successful identification of objects. However, in this study, since the context is known, mere detection of objects using tonal contrast on change images enables their identification as landslides.

For the recognition of processes on unstable slopes, IKONOS Pan-sharpened images may replace the 1:5000 scale aerial photographs recommended by Sissakian et al. (1983) for this purpose. Thus Plate IIa, the digital orthophoto and Plate IIb, the IKONOS Pan-sharpened image, show many ground details as well as differential and discontinuous vegetation phenomena. To the upper right of the image, relict landslide trails now invaded by Rhododendron shrubs can be observed, using image interpretation fundamentals such as the hue (dark green), texture (rough) and shape (spoon-shaped, lenticular crests and linear trails). The multiple crests of former landslides can be seen in the bottom right of the image, as spoon-shaped, partially revegetated areas with ground concavities revealed by shadowing. Both types of features are clearer on the Pan-sharpened image (Plate IIb) than on the digital orthophoto (Plate IIa). The greater range of green hues observed on the Pan-sharpened IKONOS image additionally suggests vegetation response to available soil moisture on this dry season image. Thus on Plate IIb, localized bright green patches suggest rapid growth of herbaceous vegetation in wetter areas possibly at seepage points, although fieldwork would be required to confirm such an interpretation.
Plate I. Extract of study area comparing the appearance of two landslides between different images: (a) legend; (b) orthophoto; (c) IKONOS multispectral image; (d) IKONOS panchromatic image; (e) IHS fused image; (f) Brovey fused image; (g) SFIM\textsuperscript{1} fused image; and (h) Pan-sharpened fused image.
Plate II. Comparison between (a) orthophoto and (b) Pan-sharpened fused images showing landslide scars, patches of disturbed ground and features of slope instability.
The main deficiency of this methodology for the qualitative interpretation of slope processes, is the lack of the height dimension offered by stereoscopic viewing of air photos. To some extent, this can be obtained from 2-D satellite images by the use of evidence such as shadow, and positional relationships to streams and ridges, as well as by draping the image over a DEM. For example, the models in Figure 5 are able to indicate the relative position and direction of landslide scars on the terrain, i.e. they mostly occur at mid-slope, near the junction between grassland and woodland.

Figure 5. (a) SPOT® image draped over DEM and overlain with NTLI landslide locations, (b) IKONOS Pan-sharpened image draped over DEM, with roads.
CONCLUSION

The study has shown that if multi-temporal images are available, the cognitive task of interpreting landslides may be simplified to automated change detection using satellite images. Due to the high contrast between landslides and their background, those of sub-pixel size can be detected. Thus approximately 70 per cent of landslides can be identified from SPOT* multispectral images with 20 m resolution, the main omissions being those smaller than 10 m. Furthermore, the Pan-sharpening method of image fusion applied to IKONOS images can provide most of the qualitative contextual parameters used in air photo interpretation (Table II), which indicate local factors such as the nature of slope materials, moisture status and erosional features necessary for landslide monitoring.

Thus, a practical scenario following a landslide event such as widespread heavy rainfall would be a dual-stage survey, as follows:

1. At reconnaissance level, SPOT* multispectral images with 20 m resolution may be used to map landslides over large areas using automated change detection. The cost is reasonably low since a single SPOT* image covering an area of $60 \times 60$ km$^2$ is priced at $\$1200$.

2. More detailed mapping and interpretation using Pan-sharpened IKONOS imagery in the areas most affected.

The new generation of advanced satellite sensors, including SPOT*, ASTER and IKONOS, which have stereo capabilities, could be utilized for landslide monitoring if the cost of images continues to fall. With reduced data costs, and advances in hardware and software, customized landslide monitoring systems using multi-temporal, stereo satellite imagery are achievable in the near future.

APPENDIX: DETECTION VERSUS INTERPRETATION (Philipson, 1997)

An object is detected when the directly observed difference in tones is abstracted to such a level that the object becomes distinguishable from its surroundings and its internal variability is suppressed, i.e. a boundary exists. Thus one can sometimes detect sub-resolution objects if their tones contrast sufficiently with their surroundings. Identification is the act of classifying, and can be based on the object’s geometry, spatial arrangement or context. Interpretation requires the assignment of meaning to the identified objects and this requires knowledge from the photographs themselves as well as from the relevant fields of study.

ACKNOWLEDGMENT

Thanks to the Geotechnical Engineering Office, Hong Kong for the loan of aerial photography and landslide data, and to H. N. Wong and W. L. Shum for discussions and advice on the topic. RGC grant A-PF69 from The Hong Kong Polytechnic University has assisted this research.

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