The Enhanced Natural Terrain Landslide Inventory

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ABSTRACT

The Enhanced Natural Terrain Landslide Inventory (ENTLI) consists of a comprehensive record of historical natural terrain landslides in Hong Kong. Maunsell Fugro Joint Venture (MFJV) was commissioned by the Geotechnical Engineering Office to compile the Inventory.

The ENTLI has been compiled from interpretation of a comprehensive set of aerial photographs taken between 1924 and 2003. The GIS-based inventory is a valuable source of information to geotechnical practitioners for undertaking natural terrain landslide and slope studies in Hong Kong, in assessing the susceptibility of hillsides to failure and potential risks posed by natural terrain landslides to the community.

This paper outlines the approach and methodology adopted in compilation of the ENTLI; presents briefly the findings of the work; and, provides discussion on the limitations of the data.

1 INTRODUCTION

The Enhanced Natural Terrain Landslide Inventory (ENTLI) is a comprehensive record of historical natural terrain landslides in Hong Kong. The inventory was compiled from interpretation of available low (<8,000feet) and high-flight (≥8,000 feet) aerial photographs and was presented on a 1:5,000-scale mapsheet basis. The locations of all identified landslides and associated data were recorded directly into a geographical information system (GIS) for ease of input and subsequent analysis. A report was produced for each 1:5,000-scale mapsheet together with a summary table showing the basic data on each landslide and a list of aerial photographs used for interpretation.

2 BACKGROUND

In the mid-1990s, the Geotechnical Engineering Office of the then Civil Engineering and Development Department of the Hong Kong Government (hereafter referred to as GEO) commenced the first phase of the Natural Terrain Landslide Study with the creation of an inventory of historical landslides occurring on natural terrain in Hong Kong (known as the Natural Terrain Landslide Inventory or NTLI), based on aerial photograph interpretation (API) using high-flight aerial photographs (≥8,000 feet) taken in 1945 to 1994. The compilation methodology for the NTLI is reported in King (1999).

Since 1998, updates of the NTLI were undertaken as part of various natural terrain landslide studies: 1995 to 1997 (Scott Wilson 1999), 1998 to 2000 (MFJV 2003a), and 2001 to 2003 by both Maunsell Geotechnical Services Ltd. (MGSL) and a Fugro Scott-Wilson Joint Venture (FSW). Up to 2003, the NTLI contains about 30,000 features. The data has been widely used in natural terrain-related studies to assess susceptibility of hillsides to failure and potential risks posed by natural terrain landslides.

The limitations of the NTLI are broadly discussed in King (1999) and discrepancies between landslide findings from site-specific natural terrain studies and those features contained within the NTLI have been discussed by others, e.g. Parry (2001), Pinches and Smallwood (2000), Pinches et al. (2002) and MFJV (2003b). In particular, the high-flight API, on the basis of which the NTLI was compiled, has a limited resolution, with many smaller natural terrain landslides or those occurring some time before the aerial photographs were taken, being difficult to identify. Identification of such landslides using low-flight aerial photographs was considered necessary to provide additional information and on a comprehensive basis, has been instrumental in the study of natural terrain landslide hazards and in detection of hillslope catchments with historical landslide activities potentially posing a risk to the community.

In early 2004, it was decided to establish an updated natural terrain landslide catalogue for Hong Kong, using both high and low-flight aerial photographs (ranging from 1,800 to 20,000 feet flight-height), in addition to years of coverage excluded from the NTLI. To develop a methodology and to evaluate required resources, a Pilot Study for 28, 1:5,000-scale mapsheets covering Hong Kong Island, Kowloon and Sha Tin foothills was undertaken by MGSL and FSW under two separate consultancy agreements. In July 2005, Maunsell Geotechnical Services Limited and Fugro (Hong Kong) Limited Joint Venture (MFJV) were commissioned to compile the catalogue for the remaining 155, 1:5,000-scale mapsheets.

The main ENTLI study was finished in March 2007. Validation of both the API mapping and the relevant digital data continued until July 2007. Updating of the ENTLI for 2004 to 2006 has subsequently also been undertaken by MGSL and FSW in 2008, under two separate consultancy agreements.

3 COMPILATION METHODOLOGY

The ENTLI compilation methodology was developed on the basis of the NTLI compilation methodology reported in GEO Report No. 74 and the GIS data-generation procedures adopted as part of the NTLI update for year 1998 to 2000 (MFJV, 2003a), with the following modifications and refinements.

The first key difference from the original NTLI methodology is that a much greater coverage of aerial photographs has been used during preparation of the ENTLI than in the NTLI (approximately 20,000 aerial photographs were reviewed during compilation of the NTLI as compared to approximately 105,000 reviewed as part of ENTLI compilation). The second is the greater detail in the treatment of relict landslides (see Section 3.1.2 below).

The third major difference is the interpretation of what construes ‘development’ and ‘natural terrain’. In the previous NTLI study and updates, each sequential period of aerial photographic coverage was used to generate and update a plan showing development lines, separating natural terrain from development. As described in GEO Report No. 74, natural terrain was defined as “*Terrain that has not been modified substantially by human activity but including areas where grazing, hill fires and deforestation may have occurred.*” Interpretation for the NTLI was restricted to the area defined as natural terrain.

Under the present ENTLI compilation procedure, the interpretation was not restricted to a tight definition of natural terrain as constrained by a development line. Instead, the interpreter was required to evaluate the origin and nature of a targeted feature with respect to the aerial photographs reviewed, evaluating if the feature was clearly a man-made slope feature (e.g. cut or fill slope failure), or a natural terrain feature.

The ENTLI compilation methodology comprises two major components: Firstly, the interpretation of recent and relict landslides from available aerial photographs and secondly, the creation of the associated landslide dataset. Existing features in the NTLI (up to year 2003) were checked and validated, with positional amendment and deletion made where appropriate. Additional landslides interpreted and not previously recorded by the NTLI were then digitised, with the complete catalogue compiled using GIS.

3.1 Definition of recent and relict landslides

During compilation of the ENTLI, landslides were classified into two groups: recent if they occurred within the time scale of the available aerial photographs and relict if they occurred earlier.

3.1.1 Recent landslide classification

Recent landslides are defined as those features that clearly occurred within the time scale of the available aerial photographs. GEO Report No. 74 elaborated that “*The scars of recent landslides have a distinctive light tone on aerial photographs and are generally bare of vegetation, being in vegetation cover Classes A or B* [completely or partially bare of vegetation]. *The time period in which they occurred can be confirmed by reference to earlier aerial photography"*. The ENTLI definition of recent landslides follows that used by the NTLI study.

Recent landslides recorded by the ENTLI were classified into three principal types: open hillslope, channelised or coastal.

- Open hillslope landslides are those where landslide debris could be observed extending directly downslope, with no evidence of deviation or redirection caused by localised channelisation along topographic depressions.
- Channelised landslides are those where the landslide debris could be observed to deviate from a vertical trajectory due to the influence of localised topographic depressions (e.g. stream courses).
- Coastal landslides are those where the landslide was considered to have been caused by under-cutting from wave erosion. Where the landslide source was adjacent to the coast but did not intersect the shoreline or was protected from wave erosion (e.g. at the crest of a rock cliff), it was not classified as a coastal landslide.

3.1.2 Relict landslide classification

Relict landslides are those that occurred earlier than the time scale of the available aerial photographs. GEO Report No. 74 stated that "*Relict landslides are covered in grass, shrubs or trees (vegetation classes C or D)* [completely covered by grasses or by shrubs and trees] *but the ground still shows some clear characteristics of a landslide scar. They were mapped when a spoon-shaped depression with a sharp main and/or lateral scarps was either visible or could be reliably inferred from vegetation characteristics.*"

Under the ENTLI study, the relict landslide definition was modified to provide a more comprehensive record of relict features than the NTLI and to include an expression of the relative certainty behind the interpretation. ENTLI relict landslides were further classified as A, B or C-Class features with an indicative probability of interpretation of 80%, 50% and 10% respectively, together with additional S-Class records for coastal landslide features caused directly by under-cutting from wave erosion (Figure 1).

3.2 Aerial photograph interpretation procedures

3.2.1 Aerial photographs used

Recent landslides were identified from sequential interpretation of 1924 to 2003 aerial photographs. These included both high-flight and low-flight photographs taken at 1,500 to 20,000 feet, giving nominal scales of 1:3,000 to 1:40,000.

Relict landslides were principally identified by interpretation of 1963 aerial photographs, in order to facilitate a consistent baseline review process. The 1963 aerial photographs comprise the earliest high-resolution, HKSAR-wide aerial photographic coverage taken at 2,500 to 8,000 feet. The reduced post-war vegetation density also facilitates improved observation and interpretation of underlying hillslope terrain.

Additional years of aerial photographs were only reviewed as part of the relict landslide mapping process under two scenarios. The first was where relict NTLI landslides were recommended for deletion following 1963 aerial photograph review. For such cases, the year of aerial photography recorded for the NTLI feature (typically 1945 or 1964) was also reviewed to further validate the proposed deletion. The second was where no 1963 aerial photographic coverage existed for a particular mapsheet. For such cases, the highest resolution, lowest flight-height aerial photographs nearest to 1963 were reviewed.

3.2.2 Aerial photographs selection

A GIS solution was developed to facilitate aerial photograph selection. The system converted the aerial photograph centroid data into coverage footprints using flight-height, camera focal length and aerial photograph print dimensions. Algorithms were also developed to determine flight path vectors so as to ensure correct orientation of generated aerial photograph footprints. Aerial photographs relevant to particular 1:5,000-scale mapsheets were automatically selected and aerial photograph lists then generated.

Class A1	Class A2

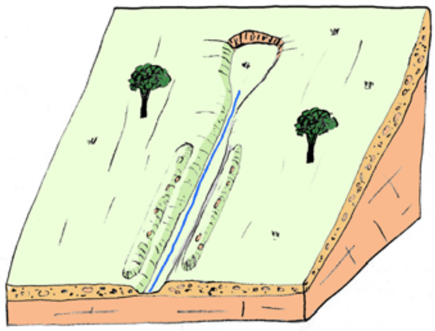
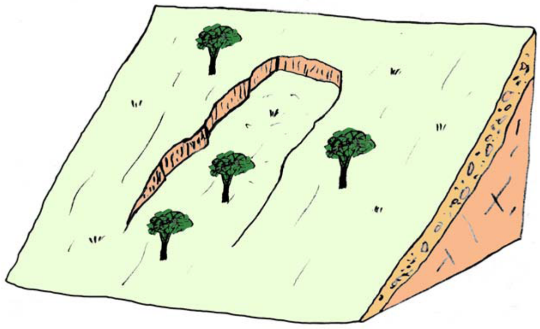
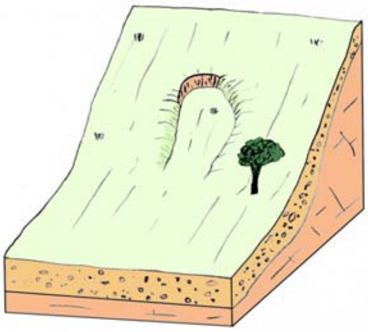
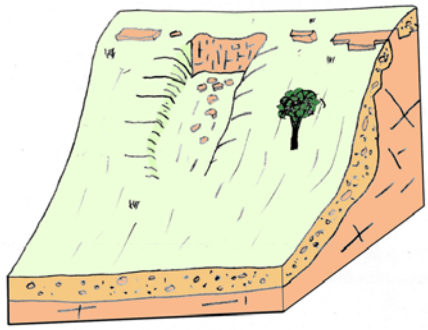
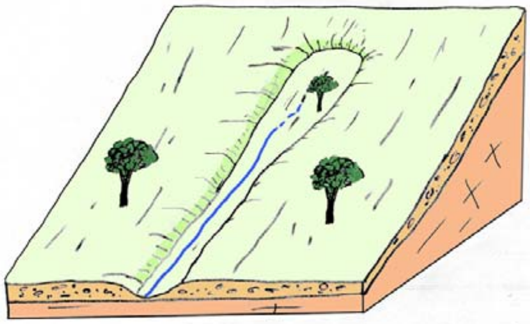
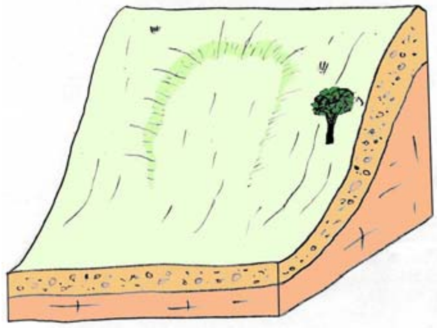
	
• Debris evident (levees), which are clearly related to source. • Source area scarp mainly rounded. • Vegetated source and debris. • Well-defined drainage line. • Assigned certainty 80%	• No debris evident. • Source area scarp mainly sharp. • Vegetated source. • No drainage line present. • Assigned certainty 80%
Class B1	Class B2
	
• No debris evident. • Source area mainly rounded. • Vegetated source. • No drainage line present. • A depression inconsistent with adjacent slope morphology. • Assigned certainty 50%	• Possible subsequent rockfall debris. • Source area scarp mainly rounded. • Vegetated source. • No drainage line. • Rock outcrop forms part of scarp. • Assigned certainty 50%
Class C1	Class C2
	
• No debris evident. • Source area mainly rounded. • Vegetated source. • Head of drainage line. • No clear evidence of mass movement. • Possibly result of fluvial erosion. • Assigned certainty 10%	• No debris evident. • Broad depression bounded by gentle break in slope. • Vegetated source. • No drainage line present. • No clear evidence of mass movement. • Assigned certainty 10%

Figure 1: Schematic examples of landslide classifications

3.2.3 Aerial photograph review procedures

Available aerial photographs were collected for review on the basis of three principal criteria. These were:

(i) Low-flight height. As the aim of the ENTLI was to improve and update the preceding NTLI, review of low-flight aerial photographs was imperative. Where low-flight aerial photographs were unavailable or inexistent, relevant high-flight aerial photographs were reviewed.

(ii) Fullest coverage. Full mapsheet coverage of reviewed aerial photographs was required to ensure that mapsheets had been effectively surveyed. Where low-flight coverage was incomplete, high-flight aerial photographs were reviewed.

(iii) Post wet-season. Review of post wet-season aerial photographs (August to December) was prioritized in order to reduce the number of aerial photographs requiring review. It was also considered that such photographs would more likely contain landslide-related features warranting incorporation into the ENTLI. Where post wet-season aerial photographs were unavailable, inexistent or incomplete, pre wet-season aerial photographs were reviewed.

The review of 1963 aerial photographs for relict landslides identification was solely undertaken by senior API personnel to ensure consistency of interpretation and judgment. Internal cross-checking was arranged to confirm aerial photograph review procedures and ensure product consistency.

4 DATA COMPILATION & DIGITISATION

Data, particularly feature positioning, was input directly into a GIS, facilitated by digital orthophotographs and 1:1,000-scale topographical baseplans. The availability of 1963, 1973, 1982, 1993, 2000 and 2002 orthophotographs and 1:1,000-scale topographic data, provided greatly improved positional accuracy against the NTLI wherein data was manually drawn onto 1:5,000-scale baseplans and was subsequently digitised.

5 RESULTS

The ENTLI identified a total of 105,364 landslide features up to year 2003. These landslides included 15,794 recent and 89,570 relict records.

As part of the ENTLI compilation, 29,669 NTLI features up to year 2003 were reviewed. Of these, 7,954 features (26.8%) were deleted; locations for 20,559 (69.3%) features amended and only 1,156 features (3.9%) retained in their original locations. Most of the features recommended for deletion were determined to be non-landslide features such as gullies, rock outcrop and erosion, or man-made features with appearances similar to small-scale landslides (e.g. graves and ground investigation locations). Such features were likely to have previously been misinterpreted due to only high-flight aerial photographs having been reviewed in compiling the NTLI.

Of the 15,794 recent landslide features recorded by the ENTLI, the majority were classified as open-hillslope failures (10,551 records) with fewer channelised landslides recorded (5,020) and only very few coastal landslides considered to have been caused by coastal undercutting (223). These figures appear to identify the prevailing Hong Kong failure mechanism, although difficulty in differentiating channelisation from aerial photographs suggests that such judgments should be reserved and that the capacity of open hillslope failures in becoming channelised (given the presence of specific ground form characteristics), not be discounted.

Relict landslides represent the largest proportion of the ENTLI (89,570 records). Of these records, 19,624 represented landslides with 80% indicative probability of interpretation (Class A1 and A2), with only 1,207 of these records interpreted to demonstrate trails definitively associated with downslope debris accumulations (Class A1 only). A further 35,527 records represented landslides with 50% indicative probabilities (Class B1 and B2), with the majority of these records relating to the presence of degraded depressions interpreted to have been probably formed due to historic landsliding (Class B1). Only 9,269 of these records were interpreted to relate to failures emanating from rock-based areas with rocky backscarp features (Class B2). The remaining 34,407 ENTLI records comprised landslides with 10% indicative probability of interpretation (Class C1 and C2, 30,115 records) and coastal landslides interpreted to have been initiated due to coastal undercutting (4,292). These results are summarised for ease of reference in Table 1.

Table 1: Final ENTLI summary results

Slide Type	No. of Recents
C	5,020
O	10,551
S	223
Total	15,794

Class	No. of Relicts
A1	1,207
A2	18,417
B1	26,268
B2	9,269
C1	19,674
C2	10,441
S	4,292
Total	89,570

6 LIMITATIONS

6.1 Recognition

The ENTLI retains some of the intrinsic limitations of the NTLI that may lead to omitted or misinterpreted landslides. These limitations can be caused by the relative angle of the photograph and the observed feature, the presence of shadows, cloud and vegetation cover, the low and poor resolution of earlier photographs, and the possibility of an incomplete set of photographs for a particular area. It is also possible that some of the identified features are in fact not landslides, but had the attributes of landslides when viewed from aerial photographs. Furthermore, none of the landslides were examined or verified by site assessment and field mapping.

The ENTLI should only be used to provide a general indication of the distribution of landsliding on natural terrain and should not be relied upon for specific assessments of individual sites. Such assessments should include, amongst other things (c.f. Ng et al. 2003), a thorough review of all available high- and low-flight aerial photographs, backed up by detailed field mapping by experienced practitioners.

6.2 Date of occurrence

The year of photography on which recent landslides were first identified and the year of preceding aerial photography on which the landslide was not present, have been recorded. These years simply bracket the time period within which the landslide is considered to have occurred. Precise dating of the landslide event cannot be determined.

The date of occurrence of relict landslides also cannot be determined, as these features may relate to events that occurred hundreds or thousands of years ago.

6.3 Classification

Most of the landslides recorded in the ENTLI consist of channelised and open hillslope debris slides, debris flows, complex debris slide-flows, or composite slide-flow falls (Cruden and Varnes 1996).

Despite these variations, all ENTLI landslides are represented in the same way by a point representing the landslide crown and a line depicting the debris trail or the length of the landslide source area. The ENTLI feature will not reflect variations in the significant change of hazard that this represents. A small volume landslide of little consequence has been recorded in the same way as larger events, although this has been partially redressed through the incorporation of source area width and length data together with the recent and relict landslide classifications.

6.4 Relict landslides

Many limitations in identifying and recording the relict landslide dataset exist, given that they are very old, overgrown and often severely degraded topographical features, requiring considerable skills to interpret. In addition, the methodology of relict landslide interpretation and digitisation targeted the identification of single landslide features rather than large composite features.

It must be emphasized that the debris trail length has only been recorded for Class A1 features, with the digitized trails for the remaining relict landslide classes (A2, B1, B2, C1, C2 and S) only referring to the interpreted length of the landslide source area. Thus, the trail length recorded for these relict landslide classes differs considerably to that of recent landslides.

The above limitations pertaining to recorded ENTLI relict landslides further highlights the need for detailed site-specific API and desk study, backed up by comprehensive field studies.

6.5 Relevant aerial photograph selection

Given the tight programme for the ENTLI, selection of relevant aerial photographs was undertaken in accordance with the methodology detailed in Section 3.2. This methodology considerably reduced the number of aerial photographs requiring review. It is likely that additional ENTLI features would have been identified had all relevant aerial photographs of all flight heights been reviewed.

7 CONCLUSION

The Enhanced Natural Terrain Landslide Inventory (ENTLI) consists of a comprehensive record of historical natural terrain landslides in Hong Kong. The inventory was compiled from interpretation of available low and high-flight aerial photographs with records presented on 1:5000 scale map sheets and a geographical information system (GIS) for ease of input and subsequent analysis of the results. The basic information with the derived recent and relict status of the landslide has been incorporated into the GEO Slope Information System (SIS) for easy reference.

The ENTLI provides a useful indicator of the presence of past landsliding near a site but should always be supplemented with detailed site-specific interpretation of low-flight aerial photographs and detailed field mapping by experienced engineering geologists and engineering geomorphologists to bring it up to date, better classify the landslides and understand the history and geomorphology of slopes adjacent to a site.

With regular updating and ongoing correction of the ENTLI, it will form an up to date listing of all identified natural terrain landslides in Hong Kong.

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