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Application of high-resolution stereo satellite images to detailed landslide hazard assessment

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Abstract

This study investigates and demonstrates the state of the art in remote sensing techniques for detailed landslide hazard assessment applicable to large areas. Since the most common methods of landslide hazard assessment using simple inventories and weighted overlays are heavily dependent on three-dimensional terrain visualization and analysis, stereo satellite images from the IKONOS Very High Resolution (VHR) sensor are used for this study. The DEMs created from IKONOS stereo images appear to be much more accurate and sensitive to micro-scale terrain features than a DEM created from digital contour data with a 2 m contour interval. Pan-sharpened stereo IKONOS images permit interpretation of recent landslides as small as 2–3 m in width as well as relict landslides older than 50 years. A cost–benefit analysis comparing stereo air photo interpretation with stereo satellite image interpretation suggests that stereo satellite imagery is usually more cost-effective for detailed landslide hazard assessment over large areas.

Keywords: Landslide; IKONOS; DEM; Stereo model; Hong Kong

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1. Introduction

Techniques for landslide hazard assessment generally require the collection of highly detailed information over large areas. Soeters and Cornelis (1996) defined four scales of slope instability assessment for landslide hazard: national, regional, medium and local. At the local level, only a few tens of square kilometers can be studied, and areas as small as 1 ha or less should be clearly defined. However, our experience in Hong Kong indicates that even such local-scale surveys give only an over-generalized ground situation, and that observation and mapped units need to be at a micro-scale between 10 m and a few centimeters. This is because the majority of Hong Kong has finely dissected rugged topography with highly complicated land use.

The most useful direct indicators of landslide susceptibility are considered to be evidence of past landslides as well as tension cracks and other detectable earth movement. Therefore, the simplest type of landslide hazard assessment comprises an inventory of previous landslides and signs of mass movement, based on the premise that an area with past landslides is landslide-prone and has a high probability of new landslides (Odajima et al., 1998). Indeed, for planning purposes, any landslides with historic movement during the last 100 years have been considered active in the western USA (McCalpin, 1974). Except in arid zones or under thick forest (Brardinoni et al., 2003), recent landslides can be readily identified on air photos due to high contrast with the darker vegetated background, although

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they become increasingly indistinct with time (Malamud et al., 2004). Our observations in Hong Kong suggest that older landslides may be identified from a marked linear depression, or distinctive early successional vegetation communities in the failed area.

A combination of field measurements and observations, and stereo air photo interpretation satisfies these requirements for landslide studies, although the task is labour-intensive. For instance, approximately 400 photo prints at a scale of 1 : 10,000 are required for a complete stereo cover of an area of 1000 km^2. Moreover, such a detailed air photo cover is costly, and manual methods of stereo air photo interpretation are time-consuming, especially if the results of the interpretation are to be input to a GIS database for weighted overlay analyses (Table 1). In such a case a Digital Elevation Model (DEM) is also required for orthorectification and the production of a slope map. However, even in developed countries, DEMs at grid resolutions higher than 50 m are not always available. Furthermore, provided that an accurate DEM is available, orthorectification of a single air photo may take 5 h of skilled work.

Although Mantovani et al. (1996) suggested that satellite images are unsuitable for landslide studies, Nichol and Wong (2005) demonstrated that approximately 70% of 495 recent landslides in Lantau Island, Hong Kong, including those in forested areas, could be detected by automated change detection using SPOT multispectral satellite images with a 20 m spatial resolution. The detected landslides included small ones down to 7–10 m wide. If stereo images are unavailable, the simple concept of 'detection' of bright objects from their background needs to be applied. The 'identification' and 'interpretation' of the features as landslides (Philipson, 1997) would require higher deductive processes based on stereo viewing of the topographic position and slope morphology.

The stereo capability of air photos (Table 1) that aids interpretation of slope morphology (Brunsden et al., 1975), as well as their higher resolution has mitigated against the use of satellite images (Mantovani et al., 1996). However, the improved spatial resolution and stereo capability of recent satellite sensors such as SPOT-5 HRG, Terra ASTER and IKONOS may give topographic details comparable to air photos in both 2D and 3D, with the advantage of a single mapping base covering large areas. Although Liu et al. (2004) constructed a 45 m DEM from Terra ASTER stereo images for a regional scale landslide hazard assessment around the Three Gorges Dam in China, the DEM was too coarse to represent steep and small valleys with gullies, which are often more susceptible to slope failure than main valleys. Eckert et al. (2005) also generated DEMs from ASTER images for mountainous terrain but obtained a large RMS error of 30 m.

To enable precise interpretation and visualization of slope morphology, 3D viewing is available using one of several techniques such as (i) direct stereo viewing of the image on a stereo-plotter, (ii) anaglyph construction, and (iii) draping the image over the DEM created from the same stereo satellite images. Measurement of elevations can be done either from the generated DEMs, or if ERDAS Imagine software is available, directly from the digital anaglyph. Since the latter is a manual technique it is considered to be more accurate than automatically processed DEMs. However, if the DEM is accurate and detailed enough to show minor changes in terrain height, the traces of small landslides may be identified even under relatively thick vegetation.

This paper describes an approach using high resolution stereo satellite images for assessment of landslide hazard at a detailed level corresponding to or finer than Soeters and Cornelis's (1996) local scale of analysis. The results demonstrate that the detection of meter scale micro-relief features and differences in surface texture indicative of micro-scale surface processes is now possible from high resolution satellite sensors. This study also evaluates the costs and benefits of applying techniques for detailed landslide surveys over larger areas.

Table 1
Traditional methods for landslide hazard assessment

Assessment method	Data required	Minimum resolution required	3-D (stereo) required	Area covered/scale of measurement
1. Direct observation of ground movement	field plot measurement	10 cm	no	sub-meter
	multitemporal air photos	10 cm	no	sub-meter
2. Heuristic (weighted overlays)	thematic maps, DEM/slope maps and past landslide locations	20 m	yes	medium to regional scales where detailed data are unavailable >1000 km^2
3. Inventory (past landslides)	air photos and field observations	10 m	yes	local to medium scales 100–1000 km^2

2. Study area and methods

The study area for this research covers a 24 km^2 part of Lantau Island in Hong Kong, (Fig. 1) with a relative relief of ca. 800 m. Broadleaf forest covers most valleys in the study area, with shrub and grassland on higher ridges and summits. The area is underlain by Jurassic volcanic tuff and lava.

Stereo IKONOS images acquired in January 2003 were used. They have forward and backward off-nadir viewing angles of 15.22° and 18.43° respectively, thus giving a base to height ratio of approximately 0.6. The images have an overlap area of about 93%. Their mean ground pixel size was 0.87 m at the acquisition time and it was later resampled to 1.0 m. The average sun azimuth and elevation angles at the acquisition time were 152.24° and 44.63° respectively.

Twenty-eight well-distributed ground control points (GCPs) and 35 checkpoints were digitized from recent 1 : 1000 digital maps produced by the Lands Department of Hong Kong. The points correspond to clearly identifiable landmarks and intersections between roads or footpaths. The measurement error of the image coordinates of the points was within half a pixel (43 cm). The elevations of these points were also taken from a DEM with a grid resolution of 2 m, produced from recent topographic maps with a contour interval of 2 m.

IKONOS stereo images are usually provided with the rational polynomial coefficients (RPC) which represent the relationship between the image and the object spaces. Research conducted on the RPC-based model (see Fraser et al., 2002; Grodecki and Dial, 2003) shows that there are systematic errors in the sensor exterior orientation of IKONOS which can be removed by using GCPs in the RPC-based model to achieve an accuracy up to 1 m. The 3D affine transformation model (Fraser et al., 2002; Shi and Shaker, 2003; Shaker and Shi, 2003) and the three-dimensional CCRS multisensor physical model (Toutin, 2003, 2004) have also been tested and in most cases the resultant accuracy is up to 1 m in planimetric position and 1.5–2 m in height. In our work, the RPC-based model was used to create the stereo model and generate the DEM because of its slightly better accuracy and availability in the accessible software: Image Station for digital photogrammetry and ERDAS Imagine.

The image coordinates of both the GCPs and the checkpoints were input to the software for the step of sensor (camera) modeling and orientation. In order to eliminate some positional bias and small observed rotations, the GCPs were used to calculate modified coefficients of the sensor model, following the practice of Fraser et al. (2002) and Grodecki and Dial (2003). Then absolute orientation was carried out based on space-

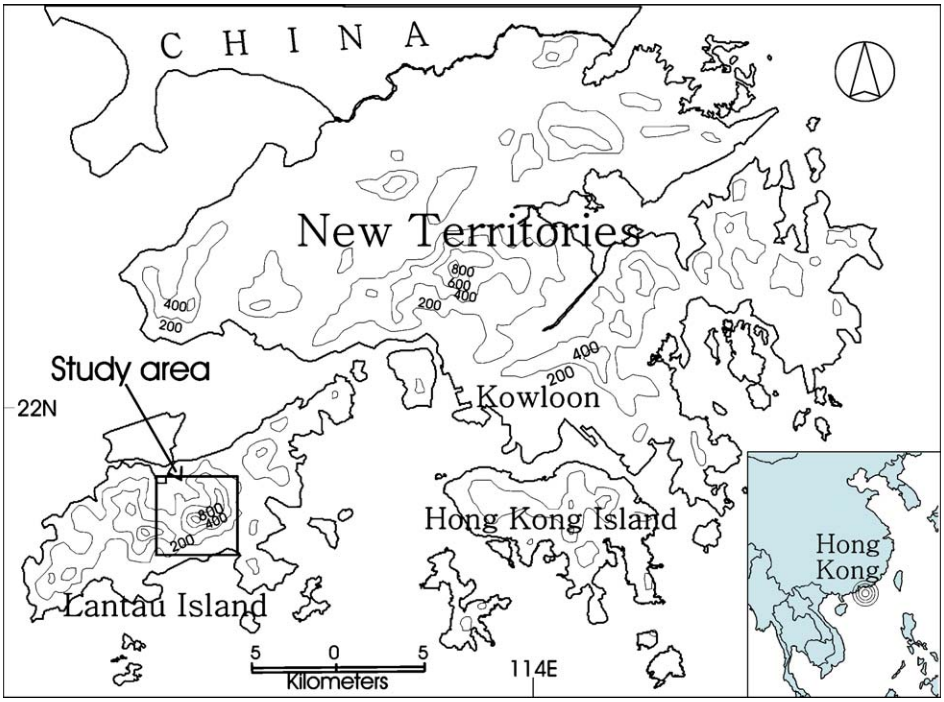

Fig. 1. Location of study area in Lantau Island, Hong Kong.

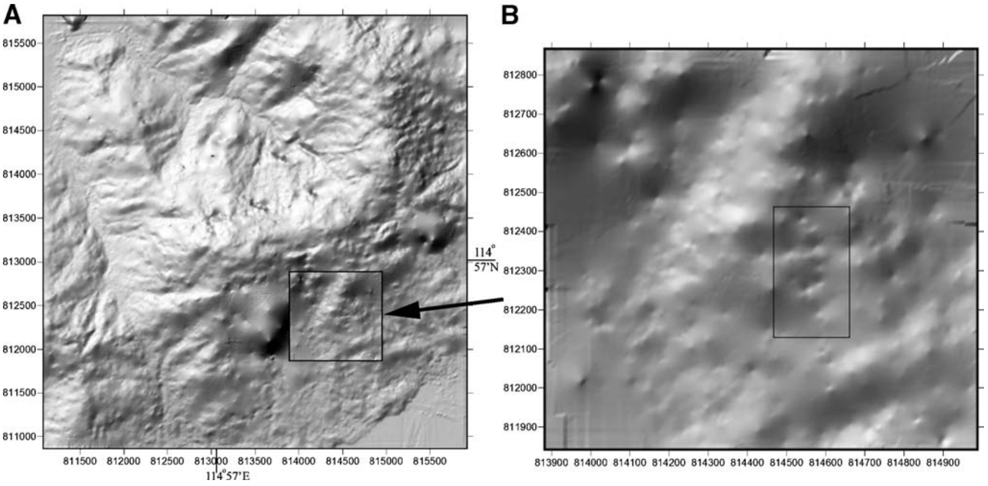

Fig. 2. Shaded relief models of DEMs generated from IKONOS stereo images. (A) whole study area (24 km^2) with cell size of 5 m, (B) specific area of interest (1.14 km^2) with cell size of 1 m. Box in (B) shows location of Fig. 3.

intersection to calculate 3D coordinates from the stereo images. The accuracy of the orientation results was assessed using the 35 checkpoints.

Automatic image matching was conducted to define points in the overlap area between the two stereo images. Although the matching process produced a number of tie points, small areas with highly variable terrain elevations could not be matched. Therefore, 23 additional points were manually digitized in these areas and used for interpolation to produce a 5 m DEM for the overlap area. The quality of the generated DEM (Fig. 2A) was then assessed by comparing the elevations of 42 well-distributed checkpoints with those on a 0.5 m DEM generated photogrammetrically from false colour diapositive air photos with a very high (8 cm) resolution.

Since the main focus of this study is small landslides on steep slopes, another 1 m DEM was generated for a specific area of interest (Fig. 2B). The accuracy of this DEM was assessed by comparing the elevations of 14 locations along a longitudinal section of a landslide trail and four points along a section across the landslide crown (Fig. 3) with (i) the existing DEM from 2 m contour maps, (ii) measurements on the anaglyph generated from IKONOS stereo images, and (iii) measurements on an anaglyph generated from the 8 cm resolution air photos. The Natural Terrain Landslide Inventory (NTLI) database of the Geotechnical Engineering Office of the Hong Kong Civil Engineering and Development Department, which includes records of all landslides since 1945, was also used as a reference for the proportion of landslides, which could be identified using either stereoscopic air photos or IKONOS images with both planimetric and stereoscopic viewing.

3. Results and discussion

3.1. DEM accuracy

The results of the orientation process using the RPC-based model gave total RMS errors at the checkpoints of 0.77, 1.40 and 2.74 m and maximum residual errors of 1.33, 3.10 and 5.74 m in X, Y and Z directions, respectively. This was achieved by using only four

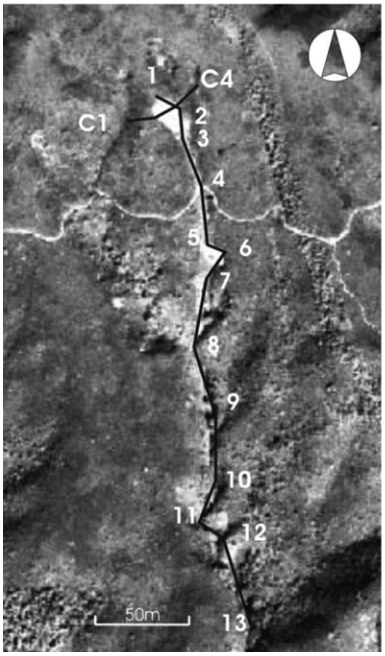

Fig. 3. Location of 14 traverse points and cross section shown on IKONOS image. Footpath intersecting with landslide trail at point 4 is ca. 1.5 m wide. See Fig. 2B for location of this image.

appropriate GCPs and there was almost no improvement in the accuracy by adding more GCPs. The accuracy of the RPC-based model applied to the IKONOS stereo images in our study is slightly lower than that of previous similar research by Fraser et al. (2002) and Toutin (2004). The main reason for this may be much greater relative relief and ruggedness in our study area.

Assessment of the IKONOS 5 m DEM at 42 checkpoints using the DEM from the air photos as reference shows that most of the points have height errors between − 1.50 and 2.5 m, but a few steeply sloping areas have larger errors up to 5.0 m. The total RMS error and the linear error with a 79% level of confidence (LE79) of the 5 m DEM were 4.13 and 5.0 m, respectively.

The mean height difference between the measurement on the IKONOS anaglyph and that on the air-photo anaglyph was ca. 1.0 m along the longitudinal section (Fig 4A) and less than 0.5 m along the cross section (Fig. 4B). Elevations from the IKONOS 1 m DEM are much closer to those from the air-photo anaglyph than are those from the DEM derived from the 2 m contour maps. The contour-based DEM suggests only a 3 m deep, V-shaped topography along the cross section, whereas the measurements from the IKONOS anaglyph indicate a 5 m deep U-shaped topography (Fig 4B). The difference would be crucial for volumetric studies, since the IKONOS stereo suggests a much greater volume of material removed from the landslide crown. Thus, for detailed morphometric analyses, IKONOS stereo images seem to be more useful than existing DEMs and give similar accuracy to the stereo air photos.

3.2. Data visualization and interpretation

IKONOS stereo images may be visualized using three different approaches: creating anaglyphs (Fig. 5),

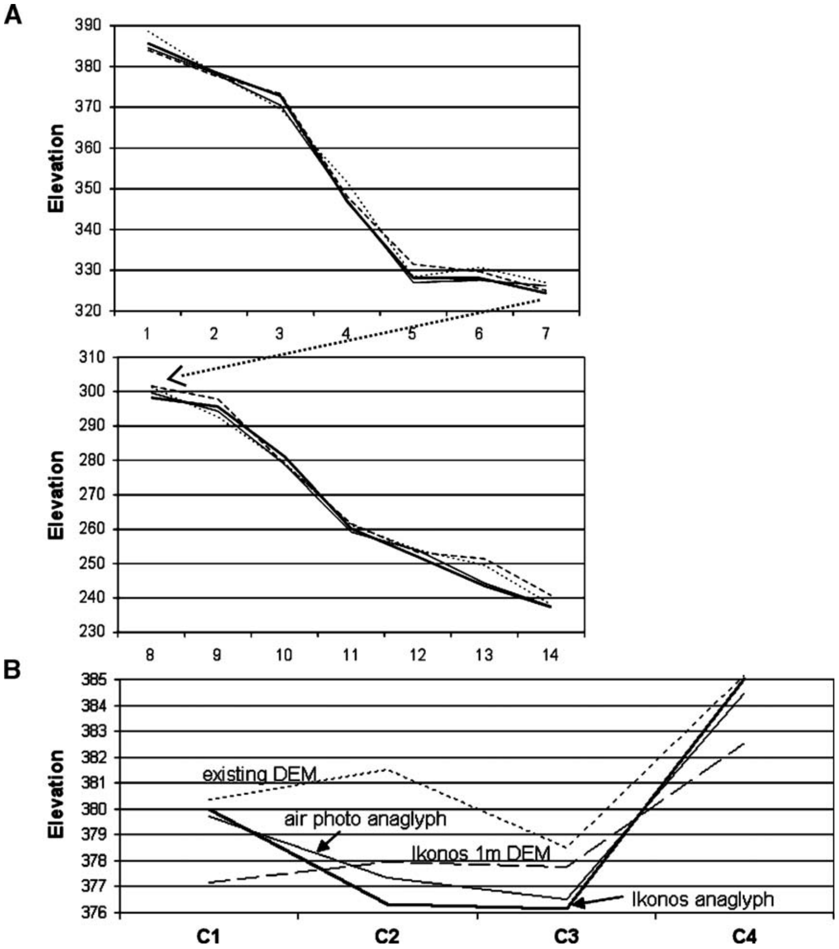

Fig. 4. Comparison of elevations (m) obtained at statios along and across landslide trail among IKONOS anaglyph, IKONOS 1 m DEM, existing DEM from 2 m contour maps, and anaglyph from high-resolution air photos. (A) Points 1–14 along longitudinal section; (B) Points C1–C4 along cross section. See Fig. 3 for their locations.

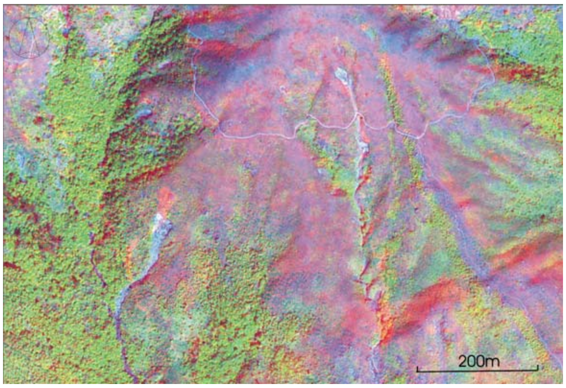

Fig. 5. Anaglyph produced from pan-sharpened IKONOS stereo imagery, which may be viewed in 3D using red-blue glasses. Foothpath in upper centre is ca. 1.5 m wide.

draping the IKONOS ortho-images over the generated DEM (Fig. 6), and creating stereograms (Fig. 7). The main aim of the 3D visualization is to contribute additional contextual, locational and morphological information to planimetric image interpretation.

The NTLI database shows that 42 landslides occurred in the area covered by the 1 m DEM (Fig. 2B), between 1945 and the image date (January 2003). Of these, only the large and recent landslides (about 20%) can be identified on the pan-sharpened, planimetric IKONOS image. However, with the direct 3D viewing of the IKONOS images on the stereo plotter, the colour, shape, topographic position, and vegetative details were visible, permitting an experienced interpreter to identify approximately 50% of the landslides. Additionally, some old landslides which occurred before 1945 could be identified. These include a landslip at A on Fig. 6, in the form of a marked inverted V-shaped scarp, and smaller spoon-shaped concavities elongated downslope at B, C, D and E. Some of these are in the shrub stage of succession to forest (B and D). All the landslides less than eight years old including those with a small width of 2–3 m were identified. However, sub-meter features such as tension cracks were not visible.

Stereoscopic interpretation of 1 : 10,000 scale aerial photographs, commonly used for constructing landslide inventories in Hong Kong, showed a similar result, i.e., 21 of the 42 landslides were detected. Although the air photos potentially have a very high spatial resolution of 63 line pairs per mm, or 8 cm on the ground, they did not lead to a significantly improved result. In addition, their interpretation is often tedious due to the restricted field of view under the binoculars and the fixed viewing base of standard mirror stereoscopes. On the other hand, IKONOS stereo images are easier to manipulate since they can be viewed at various scales and fields of view. Anaglyphs are also available for detailed 3D viewing of small areas such as scarps, rock outcrops and tension cracks. Furthermore, the 4-band, 11-bit data format of IKONOS gives superior image quality to air photos. Nichol and Wong (2005) demonstrated that among the four image fusion techniques, the PCI-Geomatica method of pan-sharpening (Zhang, 2002) was able to preserve both the spatial details of the 1 m IKONOS panchromatic band as well as the spectral details of the multispectral images. The NTLI database records only the length and position of landslides, not the width and volume. However, the volume of material removed may be calculated automatically using digital cross sections from the IKONOS 1 m DEM (Fig. 4) and may be used to estimate sedimentation rates and water quality in the lower catchments.

3.3. Cost comparisons

In countries such as Hong Kong, air photos are routinely taken by the government and are distributed free of charge to various institutes. It is easy to understand why air photos remain the preferred medium for creating landslide inventories. However, in areas where the availability of such data is low, or when the objective of the project is to integrate a landslide inventory with other digital data for regional landslide hazard assessment, the use of satellite images is a viable option. Table 2 presents costs and benefits for the current ‘state of the art’ stereo satellite sensors for mapping an

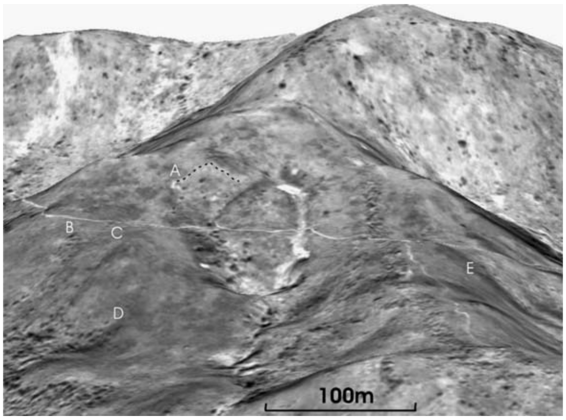

Fig. 6. Panchromatic ortho-image draped over IKONOS-derived DEM showing detailed terrain information. Landslide trail in image centre is ca. 7 m wide, and footpath crossing from left to right is 1–2 m wide. Landslides older than 50 years can be detected; inverted V-shaped scarp (A) and inverted spoon-shaped concavities (B, C, D and E). At B and D shrub crowns (darker patches) indicate early stages of vegetation succession toward forest.

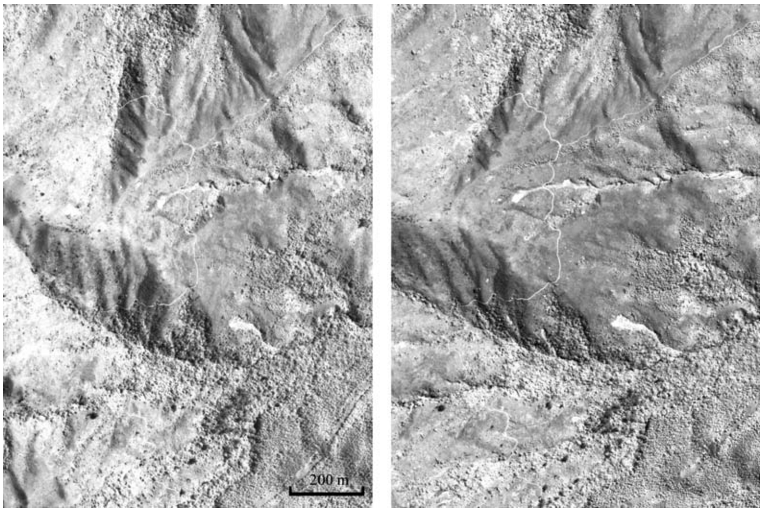

Fig. 7. Stereogram from Pan-sharpened IKONOS stereo imagery, for 3D viewing using stereoscope.

area of 1000 km^2, an area equivalent to the land area of Hong Kong. If air photos have already been taken and are available, the overall cost of the air-photo-based approach is similar to that of the IKONOS-based approach. If flying costs to take new air photos are added, the cost of the air-photo-based approach becomes 46% higher, or 41% higher if tasking of IKONOS is required. A comparison of all image types for the total job cost indicates that the use of Terra ASTER stereo images is incomparably cheap. However, Liu et al. (2004) observed that even for a regional scale landslide hazard assessment for a large area of ca. 6000 km^2, local topographic details were still required for depicting landslides in steep minor valleys, and that an image resolution of 15 m and a DEM resolution of 45 m from Terra ASTER were not adequate. Furthermore, the RMS error of 30 m achievable from Terra ASTER DEMs (Eckert et al., 2005) is obviously inadequate for the identification of revegetated landslides and their volumetric estimates.

4. Conclusions

This study has demonstrated that IKONOS stereo images can more than satisfy the requirements of landslide hazard assessment at local and medium scales (Type 3 in Table 1) where the scale of observations is between 10 and 100 m and where micro-scale features to be identified have dimensions of 1 to 10 m. The IKONOS images viewed in 3D were adequate for identifying

Table 2

Relative costs ($US) of data acquisition and processing for landslide survey in 1000 km^2 area based on stereo images

	Air photos (1 : 10,000 scale)[a]	Pan-sharpened IKONOS	Pan-sharpened SPOT 5	ASTER
No. of images for stereo cover	400	32	4	2
Image resolution (m)	0.2 (63 lppm)	1	2.5	15
DEM resolution[b]		1	7.5	45
DEM accuracy (RMSE) (m)	0.6–1.0	2.5–5.0	6.5 (Toutin, 2004)	30 (Eckert, 2005)
Material cost of images	11,000 (20 per print)	46,000[c]	9000	120
Time (h) / cost[d] (geo-referencing)[e]		48 / 960	6 / 120	6 / 120
Time / cost (DEM)[d]		48 / 960	6 / 120	6 / 120
Time / cost (interpretation and mapping)[d]	960 / 19,200	40 / 800	20 / 400	10 / 200
Total job cost	30,200	48,720	9640	560
Cost with image acquisition added	56,100 (+25,900[f])	52,720 (+4000[g])		

[a] Air photo study assumes manual, not digital, processing and interpretation.

[b] Commonly three times pixel size.

[c] Cost of IKONOS images varies by country/continent: price quoted is USA price.

[d] Time in hours is costed at US $20 per hour.

[e] Assuming no ground truth is required; if required, add four days for 32 GCPs.

[f] Aircraft four days: $25,900.

[g] Tasking of IKONOS stereo: $4000.

all recent landslides as well as some very old landslides in the study area, based on slope morphology and regrowing vegetation. The level of 3D spatial detail achieved is deemed to be similar to that of 1 : 10,000 scale air photos, but IKONOS images surpass air photos in terms of spectral quality, ease of manipulation, a single image base for generation of a DEM, and cost. The DEM created from IKONOS appears to be highly accurate, surpassing even that created from digital contour data with an interval of 2 m.

Since IKONOS and SPOT satellites can be programmed to image any area, and the repeat cycle of both is within three days (off-nadir mode), stereo satellite images now provide a viable alternative to air photos for creating detailed landslide inventories at a range of scales.

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