An Interim Review of Debris Mobility for Open Hillslope Failures

GEO Report No. 318

C.F. Yam & T.H.H. Hui

**Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region**

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Preface

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H.N. Wong
Head, Geotechnical Engineering Office
April 2016

Foreword

This Technical Note presents the results of an interim review of the debris mobility of open hillslope failures (OHF) in Hong Kong. Additional back analyses have been conducted for selected OHF of high mobility. Recommendations on selection of rheological model and parameters for design of mitigation measures against OHF are given.

The review was carried out by Mr T.H.H. Hui and Mr C.F. Yam initially under the supervision of Mr K.K.S. Ho and later under my supervision. Mr W.K. Ho, Mr G.C.C. Ng and Mr H.C.K. Lee provided technical support in the mobility analyses. All contributions are gratefully acknowledged.

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Abstract

This Technical Note presents an interim review of the debris mobility of open hillslope failures (OHF) in Hong Kong. All information available for OHF in Hong Kong, including previous mobility analyses for OHF, data from the Enhanced Natural Terrain Landslide Inventory and field mapping reports of OHF, has been reviewed. Additional back analyses of mobile OHF have been carried out. The use of the friction model or the Voellmy model as the rheological model in debris mobility analyses is also discussed. Recommendations on selection of rheological model and parameters are given. An empirical approach which introduces the concept of debris velocity ceilings with the use of the friction model is recommended for the design of mitigation measures for OHF. When new landslide data or full-scale test results are available in future, the relevant recommendations in this study should be reviewed and updated.

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1 Introduction

An open hillslope failure (OHF) involves predominantly a sliding failure whereby the debris is not channelized along a stream course. According to Ng et al (2003), an OHF is typically in the form of a debris slide (i.e. debris moving along a well-defined sliding surface, with little or no disintegration of the debris mass) or debris avalanche (i.e. with debris disintegration but with only minimal surface water mixed into the debris mass during debris movement). Debris mass of OHF (debris slides and debris avalanches) may be heterogeneous in nature, and could comprise soils and boulders/corestones in various proportions at different degrees of saturation (Hungr, 2011).

This Technical Note (TN) reviews the recommendations given by GEO Report No. 104 (Lo, 2000) on estimation of debris mobility of OHF. Additional back analyses of the OHF have been carried out as part of the review. This report presents updated rheological parameters and recommendations on debris velocity prediction of OHF.

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2 Previous Studies on Debris Mobility of OHF

2.1 Previous Studies in Hong Kong

A total of 16 OHF involving predominantly debris slides or debris avalanches were back-analyzed by Hungr (1998) and Ayotte & Hungr (1998) using the friction model with the aid of the computer programme DAN. No field measurements of debris velocity and debris thickness of these landslides were conducted. The back analyses were essentially based on the debris runout distances and to some extent, the spatial distribution of debris deposition. They established a range of values of apparent friction angle (ϕ_a) and a trend of reducing ϕ_a with increasing landslide source volume.

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Lo (2000) observed that the ϕ_a values derived from the above back analyses were comparable to the corresponding travel angles based on field mapping. He combined the relevant landslide data reported by Wong et al (1998) and Franks (1998) together with the results of the above back analyses and recommended that the following lower-bound values of ϕ_a be used with the friction model to estimate of debris mobility of OHF:

(a) Landslide source volume < 400 m^3, $\phi_a = 25^o$.

(b) Landslide source volume ≥ 400 m^3, $\phi_a = 20^o$.

2.2 Overseas Studies

2.2.1 Switzerland

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Some full-scale field tests have been conducted in Switzerland in which the failure mode is similar to OHF and the debris velocities have been reported. Bugnion et al (2008) reported that test sites at Veltheim and St-Léonard, Switzerland had been set up for full-scale experiments on shallow landslides impacting on flexible debris-resisting barriers. Shallow landslides were simulated by releasing material up to 70 m^3. The test sites at Veltheim and

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St-Léonard are 30° and 50° slopes with acceleration zone of 40 m and 50 m long respectively. The measured debris velocities varied between 6 m/s to 12 m/s. However, the tests were focused on the study of interaction between landslide debris and flexible barriers. The information reported is not detailed enough for an independent back analysis of the debris mobility of the simulated shallow landslides.

2.2.2 Canada

McKinnon et al (2008) documented the results of back analyses using DAN-W for 43 coal slides, four rock avalanches and three rock slides/debris avalanches. Key observations related to the selection of rheological models and parameters are summarized below.

(a) For coal slides, runout distances of most of the cases were successfully modelled using the friction model. In some cases where the flow entered a confined channel, much greater mobility of the entrained loose and saturated debris was observed and it was necessary then to use the Voellmy model.

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(b) For rock avalanches, the best results were obtained using the Voellmy model, with ϕ_a between 1.5^o and 9^o (i.e. tan ϕ_a equal to 0.03 to 0.16) and ξ ranging from 250 m/s^2 to 500 m/s^2. Hungr & Evans (2004) also noted that the Voellmy model produced consistently good simulation results with ξ between 100 m/s^2 and 1,000 m/s^2 for other rock avalanches.

(c) For rock slide/debris avalanches, the friction model could be used in the source area, with a transition to the Voellmy model where significant entrainment of saturated soil began.

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McKinnon et al (op cit) recommended that “forward-predictions should be performed as sensitivity analyses over a range of possible parameter values, in order to identify regions of probable landslide runout for use in risk assessment and management.”

3 Additional Back Analyses of OHF in Hong Kong

3.1 Landslide Data and OHF Selected for Additional Back Analyses

The 16 OHF back-analyzed by Hungr (1998) and Ayotte & Hungr (1998), which were also presented in Figure 17 of GEO Report No. 104, have been reviewed. They involved landslides on natural terrain, quasi-natural terrain and man-made slopes in which the predominant failure mechanism was debris slide or debris avalanche. These back analyses were based on quality data collected from field inspections or extracted from detailed landslide studies.

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In the present study, additional back analyses using the friction model were carried out for 52 OHF of high mobility (runout distance ≥ 100 m) selected from the Enhanced Natural Terrain Landslide Inventory (ENTLI) including those that occurred in 1993 and 2008. In essence, all the mobile OHF in the ENTLI have been considered. Also, the site settings of these cases were reviewed to ensure that the failures had not been significantly affected by concentrated surface water flow. Field mapping of six of these OHF (i.e. five cases in 2008 and one case in 1993) were available and the respective mapped debris runout distances were used in the additional back analyses.

Also, detailed field mapping of 21 nos. of relatively 'less mobile' OHF (i.e. 16 OHF in 2008 and 5 OHF in 1993) were available and most of them had runout distances ranging from 50 m to 100 m. Additional back analyses were also carried out for these OHF. Hence, a total of 73 OHF (i.e. 52 + 21 = 73) were selected for the additional back analyses.

A review of the data sources of OHF presented in Figure 17 of GEO Report No. 104, together with details of the screening exercise for identification of OHF and observations of the mapped 2008 OHF, are summarized in Appendix A. A list of the 73 OHF selected for the additional back analyses is given in Table A3 of Appendix A.

The additional analyses were undertaken in 2012 and the details and results are presented in the following sections. In a recent study by Lo et al (2013), it is suggested that some of the OHF should be reclassified as failures within topographic depression catchments (TDF). Following this recommendation, 15 out of the 73 selected OHF can be reclassified as TDF. As the additional analyses on the 73 failures were already carried out some time ago, the reclassified failures are still included in the present study for comparison purpose. The implications of inclusion of these TDF are discussed in Section 4.6. For the sake of simplicity, the 15 failures that have been reclassified as TDF are treated as OHF in the additional analyses.

3.2 Selection of Rheological Model

McKinnon et al (2008) and Hungr & Evans (2004) observed that the Voellmy model produced consistently good simulation results for rock avalanches. The Voellmy model may, compared with the friction model, give a better simulation of the turbulent action (e.g. mass disintegration, rolling, bouncing and the effect of saturation of debris mass) involved in the debris motion of OHF.

The failure mechanism of an OHF is complex. Even for a back analysis of a past OHF, it would be difficult to distinguish in field mapping whether the debris is in undrained and liquefied conditions during failure. For design of mitigation measures, the actual degree of turbulent actions may vary significantly for different site settings, failure and movement mechanisms, degree of saturation and structural features and it would be impossible to predict whether undrained and/or liquefied conditions would occur in the course of failures.

Hungr (1998) suggested that the friction model would provide a more realistic simulation of unsaturated debris mass, whereas the Voellmy model would be more appropriate for saturated events such as debris flows. Also, Hungr (op cit) considered that the friction model would be an appropriate rheological model for simulation of debris slides and debris

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avalanches. Compared with the Voellmy model, the friction model would tend to predict higher debris velocities, and the bulk of the debris would be deposited proximally with gradual thinning towards the source in the case of the friction model.

The use of the Voellmy model requires the input of two rheological parameters (i.e. the apparent friction angle ϕ_a and turbulent coefficient ξ). Back analysis of a failure can involve a wide range of ξ combined with different values of ϕ_a to fit the same debris runout distance. Different velocity profiles can be produced with the same runout distance. An illustrative example is given in Figure 3.1 for ENTLI No. 09SED1818E. It is noted from this figure that a wide range of ξ (i.e. 200 m/s^2 to 5,000 m/s^2) combined with different ϕ_a (24.2^o to 27.7^o) can give similar debris runout distance but very different velocity profiles.

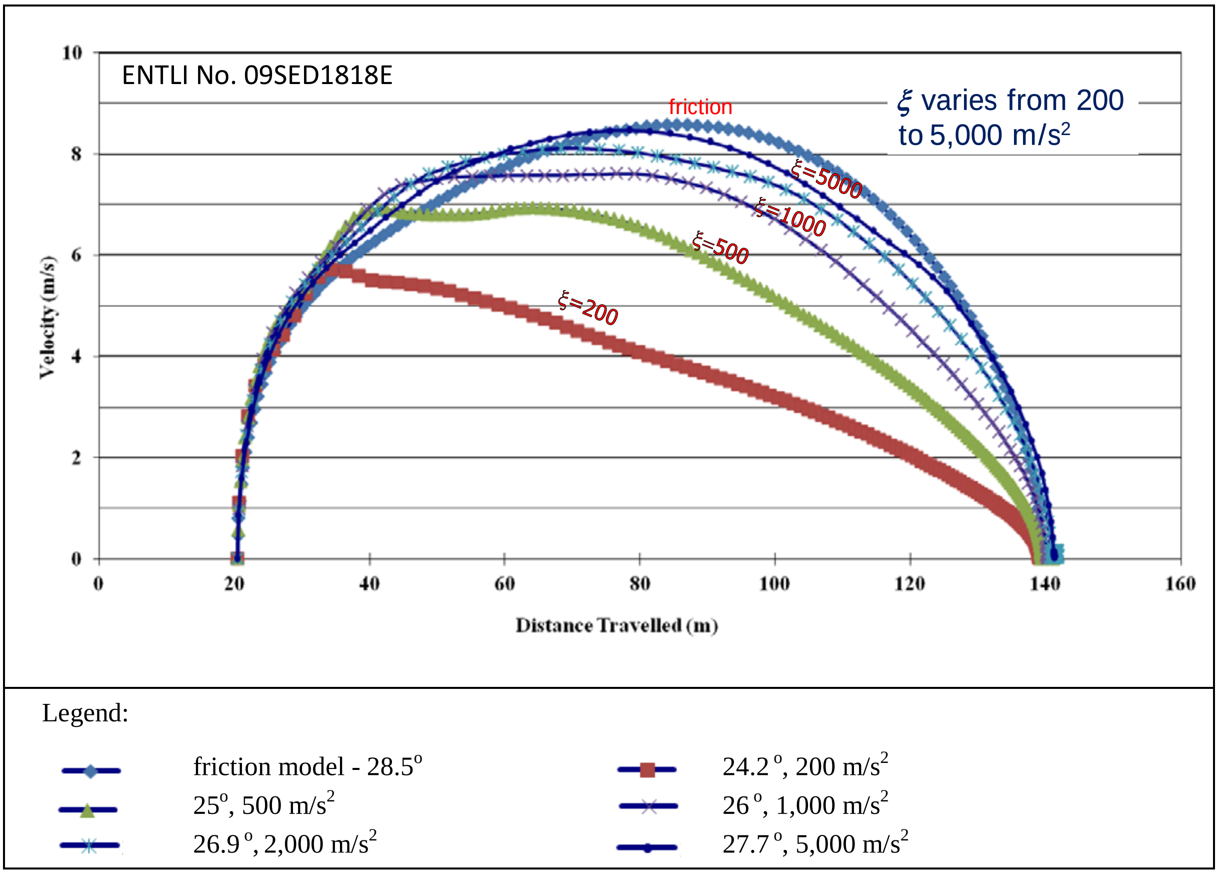

Figure 3.1 Wide Range of ξ Values that Could Give Very Different Velocity Profiles but Similar Debris Runout Distances

As no super-elevation field data of the OHF are available to calibrate the debris velocities estimated from the Voellmy model, calibration of the model based solely on the observed debris runout distances is not feasible.

Lam (2013) suggested that at a location where there is a notable change in the direction of debris flow (i.e. curved flow path or "bend") along a debris trail, the difference in crest levels of the side slopes of the debris trail could be assumed to be the respective

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super-elevation for use in the estimation of debris velocity at that location. Other factors such as material properties, failure volume, effect of secondary outwash and failure mechanism should also be accounted for in the estimation. In any case, the debris trails of OHF are usually relatively straight along the maximum slope gradient and "bends" are not common.

Yang et al (2011) reported data of flume tests conducted on dry granular flow. In the present study, back analyses of the test results have been carried out using both the friction model and Voellmy model. Results of the analyses show that the friction model produces back-calculated velocity profiles that match reasonably well with the flume test data whereas the Voellmy model does not yield satisfactory results. Details of the back analyses of the flume tests are contained in Appendix B.

In view of the results of the analyses of the flume test data and lack of velocity data for calibrating the two input parameters (ϕ_a and ξ) of the Voellmy model, the friction model is practically the preferred choice. Therefore, the friction model has been used in the additional back-analyses of OHF in this study.

3.3 Computer Model and Input Parameters

The additional back analyses were conducted using the computer program 2d-DMM (Kwan & Sun, 2006; GEO, 2010). The computer programs 2d-DMM and DAN (Hungr, 1995) adopt a similar analytical approach (i.e. continuum model using integrated approach with a depth-averaged shallow-flow solution) and the solution is obtained in time steps for a block assembly of elements, representing the landslide debris as a continuum. Both programs have been found to produce generally similar results in terms of runout distance, velocity and thickness profiles of debris in the back analyses of some notable landslides in Hong Kong. According to GEO (2011), these programs may be used for back analysis as well as forward prediction of debris mobility.

For the additional back analyses, simplification has been made in the computer model. A constant average width is assumed and side friction is also ignored in the model in view that the channelization ratio for OHF should be insignificant. In the back analyses, constant values of K_a, K_p and K_o were used. The value of K_o was taken as 1.0. The equation developed by Savage & Hutter (1989) was used to estimate the values of K_a and K_p. According to the equation, the values of K_a and K_p are dependent on the bulk friction angle (ϕ) and basal friction angle (ϕ_b) of landslide debris. For typical ranges of ϕ and ϕ_b ($20^o < \phi < 35^o$ and $10^o < \phi_b < 30^o$), the average values of K_a and K_p are 0.8 and 2.5 respectively.

Some numeral techniques were used in utilizing the 2d-DMM. In the 2d-DMM, the numerical solution for the two end blocks of landslide mass is comparatively not as accurate as the middle blocks according to GEO (2010). In the additional back analyses, the frontal velocity was based on the second last block (i.e. Block 10) of landslide mass given in the program.

The mapping/inspection reports (i.e. 21 cases in 2008 and 6 cases in 1993) provide quality information of the OHF. The runout distances given in these reports were adopted in

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the additional back analyses, where available. For OHF not mapped or inspected, the runout distances are based on the ENTLI.

3.4 Additional Back Analyses Using Friction Model

The additional back analyses were carried out using the friction model to fit the debris runout distances of the 73 OHF. The ϕ_a values in the friction model were back-calculated by trial and error to match the runout distances.

Where appropriate, fine adjustment of the input parameter (i.e. ϕ_a) was made with a view to better matching the deposition profile as recorded in the field mapping of the mapped OHF. Deposition data were not input in the computer program, but the distribution of debris deposition along the runout paths obtained from field mapping was compared with the calculated one in the computer model. Judgement was exercised in choosing the ϕ_a values to fit the deposition profiles as far as practicable. Nevertheless, in many cases where the deposition profiles were not sensitive to the ϕ_a values, the back analyses were effectively based on the runout distances.

3.5 Results of Additional Back Analyses

The maximum debris velocities of OHF estimated by the additional back analyses, together with relevant data reported in Hungr (1998) and Ayotte & Hungr (1998), are plotted against the corresponding landslide source volumes in Figure 3.2. The velocity data are grouped into four volume ranges; and the velocity ceilings for the respective volume ranges are shown as dash line in the figure.

In Figure 3.2, there are two groups of OHF of which the maximum debris velocities are above the velocity ceilings. The first group containing 5 OHF (namely ENTLI Nos. 03SEA1764E, 03SEB2750E, 08NWD1142E, 10NWB0234E and 11NWB0235E) is estimated to have maximum debris velocities only slightly higher than the ceiling value (i.e. 9 m/s). The second group containing 3 OHF (namely ENTLI Nos. 07NED0922E, 09SEB1791E and 03SEA2011E) is of different site setting and discussed in Section 4.4 separately.

The landslide source volumes of the first group were small and ranged from 25 m^3 to 90 m^3. No mapping or field inspections were available for the landslides in this group and the runout distances to be matched in the back analyses were based on the ENTLI.

The debris runout distances of the mobile OHF recorded by the field mapping are generally noted to be shorter than those in the ENTLI by more than 10%, with an average of about 20% (see Section 4.3). In the back analyses, the use of runout distances based on the ENTLI would result in higher debris velocities than those based on field mapping. The runout distances given in the mapping reports are considered more reliable as secondary outwash should have been distinguished in site inspections.

To account for the above observation, supplementary back analyses were carried out for the five critical OHF in the first group of which the debris runout distances were reduced

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by 10% in the analyses. The results indicated that the maximum debris velocities of these cases would be reduced by 1 m/s to 2 m/s (see Figure 3.2) to below the velocity ceiling of 9 m/s.

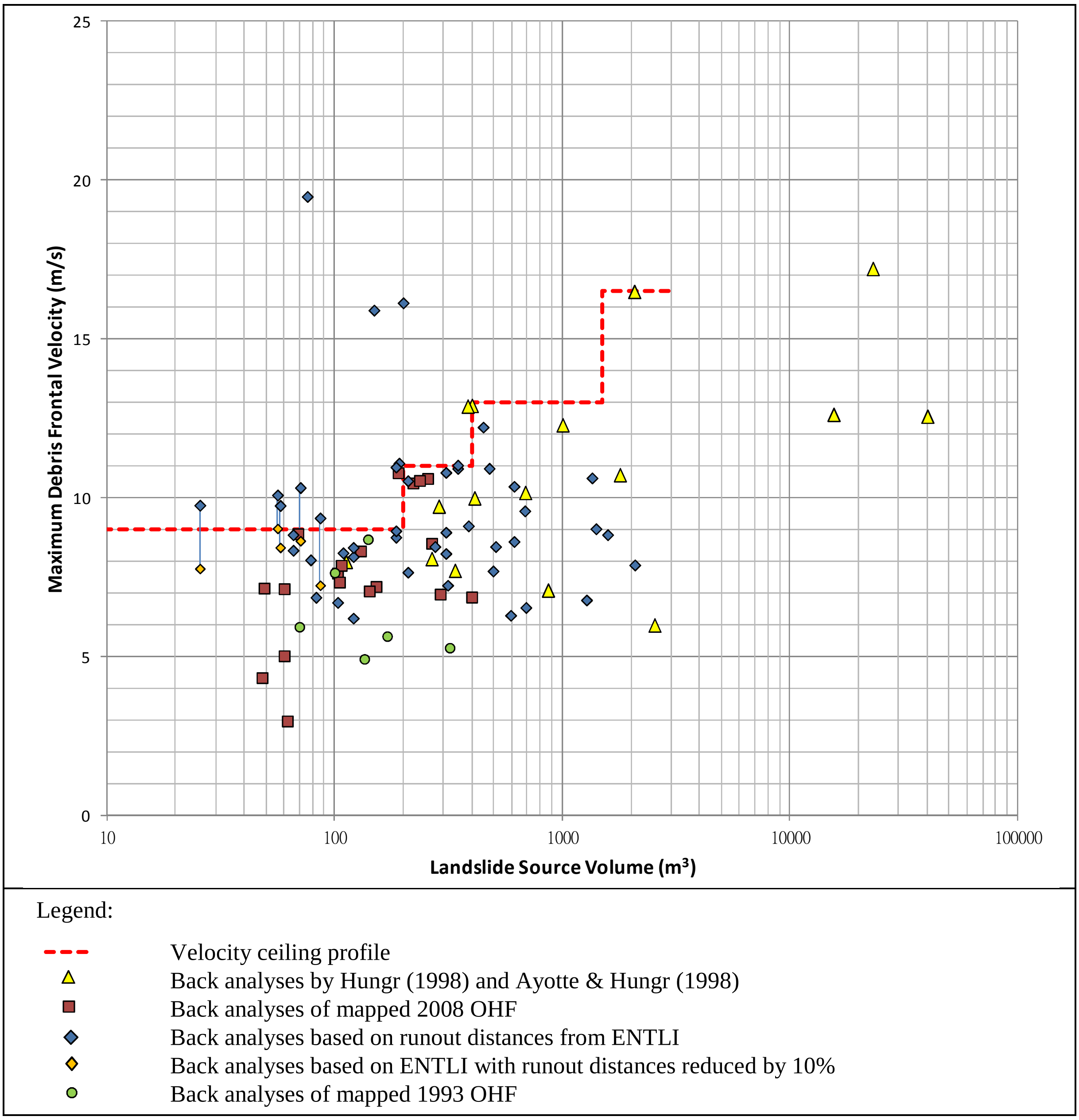

Figure 3.2 Maximum Debris Frontal Velocity of Open Hillslope Failures

3.6 Updating GEO Report No. 104 in Respect of Rheological Parameters

The landslide data of OHF (travel angle versus debris volume) shown in Figure 17 of GEO Report No. 104 have been reviewed to ensure that only those relevant and quality data with sufficient documentation are presented. The figure has been updated with quality data

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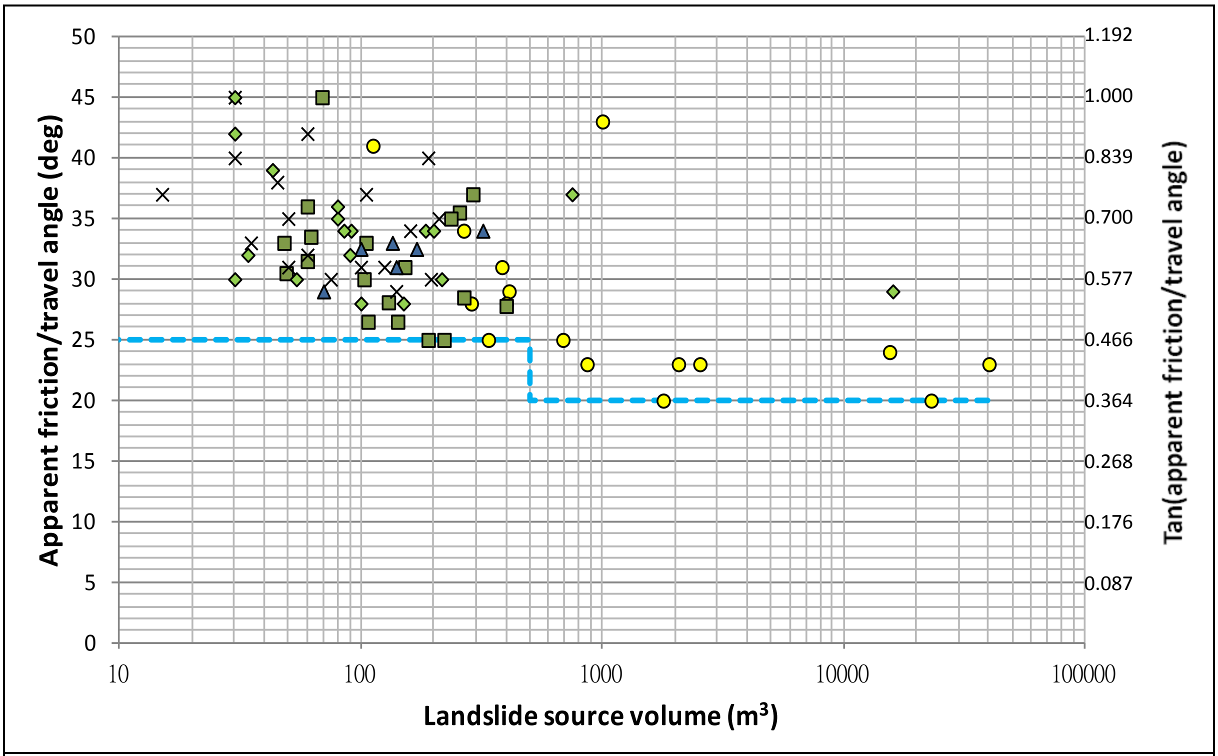
of recent OHF of high mobility collated from the field mapping (see Figure 3.3). In the review, different types of OHF are duly considered (see Appendix A). 16 landslide cases that were back-analyzed by Hungr (1998) and Ayotte & Hungr (1998) are relevant to OHF. The data for these landslides are quality data and the back-analyzed ϕ_a are therefore included in the above figure. Additional back analyses of 21 mapped OHF in 2008 and five OHF of ‘Gravitation’ type and one OHF of non-channelized ‘Mixed’ type by Wong et al (1998) were recently conducted by the Geotechnical Engineering Office (GEO). The data of these OHF are new quality data and the back-analyzed ϕ_a values are also included in the above figure.



Legend:

- - - Design envelope recommended

○ Apparent friction angles from back analyses by Hungr (1998) and Ayotte & Hungr (1998)

■ Apparent friction angles from back analyses for mapped 2008 OHF

▲ Apparent friction angles from back analyses for mapped 1993 OHF

× Travel angles of other ‘Gravitational’ and non-channelized ‘Mixed’ failures inspected by Wong et al (1998)

◆ Travel angles of other OHF studied under GEO’s systematic landslide investigation programme

Figure 3.3 Updated Apparent Friction Angle (ϕ_a) of Open Hillslope Failures

Other OHF with quality data include the remaining ‘Gravitational’ or non-channelized ‘Mixed’ type OHF inspected by Wong et al (1998) (see Table A2 in Appendix A) and those examined under the GEO’s systematic landslide investigation programme (see Table A4 in Appendix A).

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The runout distances of OHF determined from mapping were in general shorter than those identified in the ENTLI (see Section 4.3 for details). As such, the back-analyzed ϕ_a values tend to be under-estimated for OHF without field mapping. Hence, the results of the back analyses for those OHF with runout distances based on ENTLI are not included in Figure 3.3.

It can be deduced from Figure 3.3 that the lower bound values of ϕ_a for landslide volumes ≤ 500 m^3 and > 500 m^3 are 25^o and 20^o respectively.

4 Discussions

4.1 Lower-bound Approach for Estimation of Debris Runout Distance

The calculated debris runout distances of OHF using the friction model are very sensitive to the value of ϕ_a used in the mobility assessment. In predicting the maximum runout distance of an OHF, care should be exercised in the selection of ϕ_a, as it would dictate whether mitigation measures should be provided or not to protect downslope facilities.

However, the uncertainties on locations of landslide sources would cast doubt on the estimated distance that would be travelled by the debris mass before reaching downslope facilities. Examples and key observations in respect of uncertainties on runout distances are given in Appendix C. There are a number of cases in the ENTLI indicating that OHF with similar site settings and failure volumes could have significant differences in their debris runout distances given different rainfall characteristics. With the current limited knowledge and understanding of the factors that combine to give rise to debris runout, the use of the empirical approach involving the adoption of lower-bound values of ϕ_a for different volume ranges for the prediction of runout distance is proposed in the interest of robustness. The consideration is that any under-estimation of runout distance may result in direct exposure of facilities and their occupants to landslide threat. In the forward prediction of debris runout distance, the predicted values are bound with errors, and that it is important to ascertain that the errors are on the safe side. Hence, a robust approach to adopt the lower-bound values of ϕ_a is needed for the estimation of debris runout distances, which is similar to the approach suggested in GEO Report No. 104 (Lo, 2000).

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The use of the lower-bound values of ϕ_a for different volumes ranges as deduced in Section 3.6 and shown in Figure 3.3 should be sufficiently robust for estimating debris runout distances of OHF.

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4.2 Debris Velocity Ceiling Approach for Design Using Friction Model

If the lower-bound values of ϕ_a are used with the friction model for assessing the mobility of OHF, the corresponding predicted debris velocities would be on the high side in most cases. With the use of the above lower-bound values, debris mass will undergo continuous acceleration in the friction model if the terrain gradient is greater than ϕ_a. The predicted debris velocity would become unrealistically high. This may result in serious cost and practicability implications for vast majority of the hillside settings in Hong Kong. The results of the additional back analyses indicate that the back-calculated ϕ_a is dependent on the ground profile of the debris pathway; and the velocity profile of OHF is always lower than that

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derived using the lower-bound value of ϕ_a.

A pragmatic approach is to group the velocity data into four volume ranges and select the appropriate velocity ceiling for each volume range. In this approach, the prediction of runout distance is based on the friction mode with the use of lower-bound value of ϕ_a, but the debris velocity is capped at the ceilings determined from the above back-analyses. This empirical design approach is illustrated in Figure 4.1. For a case analysed by the friction model, there should be a velocity profile which can be fitted to touch the line of velocity ceiling, corresponding to a certain value of ϕ_a. If it is compared with the proposed design velocity envelope bounded by the velocity ceiling and the velocity profile calculated by the lower-bound values of ϕ_a, their difference enhances the robustness of designs of the mitigation measures.

On the other hand, the velocity envelope should cover the velocity profiles of all possible landslides at different locations along the runout path (see Figure 4.2). As such, the velocity envelope is not the result of an analytical assessment of the debris motion of a single landslide, but rather the overall effect of different possible landslides.

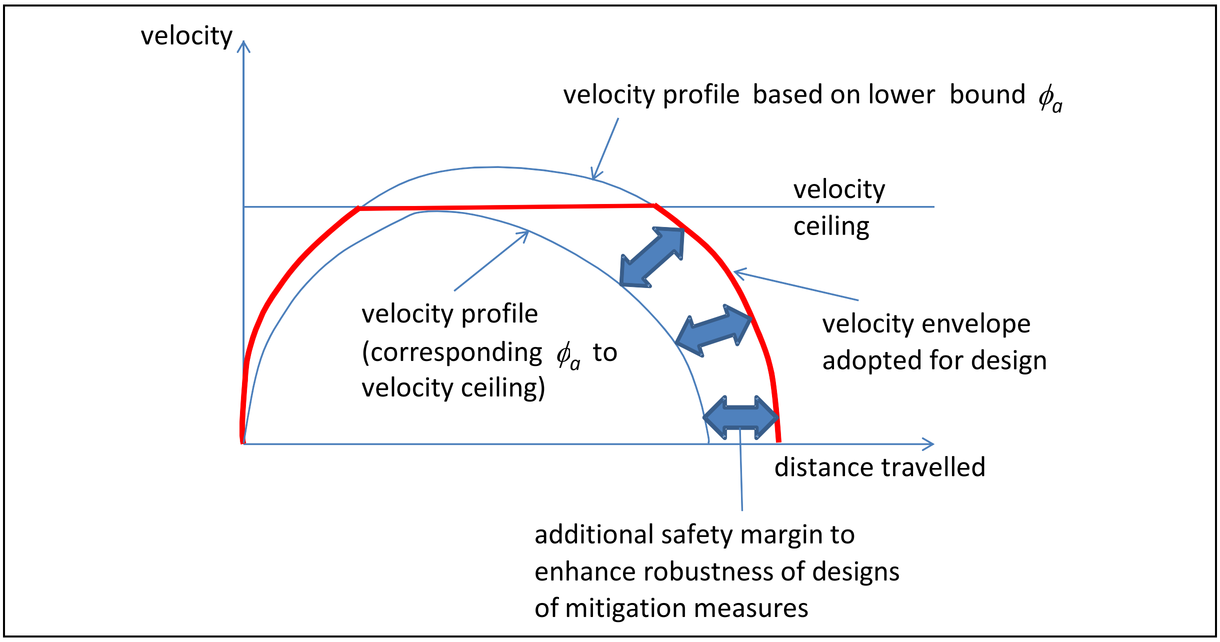

Figure 4.1 Illustration of Concept of Velocity Ceilings

Figure 4.3 shows the proposed lower-bound values of ϕ_a and velocity ceilings for different volume ranges. As only isolated cases with the back-analysed ϕ_a and debris frontal velocities are close to the bounds, the adoption of the recommended velocity envelope would achieve the following two purposes:

(a) being robust in estimation of debris runout distance for assessing the need to provide mitigation measures; and

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(b) being more realistic in estimation of debris velocity for use in the design of mitigation measures.

Given the empirical nature of the proposed approach and the consideration on robustness, both the predicted debris runout distance and debris velocity would likely be on the conservative side.

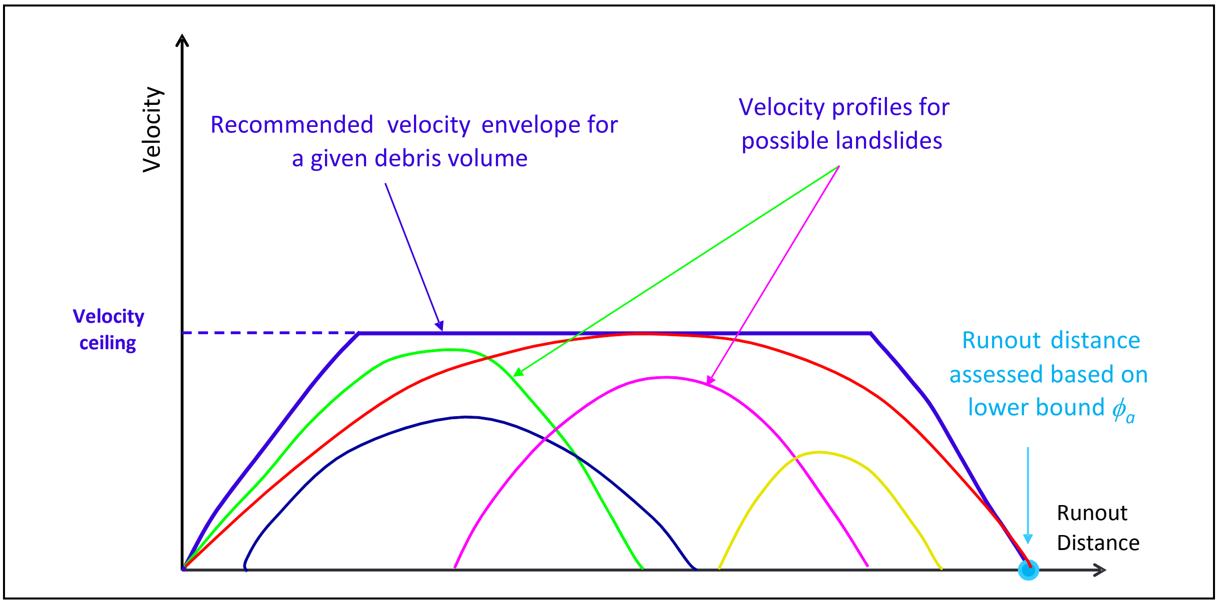

Figure 4.2 Velocity Envelope to Cover Possible Landslides at Different Locations

4.3 Observations of the Mapped 2008 OHF

In the field mapping of the 2008 OHF, relevant landslide data comprising landslide type, runout distance, source volume, entrainment and deposition were recorded. All these OHF were debris avalanches involving a mixture of boulders/corestones and soil in various proportions. No debris super-elevation data were available for estimating debris velocities along the runout paths. No field velocity data are available for OHF.

No significant signs of entrainment were observed from the 2008 OHF. Deposition usually took place readily along the runout paths, but with significant variations in deposition rate. In one case (ENTLI No. 09SED1962E), the majority of the debris mass was deposited at the distal end with a maximum thickness exceeding 2 m. The lower-bound value of the average deposition rate is about 0.5 m^3/m plan-distance-travelled, whereas the upper-bound exceeds 5 m^3/m plan-distance-travelled.

Debris runout distances of the mapped OHF are mostly shorter than those identified in the ENTLI, particularly for cases of high mobility (see Figure 4.4). This is probably because API was not able to differentiate between genuine debris motion and subsequent outwash. For OHF with runout distances exceeding 100 m, the field mapped runout distances are shorter than those of ENTLI by 11% to 30% (average about 20%).

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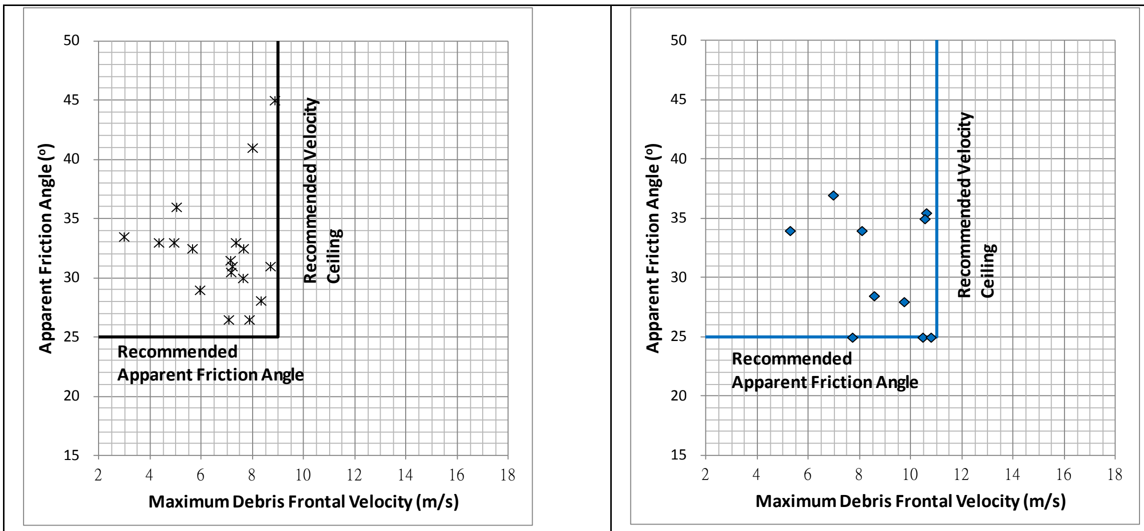
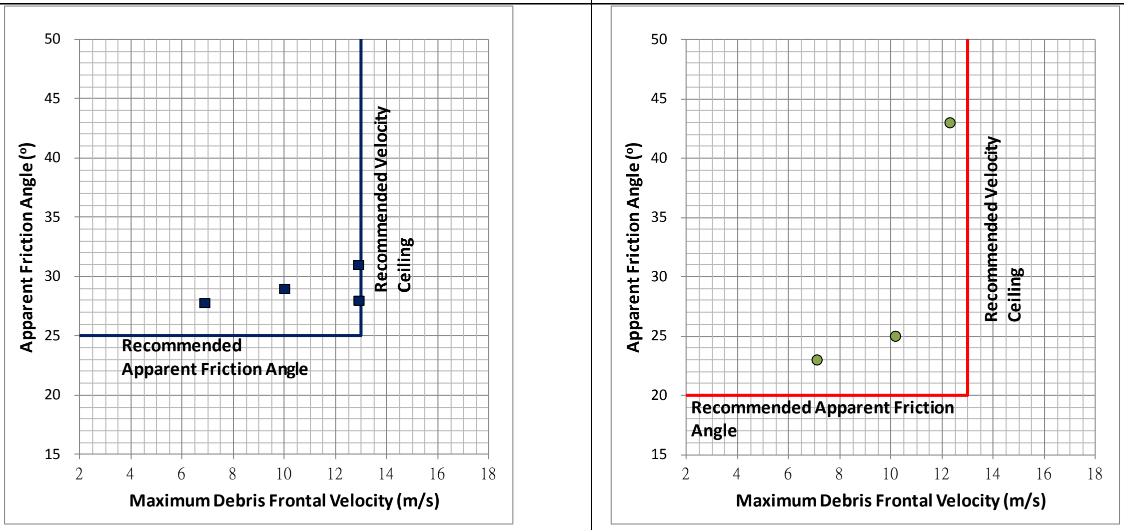


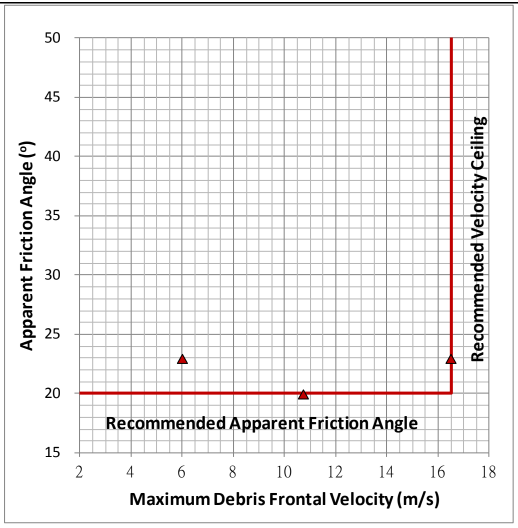
(a) Landslide Source Volume < 200 m^3

(b) Landslide Source Volume 200-400 m^3



(c) Landslide Source Volume 400-500 m^3

(d) Landslide Source Volume 500-1,500 m^3



(e) Landslide Source Volume 1,500-3,000 m^3

Figure 4.3 Back-analyzed Apparent Friction Angles vs Maximum Debris Frontal Velocities for Different Landslide Volume Ranges

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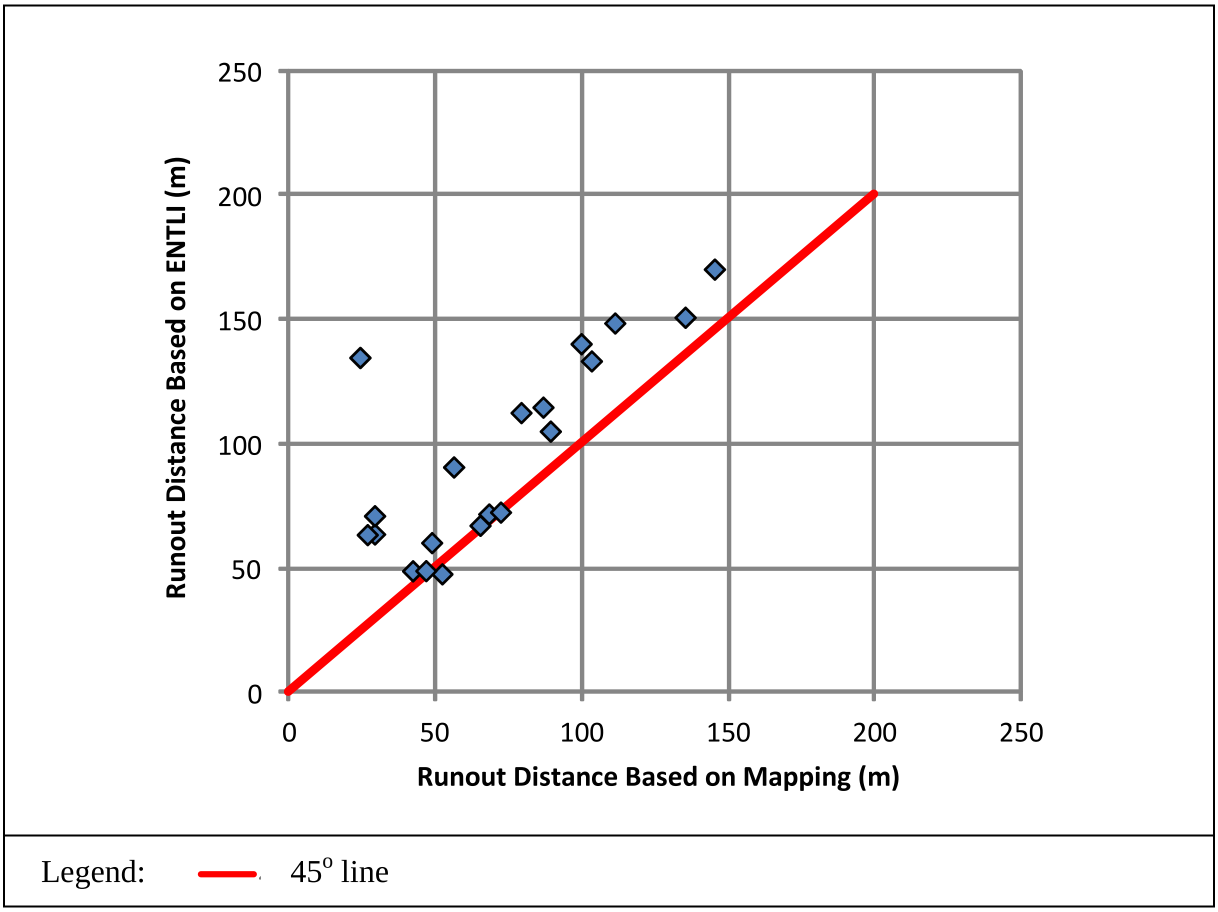

Figure 4.4 Comparison of Runout Distances from ENTLI and Mapping Report

4.4 OHF Involving Adverse Site Setting

Of the 73 OHF back-analysed, three (i.e. ENTLI nos. 07NED0922E, 09SEB1791E and 03SEA2011E) had maximum back-calculated debris velocities (i.e. 16 m/s to 19 m/s) that were higher than the velocity ceilings (see Figure 3.2 and Table 4.1). No mapping or field inspections were conducted for these OHF.

Table 4.1 Back Analysis Results of 3 OHF of Extreme High Debris Velocity

ENTLI No.	Debris Velocity (m/s) (Voellmy Model; ξ= 500 m/s^2)	Debris Velocity (m/s) (Friction Model)
03SEA2011E	12	16
07NED0922E	7	19
09SEB1791E	12	16

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Besides the additional back analyses using the friction model, back analyses using the Voellmy model were also carried out for the three cases. Assuming that the turbulence action involved in these cases was similar to that of CDF (i.e. turbulence coefficient set at 500 m/s^2), the maximum debris velocities would be in the range from 7 to 13 m/s (see Table 4.1).

A common adverse site setting along the runout paths of the three cases is a continuous steeply inclined ground surface of more than 40^o in gradient and 40 m in length on plan (see Figure 4.5 and Table 4.2). The presence of such adverse site setting can be conducive to a higher debris velocity (i.e. exceeding the velocity ceiling) as observed in the back analyses. The use of the velocity ceiling approach is therefore not appropriate for such topographical setting.

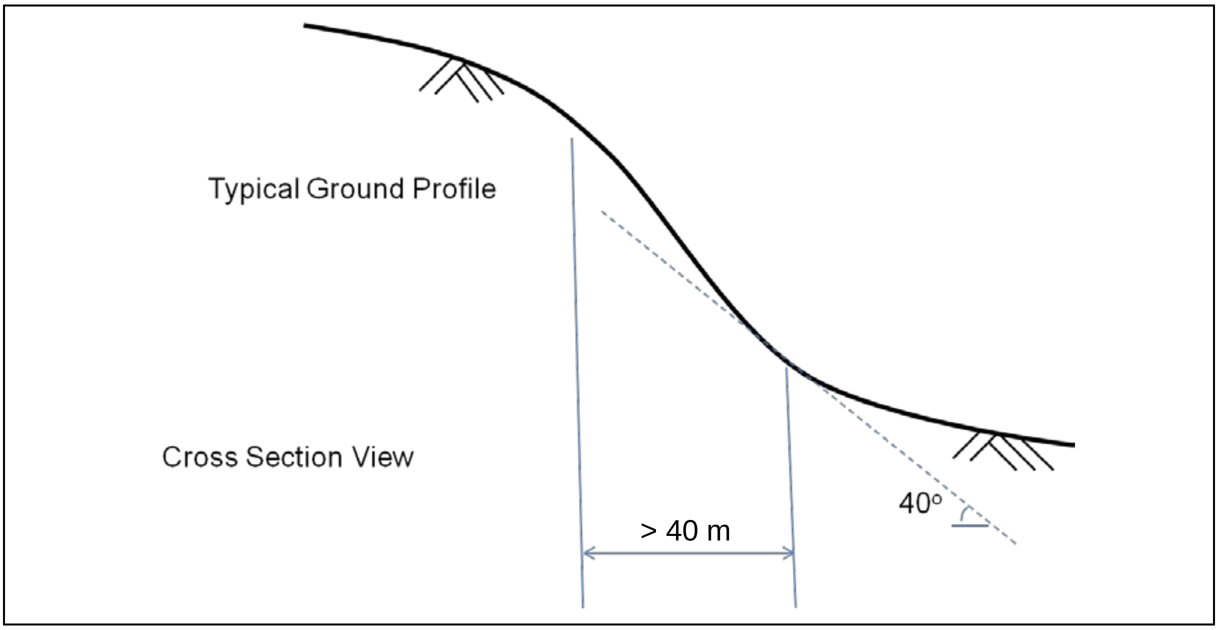

Figure 4.5 Adverse Site Setting where the Method of Velocity Ceiling is not Applicable

Table 4.2 Site Setting of ENTLI Nos. 03SEA2011E, 07NED0922E and 09SEB1791E

ENTLI No.	Site Setting of Critical Portion of Runout Path	
	Plan Distance (m)	Gradient (^{o})
03SEA2011E	60	46
07NED0922E	70	46
09SEB1791E	46	43

Natural hillsides with such adverse site setting are relatively rare in Hong Kong, particularly for OHF catchments which are relatively smaller in size as compared to channelized debris flow (CDF) catchments. It is projected that less than 5% of OHF

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catchments would have limited extent of such adverse setting (i.e. localised areas within the catchment).

4.5 Deposition of Landslide Debris

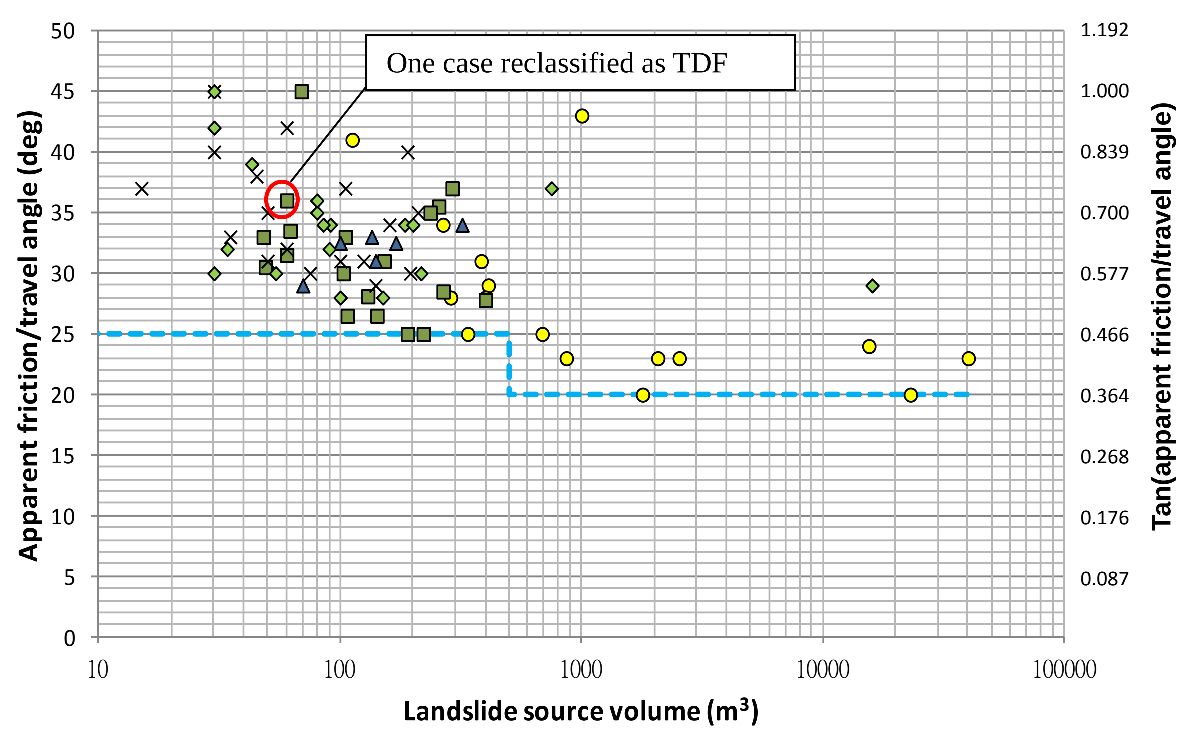
Field mapping of 2008 OHF (21 cases) indicated that deposition usually took place along the runout paths, but with significant variations in the rate of deposition. Deposition of debris along the runout path would lead to a reduction of the total active landslide volume, but the effect on debris motion is not certain. The effect may depend on the locations of detachment from the debris mass (e.g. head or tail). Further work may be required to examine the effect of deposition on mobility of OHF.

4.6 Implications of Reclassification of Some of the Failures to TDF

As indicated in Section 3.1 above, amongst the 73 OHF selected for the additional back analyses in the present study, 15 cases (i.e. one mapped OHF in 2008 and 14 OHF in other years without field mapping) were reclassified as TDF by Lo et al (2013) (see Table A3 in Appendix A).

For the one mapped 2008 OHF reclassified as TDF, the back-analysed ϕ_a using the friction model is highlighted in Figure 4.6 (modified from Figure 3.3). This back-analysed ϕ_a is well above the lower bound of the respective volume range and there is no effect of the reclassification exercise on updating the lower bound of ϕ_a.

The maximum back-analysed velocities (using the friction model) of the above 15 cases (1+14) reclassified as TDF are highlighted in Figure 4.7 (modified from Figure 3.2). As shown in the figure, even if the results of these 15 cases are ignored, many of the remaining 58 OHF (i.e. 73-15) are of high mobility with maximum debris frontal velocities close to the recommended velocity ceiling profile. Having regard to the results and the approach adopted in this study, it is considered that the recommended velocity ceiling profile is still appropriate.



Legend:

━ ━ ━	Design envelope recommended
○	Apparent friction angles from back analyses by Hungr (1998) and Ayotte & Hungr (1998)
■	Apparent friction angles from back analyses for mapped 2008 OHF
▲	Apparent friction angles from back analyses for mapped 1993 OHF
×	Travel angles of other 'Gravitational' and non-channelized 'Mixed' failures inspected by Wong et al (1998)
◆	Travel angles of other OHF studied under GEO's systematic landslide investigation programme

Figure 4.6 Updated Apparent Friction Angle (ϕ_a) of Open Hillslope Failures with One Case Reclassified as TDF

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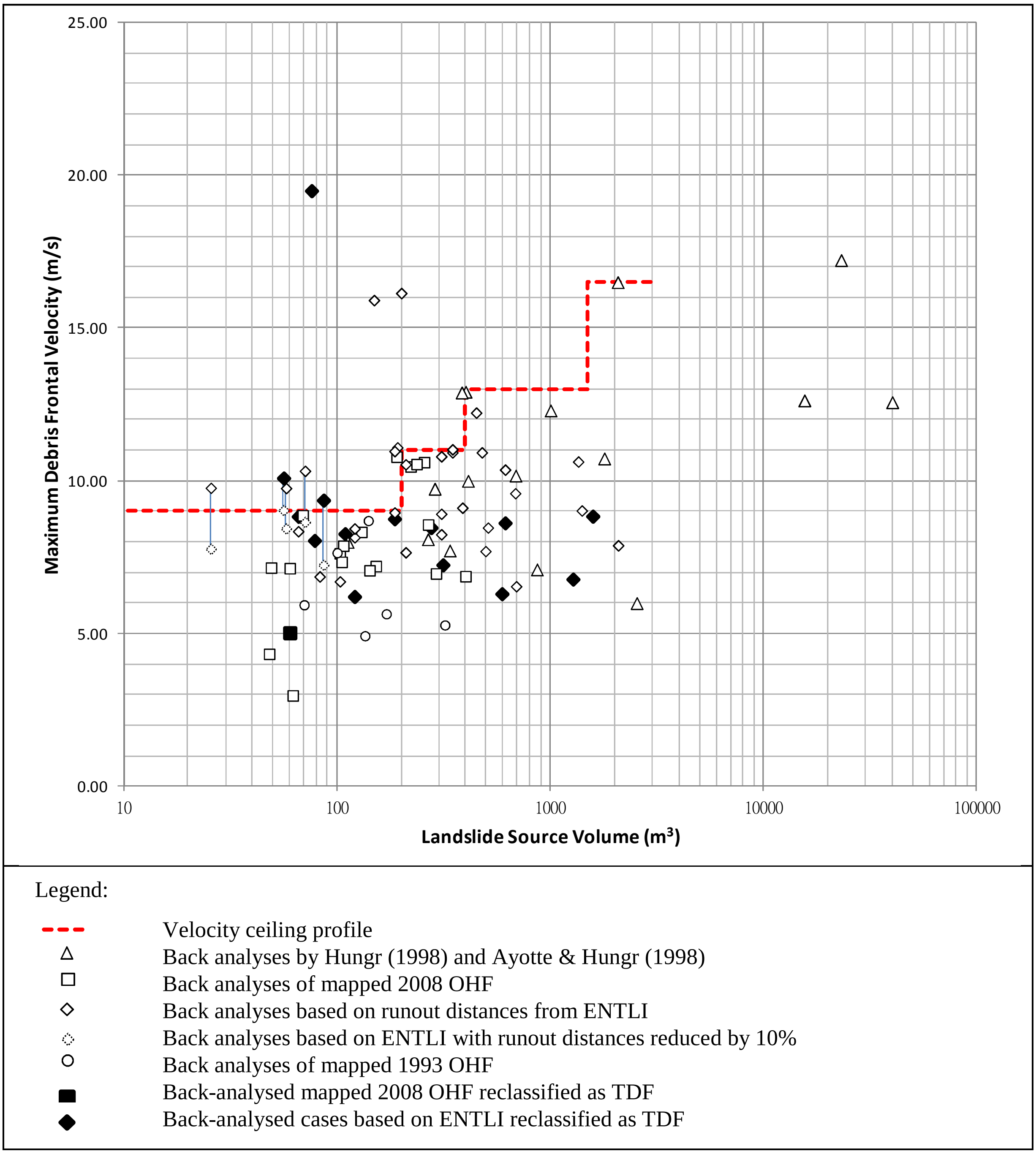

Figure 4.7 **Maximum Debris Frontal Velocity of Open Hillslope Failures with Cases Reclassified as TDF**

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5 Recommendations

It is recommended that the following approaches should be adopted in the assessment of debris mobility for OHF.

5.1 Rheological Model for OHF

Owing to the lack of field debris velocity data and the uncertainties on the debris motion (e.g. sliding, rolling and bouncing) of OHF at different site settings, it is not yet appropriate at this stage to recommend a typical value or range of ξ for use in forward prediction of the debris velocities of OHF. Hence, the friction model as recommended by Lo (2000) (i.e. GEO Report No. 104) should continue be used for assessing the mobility of OHF.

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5.2 Rheological Parameters for Estimation of Runout Distance of OHF

The following lower-bound values of ϕ_a for different volume ranges should be used for estimation of runout distance of OHF:

(a) Landslide source volume ≤ 500 m^3, $\phi_a = 25^o$.

(b) Landslide source volume > 500 m^3, $\phi_a = 20^o$.

5.3 Debris Velocity Ceiling Approach for OHF

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Based on the results of the back analyses and additional back analyses using the friction model, a more realistic prediction of the maximum debris velocity that could be attained by OHF is presented in Figure 3.2. As OHF selected for back analyses are of high mobility among the 12,500 OHF in the ENTLI, the velocity ceilings (see Table 5.1) discerned from the calculated maximum frontal velocities for different volume ranges should be representative.

Table 5.1 Recommended Velocity Ceilings for Different Landslide Source Volumes

Landslide Source Volume	Velocity Ceilings (m/s)
≤ 200 m^3	9
> 200 m^3 and ≤ 400 m^3	11
> 400 m^3 and $\leq 1,500$ m^3	13
$> 1,500$ m^3 and $\leq 3,000$ m^3	16.5

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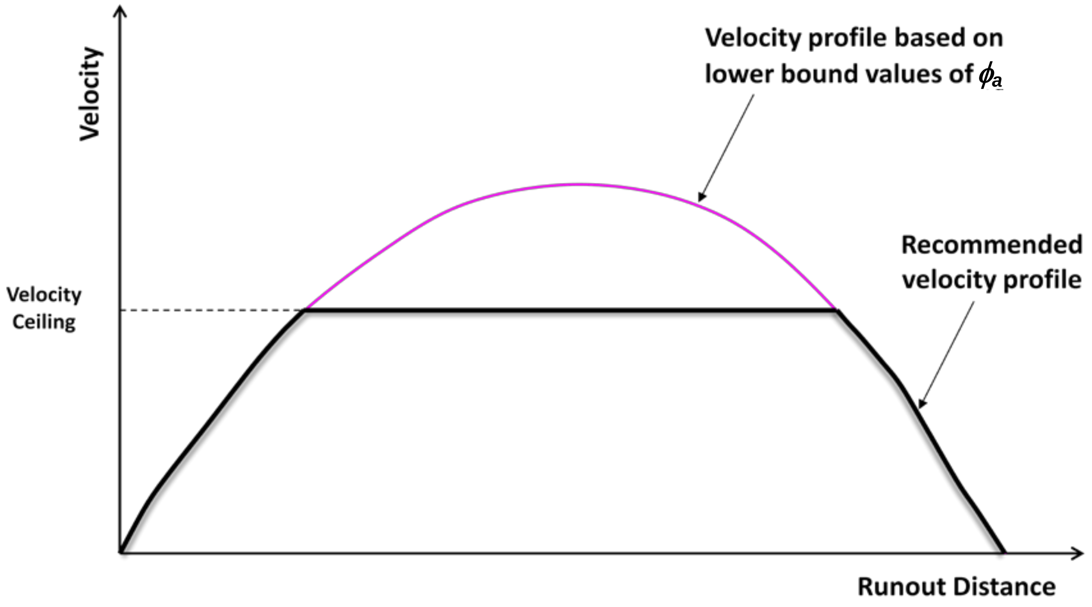
In order to improve the estimation of debris velocity of OHF in forward prediction and design of mitigation measures, an empirical method involving the use of volume dependent velocity ceilings and the calculated velocity profiles based on lower-bound values of ϕ_a can be used. The details are illustrated in Figure 5.1.



Notes:
(1) The velocity ceilings for different landslide source volumes are given in Table 5.1.
(2) If the calculated maximum velocity is higher than the recommended velocity ceiling, the recommended velocity envelope with the velocity ceiling should be used.
(3) If the calculated maximum velocity is lower than the velocity ceiling, then the calculated velocity profile should be used.
(4) The velocity ceiling should not be used for natural hillsides with adverse site setting given in Figure 4.5.

Figure 5.1 Recommended Velocity Profile for Design of Mitigation Measures

5.4 Exclusion Criteria for OHF Involving Adverse Site Setting

The use of the velocity ceiling approach is not recommended for the topographical setting of hillside areas which involve a continuous steeply inclined ground surface of more than 40^o in gradient and 40 m in length on plan-distance (see Figure 4.5).

5.5 Estimation of Debris Thickness

Debris impact force on a structure or barrier is related to both the velocity of the landslide debris and the debris thickness. The adoption of the recommended velocity envelope would require an adjustment of the corresponding debris thickness profile (see Figure 5.1). Assuming the discharge rate as calculated from a debris mobility analysis remains unchanged, the percentage increase in debris thickness would be proportional to the

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percentage reduction in debris velocity (as compared with that calculated using the lower-bound value of ϕ_a) at a given location.

5.6 Need for Reliable Digital Terrain Model

The Digital Terrain Model (DTM) to be adopted for debris mobility modelling should adequately reflect the site characteristics that affect the debris runout path and travel distance. The DTM derived using multi-return airborne LiDAR surveys should be used as far as practicable.

6 Conclusions

Information available for OHF in Hong Kong, where appropriate, has been reviewed and additional back analyses have been carried out. The recommendations given in GEO Report No. 104 have been updated and revised recommendations are given in Section 5 according to the results of the back analyses.

The use of the friction model and lower-bound values of apparent friction angle ϕ_a for prediction of the runout distances as presented in Section 5.2 and the adjustment to the velocity envelopes based on the velocity ceilings as detailed in Section 5.3 are recommended.

The limitations and uncertainties in mobility modelling of OHF, together with the considerations of using lower-bound values of ϕ_a coupled with velocity ceilings in the design of mitigation measures for OHF, have been discussed in Section 4. The recommendations above should be regarded as interim measures. When sufficient new landslide data are available in future, the recommendations should be reviewed and updated.

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Appendix A

Landslide Data for Debris Mobility Assessment of OHF

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A.1 Review of Landslide Data Given in GEO Report No. 104

Debris mobility data of OHF reported by Hungr (1998), Ayotte & Hungr (1998), Wong et al (1998) and Franks (1998) were used by Lo (2000) (i.e. GEO Report No. 104). In this review, the original landslide data have been re-examined and the respective authors consulted where appropriate.

16 landslide cases back-analyzed by Hungr (1998) and Ayotte & Hungr (1998), which were presented in Figure 17 of GEO Report No. 104, using the friction model have been reviewed (see Table A1). They involved landslides on natural terrain, quasi-natural terrain and man-made slopes in which the predominant failure mechanism was OHF debris slide or debris avalanche. The above back analyses were based on quality data collected from field inspections or extracted from detailed landslide studies.

Table A1 List of Landslides Back-analyzed by Hungr (1998) and Ayotte & Hungr (1998) Using Friction Model

Name of Landslide	ENTLI No.
Lantau C1	09SED1715E & 09SED1617E
Shum Wan Road	-
Fei Tsui Road	-
Po Shan Road	-
Ching Cheung Road	-
TC-5A10	09SEB1591E
SP-A6	09SED1669E
TC-5A13	-
TC-6A1	09SEB1555E
Pat Sin Leng 1	-
JK-410	03SWB1297E
JK-419	03SWB1306E
JK-515	03SWD2391E
Tai Mong Tsai	08SWB0905E
Lido Beach	-
Ma On Shan	07NED0967E

About 50 landslides were mapped by Franks (1998) in Tung Chung. According to Franks (2011), most of these were characterised primarily as “debris flows’’ using the

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terminology of Varnes (1978), and a significant proportion (> 50%) of these “debris flows’’ have involved abrupt changes in topography or feeding into or cut by drainage channels. Detailed landslide mapping results can no longer be traced. Given that there are uncertainties regarding the classification of the debris movement mechanism, the data set has been excluded from further analysis.

The November 1993 natural terrain landslides in three areas on Lantau Island were studied by Wong et al (1998). In the study, the 1993 natural terrain landslides on Lantau Island were categorised into three types, viz. ‘Gravitational’, ‘Mixed’ and ‘Hydraulic’. Of the 41 landslides that were mapped in detail, 21 were classified as ‘Gravitational’ failures, which involved “debris movement without a significant influence from the action of surface water’’. The mechanism of ‘Gravitational’ movement is considered relevant to that of OHF. ‘Hydraulic’ failures involved debris which had arisen principally as a result of the action of surface running water. ‘Mixed’ failures refer to landslides which were intermediate between ‘Gravitational’ and ‘Hydraulic’. In addition to the ‘Gravitational’ failures, the non-channelized ‘Mixed’ failures (total 5 landslides) are also considered as OHF in this review.

Among the above 1993 Lantau OHF, those of long runout distances (i.e. from 80 m to 105 m) were selected for the additional back-analyses. Since three of them, viz. A6, A10 and C1, were previously back-analyzed by Hungr (1998) and Ayotte & Hungr (1998), they were not re-analyzed in this review. In total, 5 landslides of ‘Gravitational’ and 1 of non-channelized ‘Mixed’ type were selected for the additional back analyses (see Tables A2 and A3).

A.2 Enhanced Natural Terrain Landslide Inventory (ENTLI)

About 120 out of 12,500 recent OHF in the ENTLI were of high mobility with runout distances exceeding 100 m. The landslide data in the ENTLI were generally based on aerial photograph interpretation (API). Although the runout distance in the ENTLI was not substantiated by detailed field inspection, it is still worthwhile to back-analyze the highly mobile recent OHF with runout distances exceeding 100 m.

Nevertheless, some mobile OHF with long runout contained substantial parts of the runout paths coinciding with drainage lines or were associated with topographic depressions along runout paths. In these OHF, secondary outwash might occur after the landslides. It is difficult to differentiate the distal end of the debris of the main failure from the secondary outwash without detailed field inspection. The runout distances of these OHF given in ENTLI may possibly be on high side. A screening exercise has been conducted to exclude those OHF where the runout paths were affected by concentrated surface runoff (e.g. debris entered drainage lines or topographical depressions). After the screening exercise, a total of 52 OHF (i.e. excluding 3 nos. that have already been studied by Hungr (1998) and Ayotte & Hungr (1998)) of high mobility were selected for the additional back analyses (see Table A3). As discussed in Section 3.1 above, 14 out of the above OHF were reclassified as TDF in the recent study by Lo et al (2013) and, for the sake of simplicity, they were treated as OHF in the additional analyses.

Table A2 List of 1993 Lantau Landslides Inspected by Wong et al (1998) which are Relevant to OHF

Back Analyses Conducted by Ayotte & Hungr (1998)		Selected for Additional Back Analyses by GEO		Not Selected for Additional Back Analyses, but the Travel Angles are Quoted in Figure 3.3	
Landslide No.	Type	Landslide No.	Type	Landslide No.	Type
C1	H	A4	M	A1A	M
A6	G	A5B	G	A2	M
A10	G	A8	G	A3	G
		A12	G	A7	G
		A14	G	A9	G
		A15	G	A11	G
				A13A	G
				A13B	G
				A16A	G
				B3A	G
				B3B	G
				B5B	G
				B6	G
				B8	G
				B10	G
				B11M	M
				B12	M
				B14	G

Note: Abbreviation - G: Gravitational, M: Mixed(Non-channelized) & H: Hydraulic.

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Table A3 List of OHF Selected for Additional Back Analyses

OHF of Runout Distance ≥ 100 m, but not Mapped [Total No. = 46]		2008 OHF of Runout Distance ≥ 100 m and Mapped [Total No. = 5]	2008 OHF of Runout Distance < 100 m and Mapped [Total No. = 16]	1993 OHF Inspected by Wong et al (1998) and of Runout Distance ≥ 100 m [Total No. = 1]	1993 OHF Inspected by Wong et al (1998) and of Runout Distance < 100 m [Total No. = 5]
ENTLI No.		ENTLI No.	ENTLI No.	ENTLI No.	ENTLI No.
02SED0864E	09SEB1619E	09SEA1143E	03SWD2602E	09SED1670E	09SED1650E
03SEA1745E	09SEB1635E	09SEB1707E	07SEC1364E	(A5B)*	(A15)*
03SEA1764E	09SEB1672E	09SED1818E	09SEB1709E		09SED1652E
03SEA1817E	09SEB1791E	09SED1819E	09SEB1726E		(A14)*
03SEA2011E	09SEC2618E	13NWB2380E	09SEB1826E		09SED1655E
03SEB2704Ea	09SED1894Eb		09SEB1849Eb		(A12)*
03SEB2712E#	09SWC0196Ea		09SEC2628E		09SED1662E (A8)*
03SEB2750E#	09SWD1930E#		09SEC2795E		09SED1676E (A4)*
03SED0510E#	09SWD2442E		09SEC2841E		
03SWD2090E	10NWB0234E		09SEC2842E		
03SWD2389E#	10NWB0235E		09SED1962E		
03SWD2394E#	10NWD0625E		09SWD2327E		
05NED1226E#	10NWD0626E#		09SWD2715E#		
05SEB1113E	10SWC2141E		10NWD0651E		
06NEC0482E#	11SWA0388E#		10SWA0875E		
07NED0922E#	11SWC0608E		13NEB0750E		
07NWA1717E#	11SWD0631E				
08NWD1117E	12SWA0374E				
08NWD1142E#	13NEB0734E				
08SEA0581E	13NWB2226E				
08SEA0604E	13NWB2254E#				
09SEB1460E	13NWB2763E				
09SEB1541E	15NWB0454E				

Legend	*	( ) is the corresponding landslide no. denoted in GEO Report No. 69
	#	Cases reclassified as TDF (see Section 4.6)

A.3 Mapping of 2008 OHF

In addition, field mapping exercises were carried out for 21 OHF that occurred in 2008. The field mapping exercise was carried out by the GEO's consultants in 2011. In the field mapping, relevant landslide data comprising landslide type, runout distance, source volume, entrainment and deposition were recorded. The spatial distribution of the debris deposition volumes along the runout paths was also estimated. It was intended to inspect all mobile OHF with long runout distance. However, some of these OHF were found to be inaccessible. Eventually, 5 cases with long runout distances equal to or greater than 100 m and 16 with runout distance less than 100 m were inspected. The maximum runout distance and the maximum total debris volume among the above mapped OHF were about 150 m and 400 m^3 respectively. All these OHF are included in the additional back analyses (see Table A3). As discussed in Section 3.1 above, one of the 2008 mapped OHF was reclassified as TDF in the recent study by Lo et al (2013) and, for the sake of simplicity, it was treated as OHF in the additional analyses.

A.4 Other Landslide Data from GEO's Systematic Landslide Investigation Programme

Some other less mobile OHF identified under the GEO's systematic landslide investigation programme were examined (see Table A4). No back analyses were conducted for these OHF, but the travel angles were quoted in updating Figure 17 of GEO Report No. 104 (see Figure 3.3).

A.5 Summary of Landslide Data for Additional Back Analyses

In summary, 52 OHF of high mobility were selected for the additional back analyses. Out of the 52 OHF, field mapping was carried out for 5 of them in 2008 and 1 in 1993. In addition, field mapping of 21 nos. of relatively 'less mobile' OHF (16 in 2008 + 5 in 1993) were also available and they were also selected for the additional back-analyses. Hence, the additional back analyses were conducted for a total of 73 OHF (i.e. 52 + 21 = 73), in which field mapping were available for 27 OHF (i.e. 21 + 6 = 27). A list of the OHF selected for the additional back analyses is given in Table A3. The selected OHF represent the top 0.5% of most mobile OHF in the ENTLI. In essence, all the mobile OHF in the ENTLI have been considered for the additional back analyses.

Table A4 OHF Examined under GEO's Systematic Landslide Investigation Programme

Location	Reference	Total Debris Volume (m^3)	Travel Angle (deg)
Tai O San Tsuen No. LS1	LSR No. 3/2001	80	35
Tai O San Tsuen No. LS4	LSR No. 3/2001	185	34
Tai O San Tsuen No. LS5	LSR No. 3/2001	200	34
North Lantau Expressway No. L8	LSR No. 7/2010	216	30
North Lantau Expressway No. L11	LSR No. 7/2010	34	32
North Lantau Expressway No. L12	LSR No. 7/2010	43	39
North Lantau Expressway No. L13	LSR No. 7/2010	100	28
North Lantau Expressway No. L14a	LSR No. 7/2010	80	36
North Lantau Expressway No. L19	LSR No. 7/2010	91	34
North Lantau Expressway No. L34	LSR No. 7/2010	30	42
North Lantau Expressway No. L38	LSR No. 7/2010	54	30
North Lantau Expressway No. L53	LSR No. 7/2010	85	34
Yu Tung Road No. L28	LSR No. 14/2009	90	32
Yu Tung Road No. L49	LSR No. 14/2009	150	28
Yu Tung Road No. L50b	LSR No. 14/2009	30	30
Yu Tung Road No. L51	LSR No. 14/2009	30	45
Shek Pik 1 Source D	Landslide Mapping Report No. LS08-0257	16,000	29
Bowen Road	GEO Report No. 214	750	37

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Appendix B

Back Analyses of Flume Tests on Dry Granular Flow

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B.1 Introduction

Yang et al (2011) carried out flume tests on dry granular flow and reported the frontal velocity as measured in the tests. The granular materials used were of grain size up to 100 mm. As observed by Yang et al (op cit), the granular flows in their tests involved rolling and bouncing of large granular particles. The flume tests may be taken to replicate the dynamics of a dry debris avalanche of OHF.

The flume was 1 m wide and about 14 m long. Granular materials stored at the high end of the flume were released by opening a flip gate. The inclination of the flume immediately downstream of the gate is 45°. Further downstream, about 4 m from the gate, the inclination reduced to 10° (see Figure B1).

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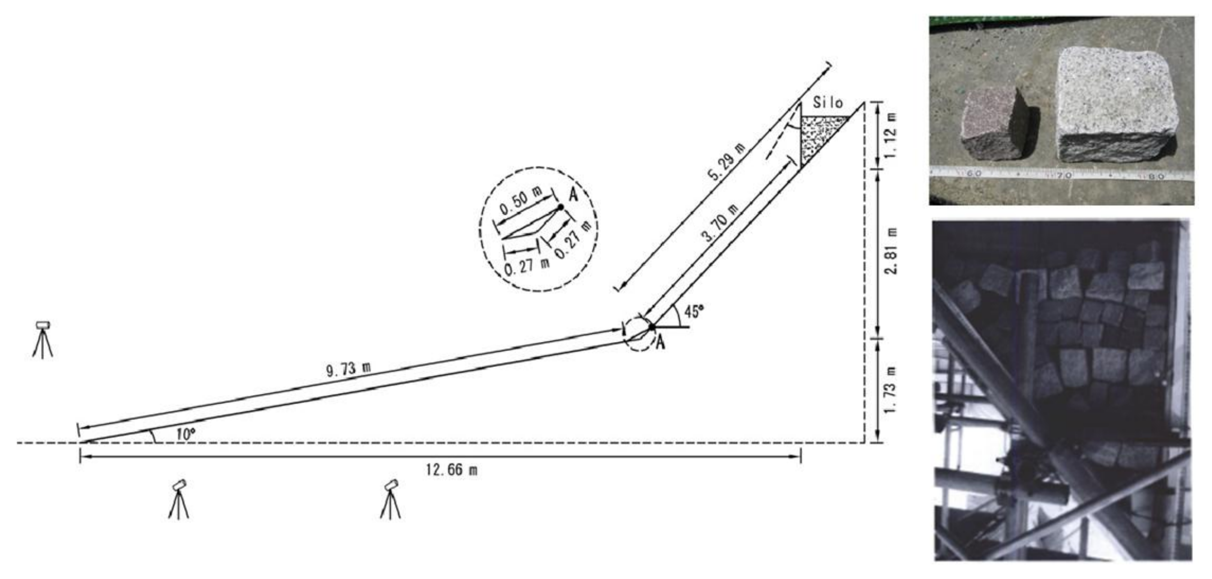

Figure B1 Profile of the Flume & Photo of Granular Materials (Extracted from Yang et al (2011))

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Several flume tests were conducted to examine the dynamics of granular flows of different grain size. Frontal velocities were estimated based on video records.

In the present study, the computer program DAN-W was used by the GEO to back-analyze the results of the tests. The rheological models used included both the friction model and the Voellmy model.

B.2 Back Analyses of Single Material Flow

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The reported frontal velocities of gravel flows, rounded-cobble flow and rectangular-cobble flow were generally similar. Figure B2 presents the results of the back analyses conducted. The orange solid line represents the best-fit data produced using the friction model. The data match with the trend, the maximum frontal velocity (5.3 m/s) as well as the runout distance (6.5 m) as measured in the tests.

With the Voellmy model, different combinations of ϕ_a and ξ have been attempted. However, none of the combination produces satisfactory results (in terms of good fit to the travel distance and frontal velocity profile) as compared with the friction model (see Figure B2).

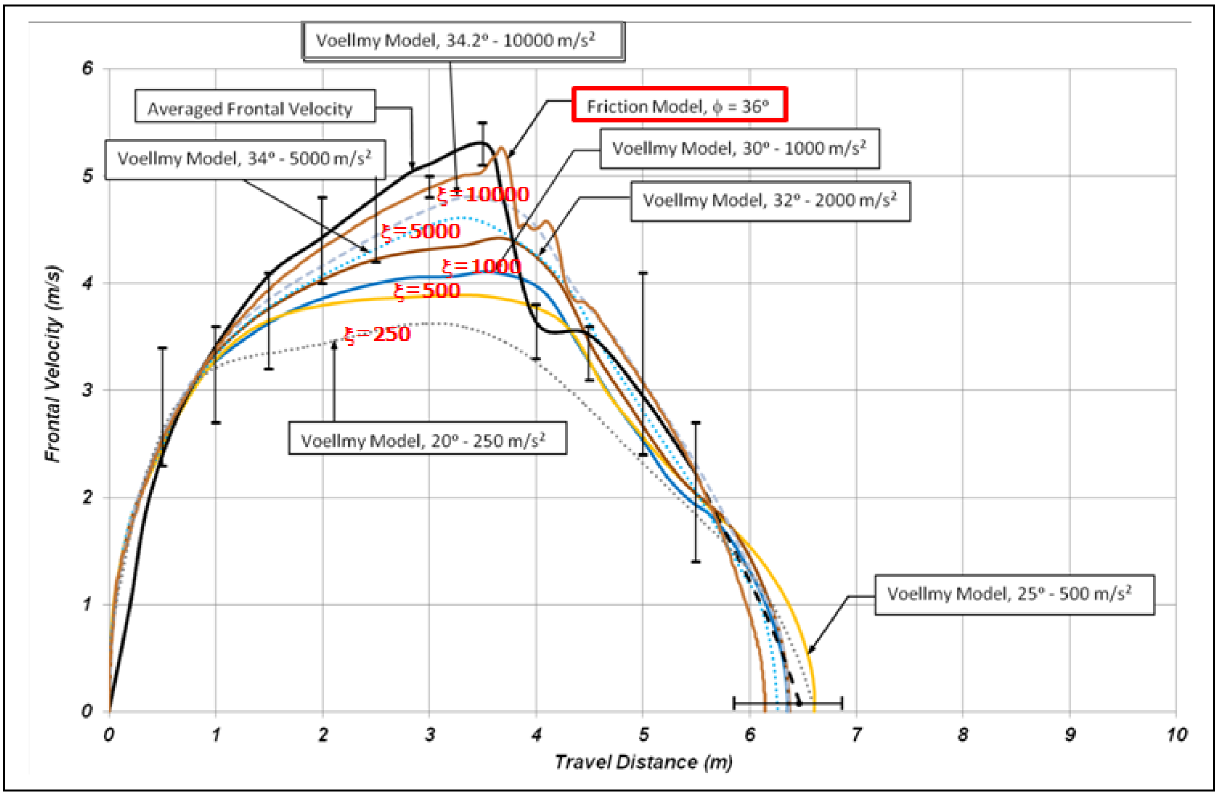

Figure B2 Back Analyses of Single Material Flows

B.3 Back Analyses of Composite Material Flow

Yang et al (2011) also reported results of flume test using composite material flow (very sandy Gravels and rectangular Cobbles). Back analyses using the friction model and the Voellmy model were carried out by the GEO in an attempt to produce results that resemble the reported maximum frontal velocity of 4.1 m/s and the observed runout distance of 5.8 m of the flume test (see Figure B3).

For this case, results based on both the friction model and the Voellmy model could match the reported debris velocity profile and runout distance satisfactorily (see Figure B3). It is noted that quite a large range of ξ (i.e. from 250 m/s^2 to 1,000 m/s^2) would give similar velocity profiles with relatively small differences in runout distances.

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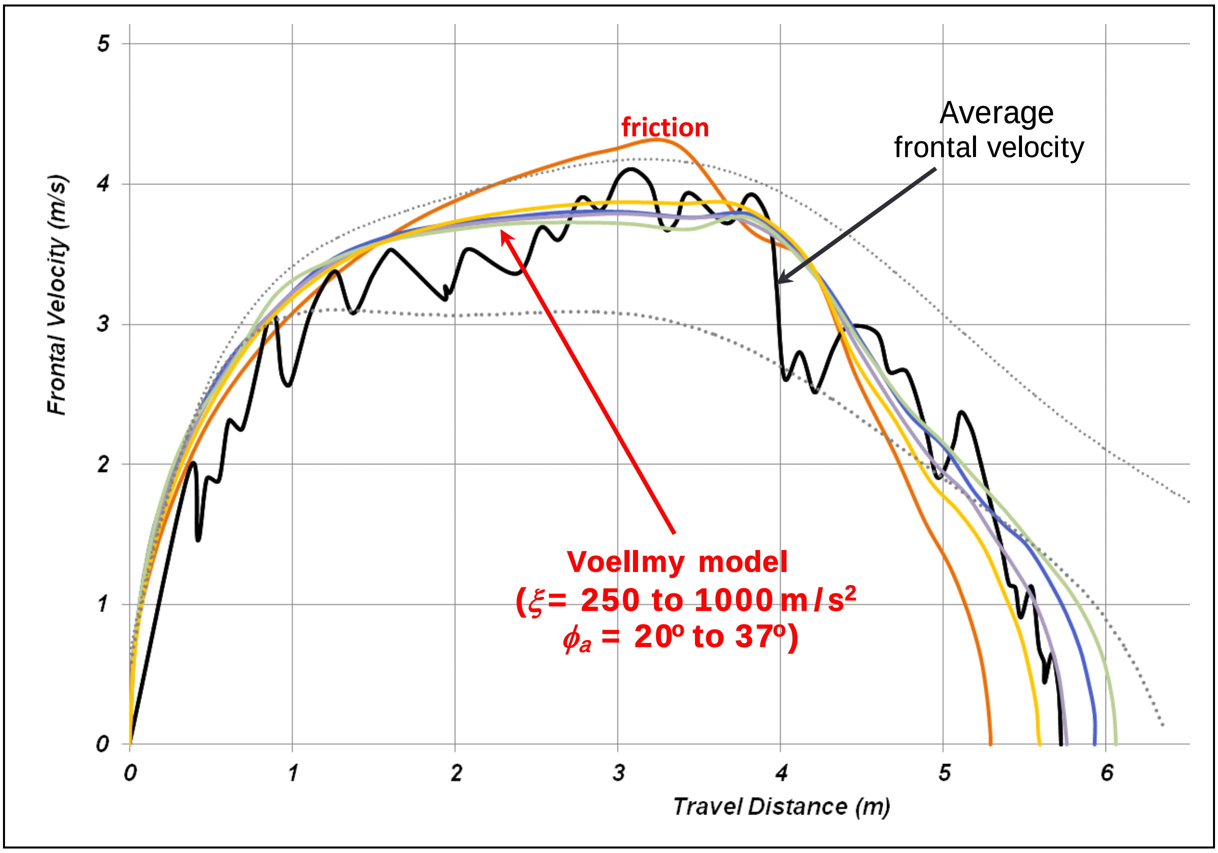

Figure B3 Back Analyses of Composite Material Flows

B.4 References

Yang, Q., Cai, F., Ugai, K., Yamada, M., Su, Z., Ahmed, A., Huang, R. & Xu, Q. (2011). Some factors affecting mass-front velocity of rapid dry granular flows in a large flume. *Engineer Geology*, vol. 122, pp 249-260.

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Appendix C

Uncertainties on Debris Runout Distances and Landslides Locations

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C.1 Uncertainties on Debris Runout Distances

There are a number of cases in the ENTLI which indicate that OHF with similar site settings and failure volumes could have significant differences in their debris runout distances at different rainstorms. Some examples are given in Figure C1 below.

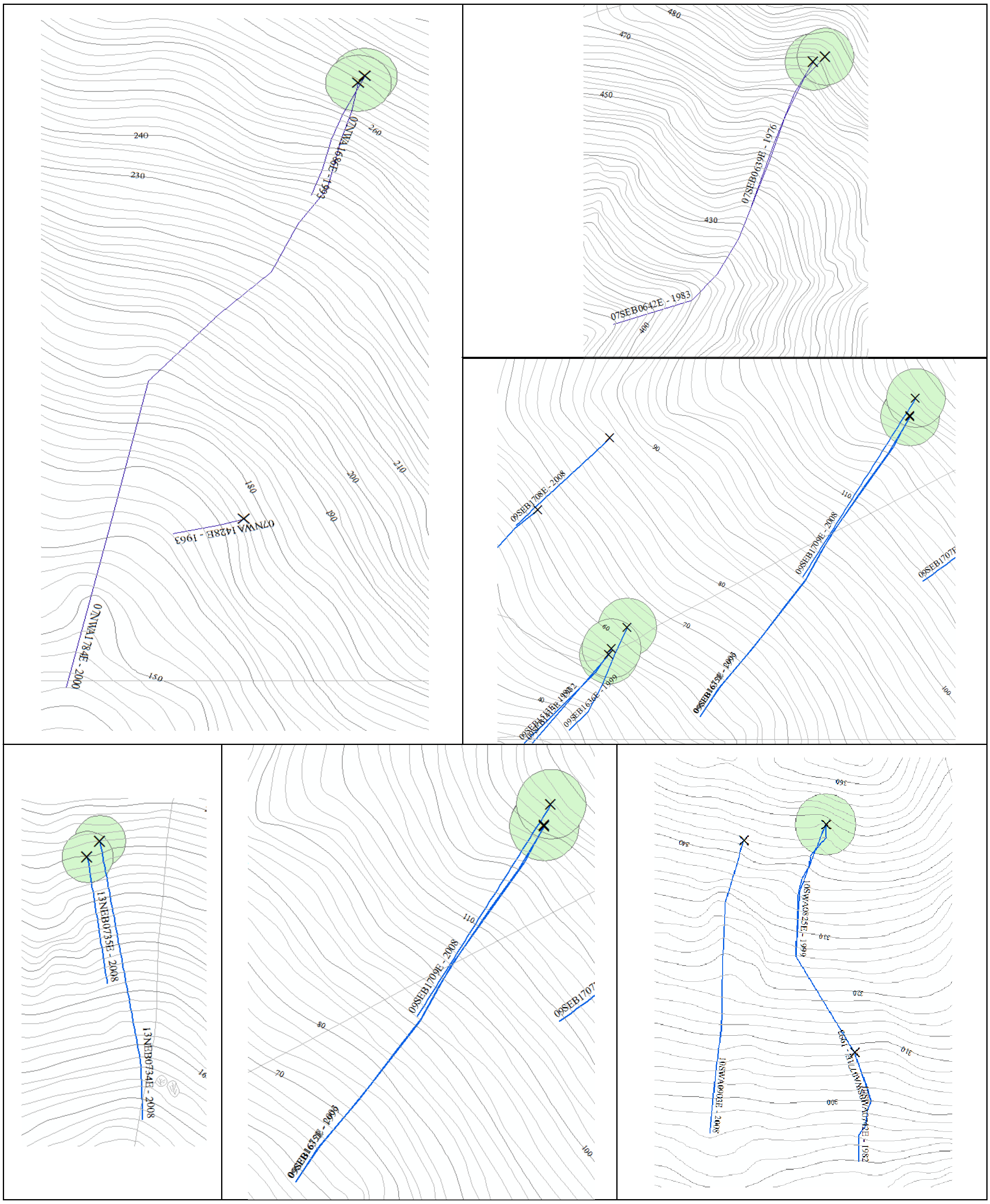

Figure C1 OHF with Similar Site Setting but Different Debris Runout Distances

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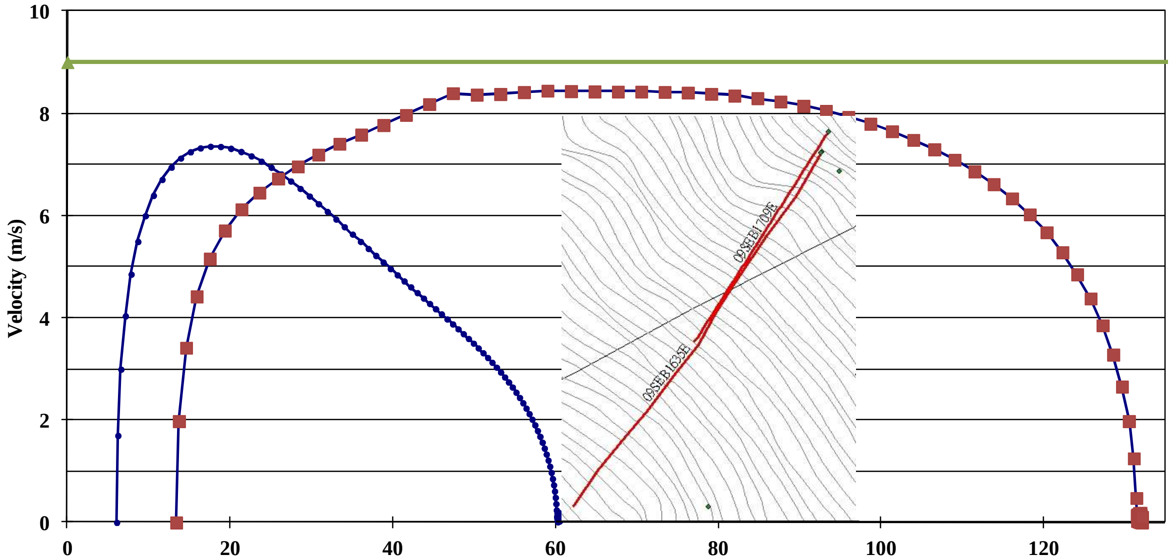
Based on the results of the back analyses using the friction model, these cases may have similar maximum debris frontal velocities but very different runout distances, even for landslides with similar source volumes (see Figure C2 for example).



ENTLI No.	Debris Volume (m³)	Year	Travel Angle (deg)
09SEB1709E	105	2008	31
09SEB1635E	121	1999	30

Legend:

—●— 09SEB1709E-Back analysis

—■— 09SEB1635E-Back analysis

—▲— Velocity ceiling

Figure C2 Back-analyzed Velocity Profiles of OHF with Similar Site Settings but Different Runout Distances

C.2 Uncertainties on Landslide Locations

Landslides could potentially occur at different locations and elevations on a natural terrain, and they could be in close proximity to the downslope facilities/barriers (e.g. the 2008 OHF at Jordan Valley). Some examples extracted from the ENTLI are shown in Figure C3.

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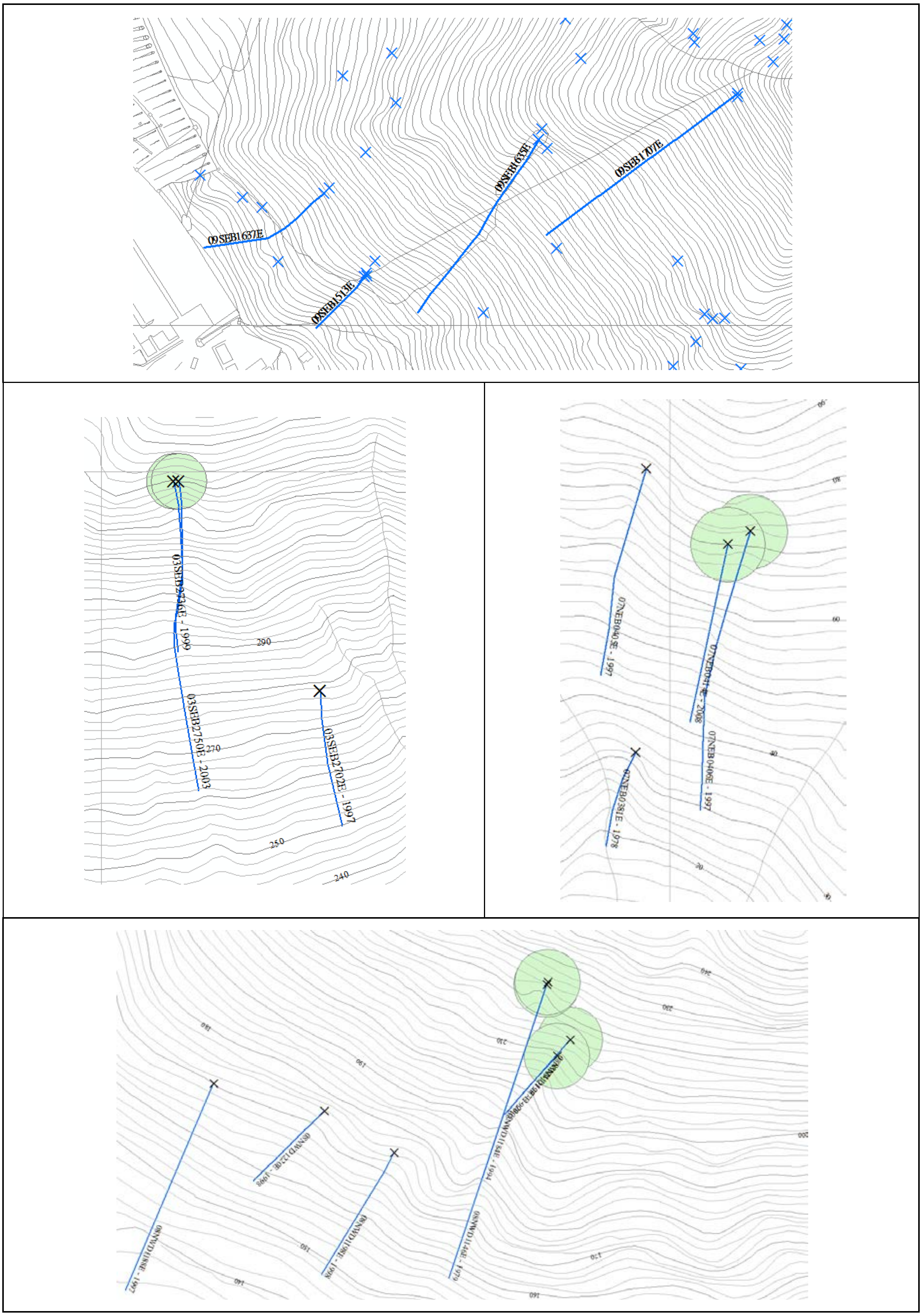

Figure C3   Examples of OHF Occurred at Different Locations and Elevations

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In the design of mitigation measures, the corresponding velocity profiles of possible landslides at different locations need to be checked to determine the most critical scenario (see Figure C4 for example).

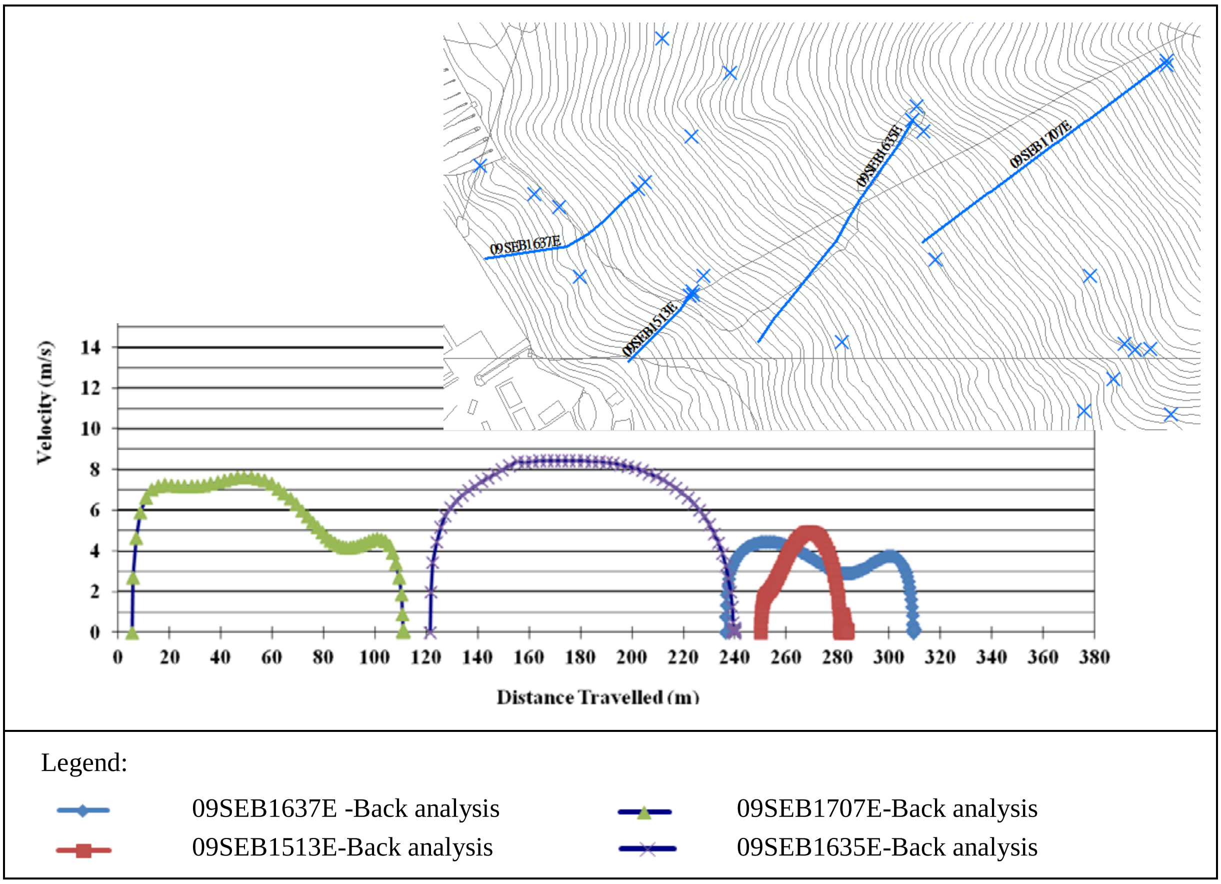

Figure C4 Back-analyzed Velocity Profiles of OHF at Different Locations

C.3 Discussions

Given the uncertainties involved in the estimation of the debris runout distance and the importance of its value with respect to the need of mitigation measures, a robust approach should be adopted in the forward prediction of debris runout distance. Hence, the lower-bound values of ϕ_a are recommended for use with the friction model to predict the maximum runout distances of OHF, similar to that proposed in GEO Report No. 104.

Based on the results of back analyses using the actual observed travel distances, the calculated velocities for different source volume ranges are in general lower than the corresponding values that are estimated using the lower-bound values of ϕ_a (see Figure C5). Figure C5 shows a typical case that the proposed method could reduce the design debris velocity by more than 50%. Since the cases selected for the back analyses are sufficiently comprehensive in terms of topographical setting (see Appendix B) and they cover the most mobile cases as well as landslides affected by severe rainstorms (e.g. 1993 and 2008 rainstorms), the velocity ceilings derived from the back analyses are considered to err on the

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caution side but are nonetheless more realistic than those estimated based on the lower-bound values of ϕ_a.

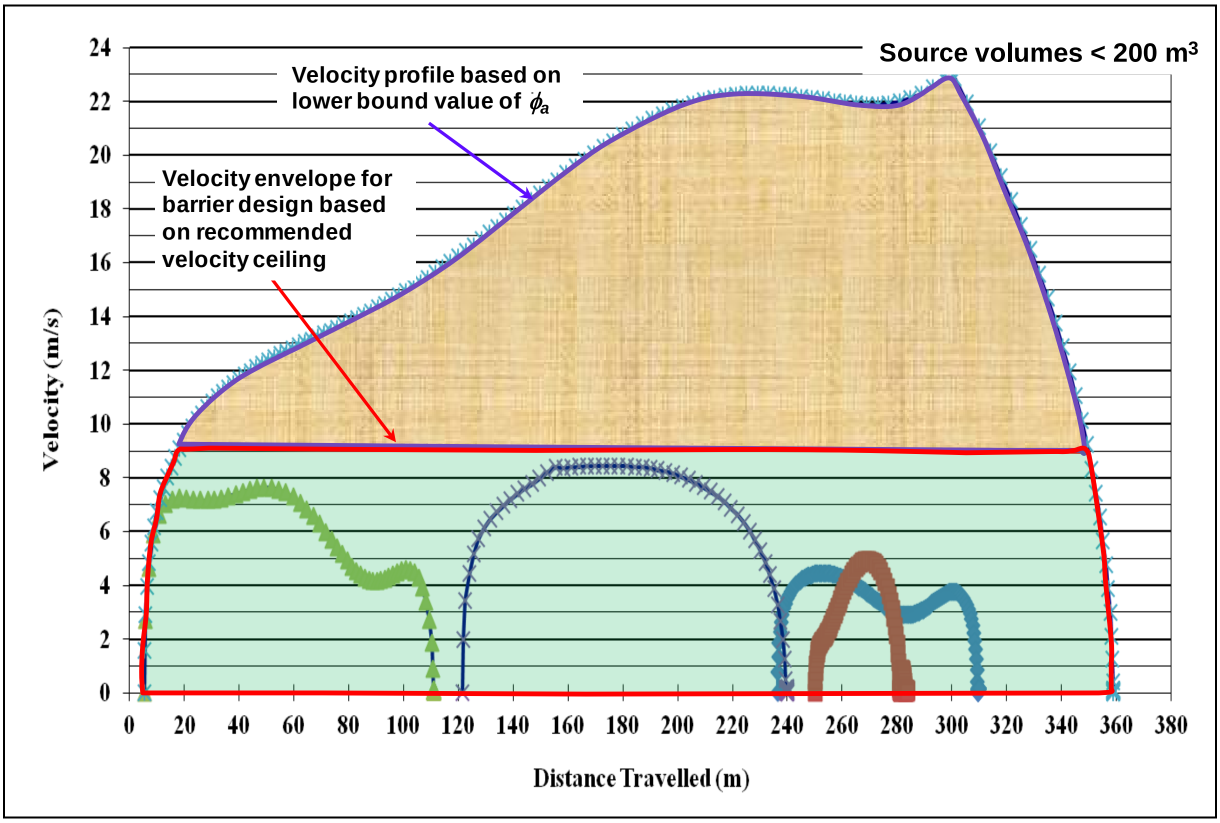

Figure C5 Velocity Envelopes Based on Different Approaches

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Geotechnical Manual for Slopes, 2nd Edition (1984), 302 p. (English Version), (Reprinted, 2011).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

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Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.
Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

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GEO Publication No. 1/2011	Technical Guidelines on Landscape Treatment for Slopes (2011), 217 p.

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The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

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