Reducing Uncertainty in Natural Terrain Hazard Studies: the Role of the Engineering Geologist

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ABSTRACT

Natural terrain hazard studies can appear deceptively simple. A limited Aerial Photograph Interpretation can be undertaken and a hazard model generated from this plus existing landslide datasets, such as the ENTLI. Geographical Information Systems can be used to interrogate the data and a series of hazard maps can be generated. However, without high quality engineering geological input, in particular field mapping, such an approach could underestimate the hazards affecting the site with potentially serious consequences. This paper illustrates how engineering geological input throughout the assessment process can reduce uncertainty with respect to critical issues such as hazard identification, magnitude, frequency and debris mobility.

1 INTRODUCTION

Unlike many regions in the world, where landslide assessments on natural slopes are carried out at a regional scale and relatively large degrees of uncertainty may be acceptable, the majority of Hong Kong's landslide assessments are of relatively small catchments or sub-catchments from which even a relatively small natural terrain landslide could impact on the site being assessed. As a result, any uncertainty could have potentially serious consequences and therefore assessments of a very high quality are necessary to ensure that all the hazards are identified and assessed.

2 NTHS vs. LPM

There are considerable differences between the assessment of foundations or man-made cut and fill slopes and the assessment of natural terrain for landslide hazards (Table 1). A Natural Terrain Hazard Study (NTHS) will result in limited "facts" and is instead dependent upon site observations, assessment and interpretation. A further key difference is that whilst "hard" engineering in the form of soil nailing may overcome limitations inherent in the LPM programme for man-made slopes, such a "safety net" may be neither economically nor environmentally suitable for widespread use on natural slopes.

Table 1: Comparison of LPM vs. NTHS

Man–made Slope Assessment	Natural Slope Assessment
Site of limited extent	Sites have a large extent, often comprising multiple catchments
Ground investigation (GI) stations are closely spaced	Limited scope for GI given large site and difficult access, means it is highly dependent on being located in critical areas
Exposures are available either before, during the GI, or during construction	Exposure limited to rock outcrop, landslide scars and drainage lines
Considerable amount of published data on geotechnical properties	Relatively limited data on the behaviour of natural landslides in Hong Kong
It may be appropriate to use simple classification of material types e.g. "colluvium"	Simple classifications are inappropriate. Classifying the superficial deposits requires an understanding of landscape evolution and geomorphological processes
Well developed software for slope stability analysis	Software programmes are not appropriate for catchment wide applications

3 DESIGN EVENT APPROACH

The most commonly adopted methodology for assessing natural terrain hazard in Hong Kong is the Design Event approach (Ng, et al, 2003). These government guidelines present a framework for assessment based on notional susceptibility of the terrain to landsliding, the type of facility, and the steepness of the terrain. Based on this either a "conservative event" (generally corresponding to a reasonably conservative estimate based on the observable failures in the last 50-100 years, i.e. within the available aerial photograph record for Hong Kong) or a "worst credible event" (WCE) (generally corresponding to the largest credible event based on API interpretation of landslides as well as interpretation of the geomorphological characteristics of the site) is adopted for design purposes. The WCE is nominally taken as being approximate to a 1 in 1000 year event, with the view that "this is intended to exclude historical events that occurred in the geological past" (Ng et al., 2003).

The Design Event approach was developed to enable a rapid evaluation of the possible magnitudes of hazards a site may face and therefore allows potential cost implications and alternative layouts to be considered at the feasibility stage. In applying the Design Event Approach, particularly at a feasibility stage, conservative assumptions may have to be made to ensure that the design requirements are not underestimated due to the lack of information. However, these assumptions should be reviewed and modified as the study progresses as assessments are very sensitive to changes in potential volume, distance between source and facility, rates of deposition and entrainment, etc. The determination of a design event i.e. a particular magnitude hazard with a certain mobility which is used for the design of the mitigation works therefore requires sound engineering geological judgement.

3 KEY UNCERTAINTIES IN NTHS REQUIRING ENGINEERING GEOLOGICAL INPUT

The four key areas in a landside hazard assessment requiring engineering geological input are:

- the identification of the various hazards;
- determination of an appropriate volume for each identified hazard, including potential entrainment where applicable i.e. magnitude of the hazard;
- an indication of the frequency of such hazards; and
- the likelihood of such hazards affecting the facilities in question, i.e. an assessment of mobility.

The data required to assess the 4 key areas will become available at different stages of the NTHS and should reduce in uncertainty as the study progresses. The derivation of the design event using engineering geological input is illustrated in Figure1 and, in this respect, the authors consider engineering geological mapping to be the critical area for reducing uncertainty.

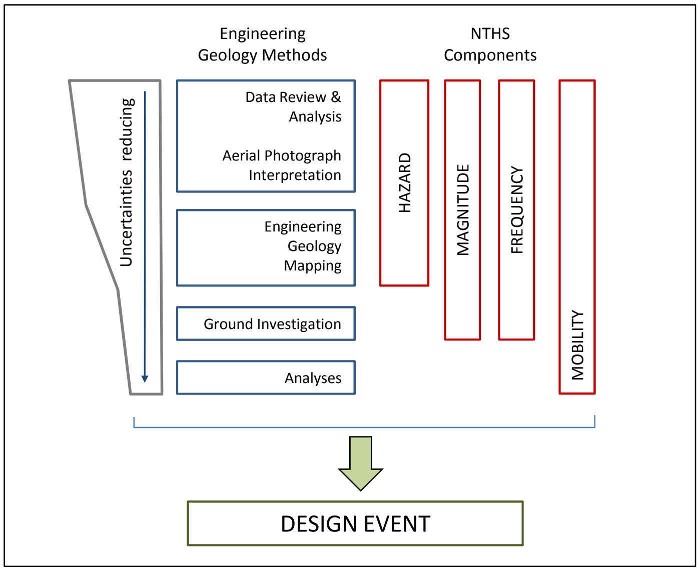

Figure 1: Engineering geological input within an NTHS

3.1 Hazard Identification

In Hong Kong natural terrain hazards have been grouped into five main hazard types on the basis of transportation, the nature of the displaced material and the topographic location (Ng et al., 2003). These are: Open Hillslope Landslides (OHL); Channelised Debris Flows (CDF); Deep-seated Slide; Rock Fall; and, Boulder Fall.

As a consequence landslides are commonly classified as OHL or CDF. However, all landslides identified should be classified in accordance with their failure mechanism (e.g. Cruden & Varnes, 1996) as these commonly reflect the geomorphological and geological setting.

The primary method of hazard identification is Aerial Photograph Interpretation (API). However, API has limitations which are well documented both overseas (Fookes et al., 1991; Hart et al, 2009) and in Hong Kong (Parry et al., 2006). As Fookes et al., (1991) note "all aerial photographic interpretation must be viewed with caution. When well done and confirmed by ground truthing exercises it can be a very valuable tool on any site. However, it should be borne in mind that it is an interpretation and hence subject to the interpreters' training, experience, skill and judgement as well as other factors such as the availability of additional information, type, scale and quality of the photographs, time available and the extent, if any of ground checking work". Despite these limitations, in Hong Kong there is often a misconception that aerial photographs display "facts" which can be extracted by staff inexperienced in geomorphological/geological mapping.

The identification of relict landslides require very careful judgement given that landslide scars progressively lose their morphological definition at rates that are dependent on factors such as vegetation, landslide size, material characteristics and location (Parry & Hart, in press). The evidence for associated landslide debris is rarely evident due to erosion or vegetation growth but maybe reflected in the presence of debris lobes. Identification of recent landslides where complete detachment does not occur (refer to the example in Figure 2a) from API is also problematic and these require careful field mapping. There is also a tendency to overestimate recent landslide run out from API due to post-landslide, fluvial re-working of the landslide debris and again field verification of such events is critical.

Alternative remote sensing approaches have been examined in Hong Kong but have not been widely adopted to date due to the excellent quality and coverage of the available aerial photographs. However, a trial of airborne LIDAR has recently been undertaken and this dataset is proving to be valuable especially in areas where dense vegetation is present in the aerial photographs. However, the processing of LIDAR data is not straightforward and specialist input is required to ensure that techniques such as DEM gridding and shaded relief maximise the relevant features, as well as ensuring that the data is not misinterpreted (Parry & Jonas, 2007). That said, LIDAR has its limitations (refer to Figure 2a) like any remote sensing technique and at the site specific scale, field mapping is essential.

Landslides are extremely complicated processes, which can be associated with a variety of depositional environments. Unfortunately there is a tendency in Hong Kong to categorise all deposits associated with mass wasting processes as "colluvium", which can lead to considerable over estimations as to the size of previous landslide events. For example, detailed engineering geological field mapping located a debris lobe associated with a recorded 1966 landslide within dense vegetation. However, given the limited exposure in the field, trial pits were excavated to assess the depth of the debris. These revealed evidence of previous mass movements prior to 1966 (Figure 2b). The horizon beneath the 1966 debris comprised sand and well sorted, sub-rounded gravel with a well developed imbrication fabric, suggesting that it was deposited by fluvially dominated processes, possibly during a debris flood. The lowest layer comprised cobbles and boulders suggesting a relatively high energy landslide event. This layer is underlain by dense structureless colluvium. Each layer exhibited a topsoil horizon and the stratigraphy suggests that landslide events in this drainage line may have been decreasing in energy, and changing from debris flow to debris floods, with time.

Engineering geological mapping carried out by experienced personnel is necessary to evaluate landscape evolution, form, processes and materials, all of which are critical to identify, characterise, predict and mitigate landslide hazards.

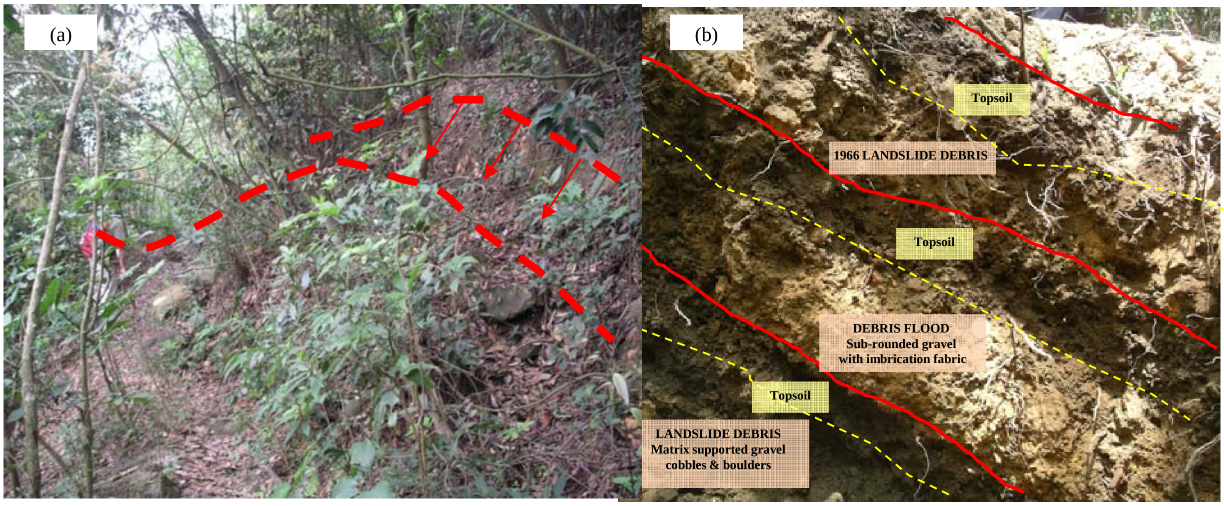

Figure 2: Identification and evaluation of landslide events during field mapping and ground investigation; (a) indicates extensive tension crack and minor displacement associated with an area of distressed ground which was not identified from API or LIDAR but only during field mapping; (b) differing landslide types and ages interpreted from a trial pit in a debris lobe identified from field mapping.

3.2 Magnitude

The GEO have developed detailed territory-wide landslide inventories since the mid-1990s. The latest Enhanced Natural Terrain Landslide Inventory or ENTLI (Maunsell Fugro Joint Venture, 2007) is a considerable improvement over the original NTLI, in particular the identification of "relict" landslides which are now based on the high quality territory-wide, low-level 1963 aerial photographs.

However, there are still limitations to this improved inventory. For example, whilst guidelines were produced to improve consistency with respect to the interpretation of relict landslides (Parry et al., 2006), the interpreters' classification varied with experience. Furthermore, given the project constraints (over 105,000 aerial photographs were reviewed in 16 months) the interpreters could only examine for relatively clear evidence of landslides e.g. obvious scarps, with very little time available to consider geomorphological settings, often critical with respect to the identification of older degraded and possibly landslide related features.

An example of the limitations with respect to degraded features is illustrated in Figure 3, which indicates the positions of landslides within the existing databases and an additional large landslide identified during the site specific API. The identified feature is considerably larger than any landslide within the existing database. Based on the field mapping it was interpreted that many of the lobate landforms identified by API were of differing origins. However, the morphology and materials of one lobe indicate that this could have been deposited as a single large rock avalanche.

Furthermore, when considering the possibility of high magnitude, low frequency landslide events, it is not only the initial landslide volume but the potential for both multiple source volumes and/or significant material entrainment that also have to be considered. Whilst in Hong Kong the most recent channelised debris flows have not involved significant entrainment, this could occur with the right combination of geological and geomorphological conditions. For example, the 1990 Tsing Shan debris flow comprised an initial landslide of $450m^3$, which induced a second landslide of $2500m^3$. The debris subsequently accelerated over a cliff resulting in extensive entrainment of the materials below with the final volume estimated at $19{,}000m^3$ (King, 1999). Section 4 of this paper gives an example of the evaluation of such a scenario.

There is concern that the existing landslide inventories, which have been developed without field verification, may be used mechanically and without appreciation of their compilation methodology and limitations, and that critically, degraded landforms, that may represent high magnitude, low frequency and that are not identified in the datasets will be overlooked.

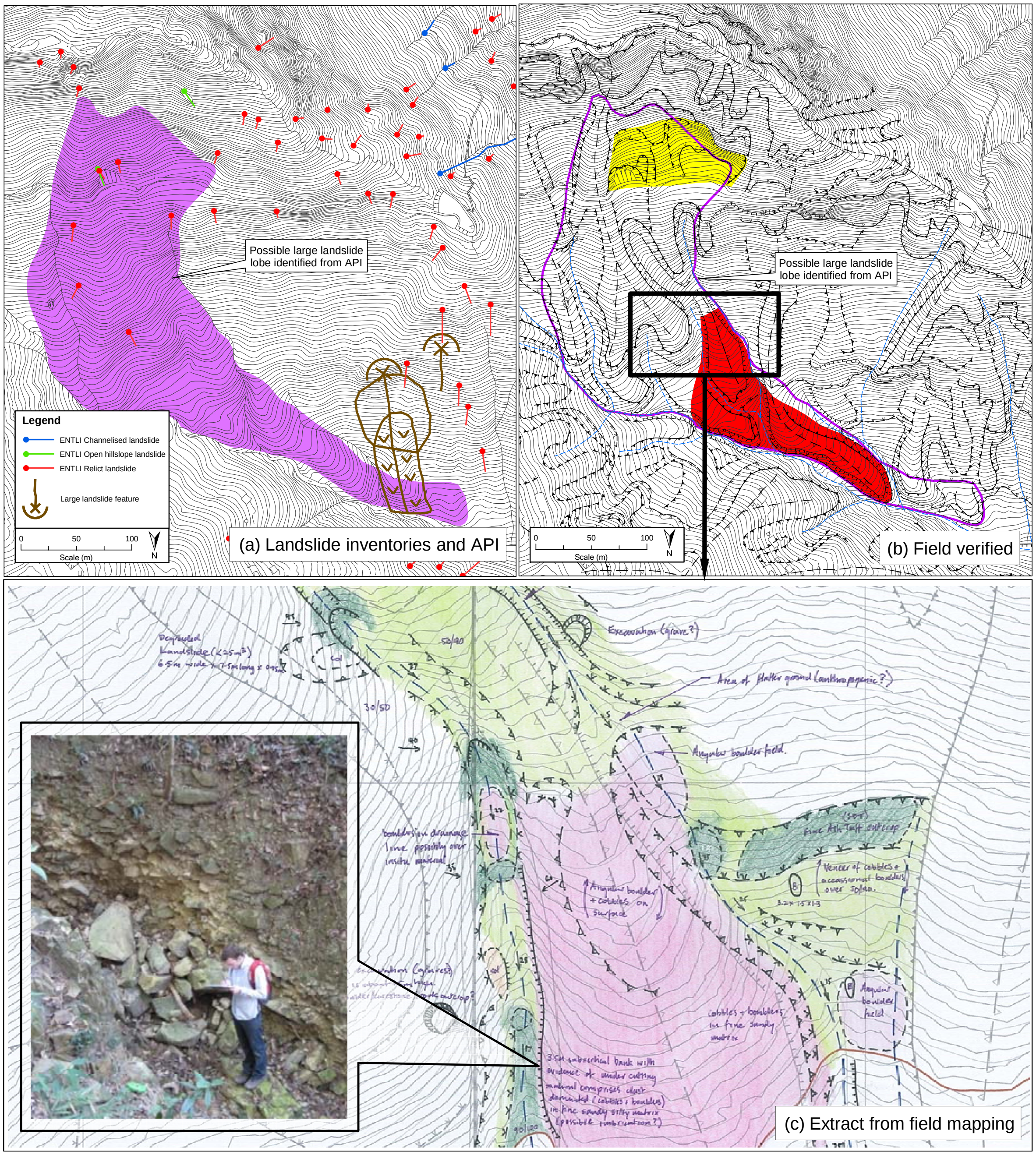

Figure 3: (a) Landslides identified in the various inventories and an additional possible large degraded landslide identified from site specific API. (b) Engineering geological mapping at 1:500-scale indicated that the lobate landforms identified from API have separate origins. For example, the feature identified in red consists of a distinct deposit comprising angular to sub-angular, slightly to moderately decomposed, clast-supported cobbles and boulders. A depression (yellow) is evident above this lobe. The field evidence suggests that the lobe may represent debris from a large rock avalanche.

3.3 Frequency

The Design Event Approach is often over simplified to assume that a “conservative event” is equivalent to the largest landslides observed within the time period of the available photographic record and a “worse credible event” is equivalent to the largest morphological depression in the landscape. The lack of absolute age dates for landslides in Hong Kong makes the assignment of ages extremely problematic. In a limited age dating study of landslides in Hong Kong (Sewell et al., 2006) the upper bound age for the features dated was 34,000 years BP. As a result, determining whether a landslide occurred less than 1000 years BP (i.e. it is a WCE) or whether it occurred "in the geological past" is extremely challenging.

There has been great progress in the use of age dating techniques for the dating of landscape evolution (Sewell et al., 2006). However, the application of these techniques depends on the landscape evolution at a site and the processes involved being understood so that the samples selected are truly representative of the hazards being dated, i.e. any dating must be within the constraints of a geological model. For example C^{14} dating of the buried soil horizons shown in Figure 1(b) could have been underatken to provide an absolute age constraint for each landslide event.

Even without absolute age dating it is possible to provide relative age dating of landforms. Figure 4 shows an API which, in addition to identifying debris fans associated with channelised debris flows (levees and individual debris lobes are evident) also provides relative ages of the fans given their juxtaposition and morphology. Again such observations are critical in understanding hazard type, magnitude, frequency and mobility.

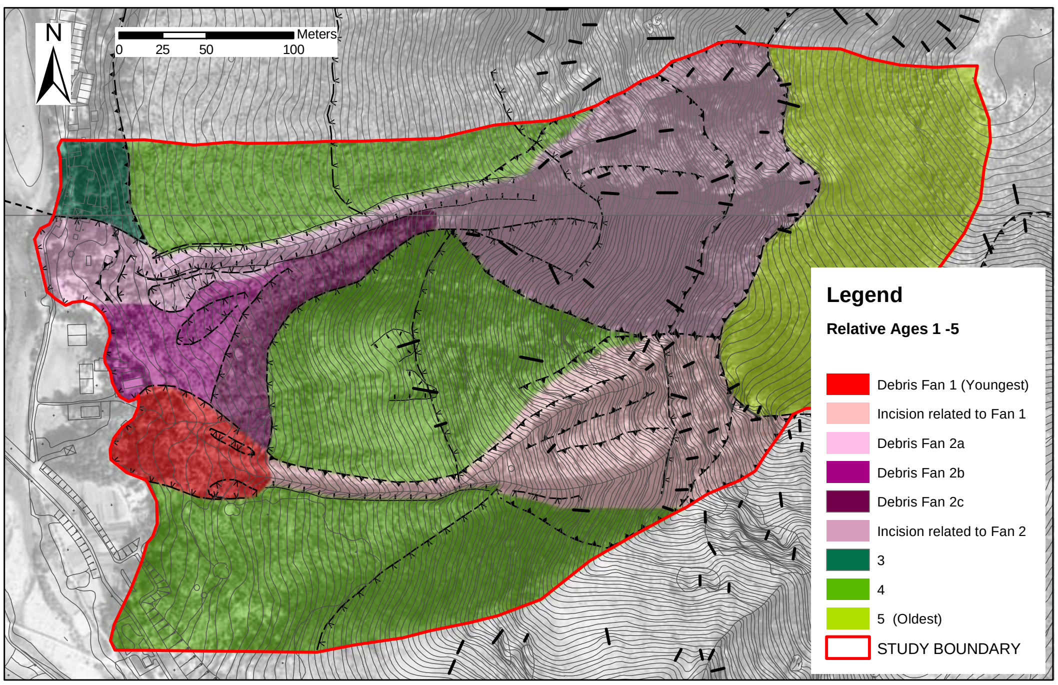

Figure 4: Relative ages of terrain units determined from API. Note that Debris Fan 2 has three distinct deposits, the ages of which are based on the sharpness of features identified. Debris Fan 1 is younger than Debris Fan 2b and 2c. The debris fans are being generated by channelised debris flows related to the incising drainage lines. Note that there are no recent landslides noted in the ENTLI (black lines). This figure also illustrates the importance of geomorphological setting with respect to landslide initiation and potential mobility.

3.4 Mobility

Having determined the potential magnitude of the design event to be adopted, mobility analyses can be undertaken to estimate the volume and velocity of the potential debris reaching the facility at risk. This can be either empirical or, more increasingly, analytical. The main contributions of engineering geology to mobility include:

- providing site-specific data with respect to drainage line characteristics, in particular the most applicable channel geometry to adopt for channelised debris flows. Where drainage lines have incised into older and larger channel forms, the correct geometry to adopt is dependent upon the magnitude of the landslide being analysed ;

- determining the possibility of secondary induced failure and general entrainability of the substrate; and
- examining evidence from historical landslides, in particular recording field evidence for features such as debris height and super elevation (Figure 3), for mobility back analyses.

All of these factors are dependent upon careful field observations. For example, the failure to distinguish between run-out distances of remoulded landslide debris and outwash material could result in significant errors in the back analysis of the landslide event.

The contour maps generated from the LIDAR are a considerable improvement on the existing 1:1000 topographical maps, with respect to evaluating run out. However, relatively small scale topographical variations which can affect the mobility analysis may not be evident from LIDAR (Figure 5).

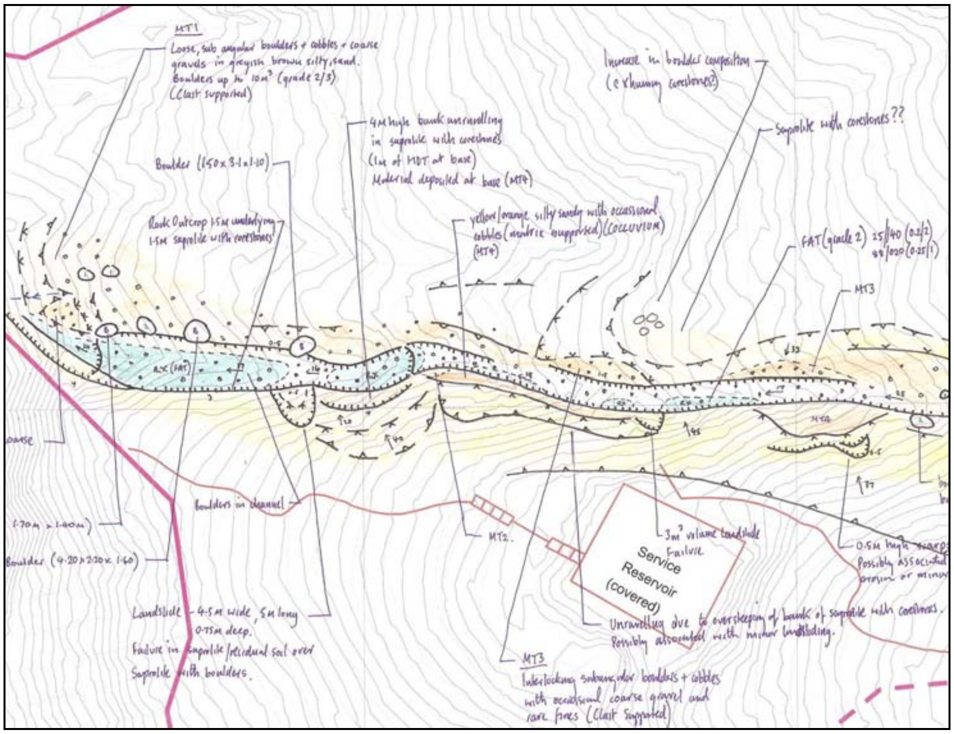

Figure 5: Engineering Geological mapping at 1:500-scale on LIDAR generated contours. The mapping identifies an incised drainage line with vertical banks up to 4m in height which are not evident from LIDAR. Such information is critical for mobility modelling. Also shown is fluvial incision resulting in over steep terrain and evidence of instability. The initial hazard models generated from API and existing data review should be re-evaluated based on such field observations.

4 DERIVATION OF A DESIGN EVENT

The derivation of a design event is an iterative process. Figure 6 shows the development of an initial design event for a hillside in the New Territories, predominately based on API (Parry & Ng, in press). The hillside of concern rises from 90mPD to 295mPD and comprises two catchments with a total area of about 56,000m^2. Figure 6a is an engineering geological map from API which shows considerable areas of rock and intermittent rock outcrop with saprolite on the spurlines and thicker saprolite in the upper terrain. Superficial deposits, predominantly comprising taluvium, are associated with the drainage lines. Figure 6a also shows the location of ENTLI features which are predominantly located in the incising terrain. Figure 6b shows an initial hazard model for the site focusing on the likely magnitude of landslides. Based on the Design Event approach a “worse credible event” (WCE) is applicable. In order to generate a WCE, the largest section of steep terrain adjacent to the boundary of the Upper Terrain unit was selected, whereby a source landslide would result in the debris impacting upon the greatest extent of taluvium within the Incising Terrain unit below. Where the taluvium is considered to be underlain by rock or intermittent rock outcrop (typically steeper terrain), it has been assumed that all the taluvium over the width of the source landslide would mobilise under the impact of the debris. The thickness of taluvium was conservatively assigned as 4m at this time. Such a WCE corresponds to an initial landslide source volume of 1500m^3 in the Upper Terrain saprolite combining with a secondary failure of 1400m^3 in the taluvium, resulting in a total volume of 2900m^3.

Obviously there are uncertainties associated with such preliminary models e.g. the potential source volumes, amount of entrainment etc, but critically such models provide focus for the subsequent engineering geological mapping and ground investigation. They also allow a preliminary evaluation of the types of mitigation works required and allow factors such as cost and environmental impact to be considered.

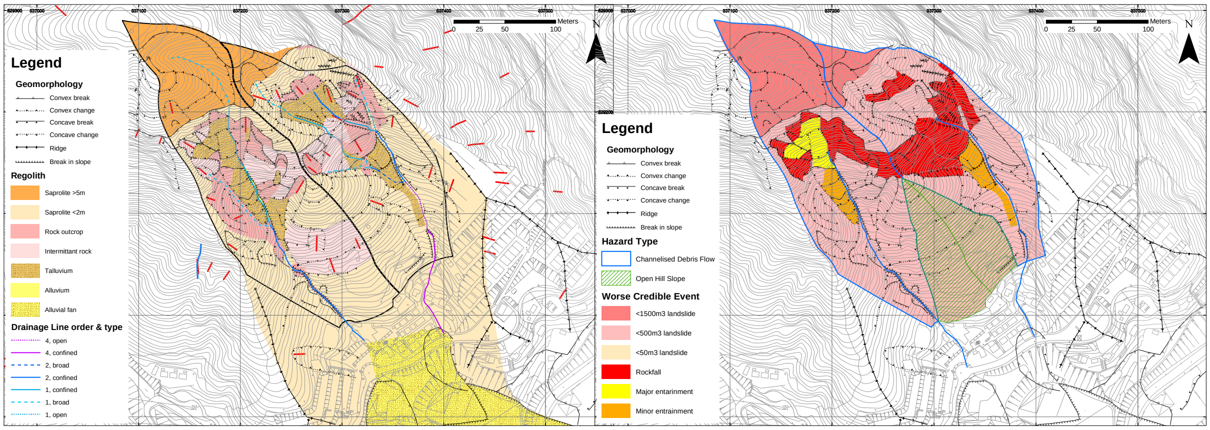

Figure 6: Initial Design Event derivation. (a) Engineering Geological map. (b) Initial Hazard Model used to generate the Design Event at review stage. Both are based on API and should be re-evaluated during field mapping.

4 CONCLUSIONS

Natural terrain hazard studies can appear deceptively simple. A limited Aerial Photograph Interpretation can be undertaken and a hazard model generated from this plus existing landslide datasets, such as the ENTLI. Geographical Information Systems can be used to interrogate the data and a series of hazard maps can be generated. However, without high quality engineering geological input, in particular field mapping, such an approach could underestimate the hazards affecting the site with potentially serious consequences. An engineering geological model, focused on potential hazards, and developed from geological and geomorphological principals and with knowledge of the terrain being evaluated, provides the key to understanding the geological controls and geomorphological processes that have affected the site in the past and may affect it in the future. Such models allow “what if” scenarios to be generated and evaluated and enable areas of uncertainty to be recorded, investigated and reduced. Models should be constantly questioned and refined as additional data becomes available; particularly important are the observations from the field mapping. Once an appropriate model has been developed it can be analysed in terms of run out and impact. Such analysis must be grounded within the site specific observations. Only with continuous engineering geological input can robust and defensible mitigation works be constructed.

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