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

GEO Technical Guidance Note No. 34 (TGN 34)
Guidelines on Assessment of Debris Mobility for Open Hillslope Failures

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1. SCOPE

1.1 This Technical Guidance Note (TGN) supplements the guidance on the assessment of debris mobility for open hillslope failures (debris slides and debris avalanches) given in GEO Report No. 104 (Lo, 2000).

1.2 Any feedback on this TGN should be directed to Chief Geotechnical Engineer/Planning and Development of the Geotechnical Engineering Office (GEO).

2. TECHNICAL POLICY

2.1 The technical recommendations promulgated in this TGN were agreed by GEO Geotechnical Control Conference (GCC) on 25 September 2012.

3. RELATED DOCUMENTS

3.1 Ayotte, D. & Hungr, O. (1998). *Runout Analysis of Debris Flows and Debris Avalanches in Hong Kong.* A Report for the Geotechnical Engineering Office, Hong Kong. University of British Columbia, Canada, 90 p.

3.2 Franks. C.A.M. (1998). *Study of Rainfall Induced Landslides on Natural Slopes in the vicinity of Tung Chung New Town, Lantau Island (GEO Report No. 57).* Geotechnical Engineering Office, Hong Kong, 102 p.

3.3 Franks. C.A.M. (2011). Personal communication.

3.4 Ho, H. Y. & Roberts, K. J. (2016). *Guidelines for Natural Terrain Hazard Studies (GEO Report No. 138, Second Edition).* Geotechnical Engineering Office, Hong Kong, 173 p.

3.5 Hungr, O. (1998). *Mobility of Landslides in Hong Kong: Pilot Analysis Using a Numerical Model*. A Report for the Geotechnical Engineering Office, Hong Kong. O. Hungr Geotechnical Research Inc., Canada, 52 p.

3.6 Hungr, O. (2011). Comments on DN 1/2012 – Suggestions on Design Approaches for Flexible Debris-resisting Barriers.

3.7 Hungr, O. & Evans, S.G. (2004). *Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism*. GSA Bulletin Vol. 116.

3.8 Lo, D.O.K. (2000). *Review of Natural Terrain Landslide Debris-resisting Barrier Design (GEO Report No. 104).* Geotechnical Engineering Office, Hong Kong, 91 p.

3.9 McKinnon, M., Hungr, O. & McDougall, S. (2008). Dynamic Analyses of Canadian Landslides. *Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management*. Quebec, Canada.

3.10 Wong, H.N., Lam, K.C. & Ho, K.K.S. (1998). *Diagnostic Report on the November 1993 Natural Terrain Landslides on Lantau Island (GEO Report No. 69).* Geotechnical Engineering Office, Hong Kong, 98 p.

4. BACKGROUND

4.1 Open hillslope failure (OHF) involves predominantly sliding failure whereby the debris is not channelised along a stream course. According to Ho & Roberts (2016), OHF is typically in the form of a debris slide or debris avalanche. However, where the site setting is conducive to concentration of surface water, e.g. presence of topographical depressions or hollows, and if there is sufficient surface water, the movement of debris may develop into a debris flow.

4.2 Debris mass of OHF (debris slide and debris avalanche) may be heterogeneous in nature, and could comprise soils and boulders/corestones in various proportions at different degrees of saturation (Hungr, 2011). The debris motion of OHF along the runout path is likely to be non-uniform and may be in the form of intermittent sliding or rolling and bouncing, with differing degrees of mass disintegration and turbulence.

4.3 A total of 16 landslides involving predominantly debris slides or debris avalanches were back analysed by Hungr (1998) and Ayotte & Hungr (1998) using the friction model. The back analyses were essentially based on the debris runout distance and to some extent, the spatial distribution of debris deposition. The back analyses established the values of apparent friction angle (ϕ_a) and a trend of reducing ϕ_a with increasing landslide source volume.

4.4 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 flows. Also, Hungr (op cit) considered that the friction model would be an appropriate rheological model for simulation of debris slides and debris avalanches. Compared with the Voellmy model, the friction model would tend to predict higher debris velocities, and that the bulk of the debris would be deposited proximally with gradual thinning towards the source in the case of the friction model.

4.5 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. In light of this, the relevant landslide data reported by Wong et al (1998) and Franks (1998) were combined with the results of the above back analyses in Figure 17 of GEO Report No. 104, with due account taken of landslide volume and the distinction between OHF and channelised debris flow (CDF). Based on this figure, the following lower-bound values of ϕ_a were recommended by Lo (2000) for use with the friction model to provide a conservative estimate of debris mobility of OHF:

Landslide source volume < 400 m^3, $\phi_a = 25^o$

Landslide source volume ≥ 400 m^3, $\phi_a = 20^o$

5. ADDITIONAL ANALYSES

5.1 Additional back analyses using the friction model have been carried out for selected OHF of high mobility (runout distance >100 m) based on the Enhanced Natural Terrain Landslide Inventory (ENTLI). Field mapping of some of these OHF that occurred in 1993 and 2008 were available and the respective mapped debris runout distances were used in the back analyses. Also, the site settings of these cases were reviewed critically to ensure that only 'genuine' OHF (i.e. without being affected by concentrated surface water) were included in the back analyses.

5.2 From the review, 52 OHF of high mobility have been identified, which include those that occurred in 1993 and 2008. In essence, all the mobile OHF have been considered. Also, field mapping of 21 nos. of relatively 'less mobile' OHF were available and most of them had runout distances ranging from 50 m to 100 m. Hence, a total of 73 OHF (i.e. 52+21=73) were selected for carrying out the back analyses.

5.3 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 summarised in Annex TGN 34A. The results and findings of the back analyses are presented in Annex TGN 34B. Based on the findings of the review and back analyses, the technical recommendations for the assessment of debris mobility for OHF are updated.

6. TECHNICAL RECOMMENDATIONS

Rheological Model for OHF

6.1 The Voellmy model may, in-principle, give a better simulation of the turbulent action (e.g. mass disintegration) involved in the debris motion of OHF. McKinnon et al (2008) and Hungr & Evans (2004) also observed that Voellmy model produced consistently good simulation results for rock avalanches. The use of Voellmy model would require the input of two rheological parameters (i.e. ϕ_a and ξ).

6.2 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) may continue to be used for assessing the mobility of OHF.

Rheological Parameters for Estimation of Runout Distance of OHF

6.3 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.

6.4 The landslide data of OHF shown in Figure 17 of the GEO Report No. 104 have been reviewed to ensure that only those relevant and quality data with sufficient documentation are presented. In the review, different types of OHF are duly considered (see Section 1 in Annex TGN 34A). Also, the figure has been updated with quality data of recent OHF of high mobility collated from field mapping (see Section 2 in Annex TGN 34B and Figure B1). The following lower-bound values of ϕ_a for different volume ranges are recommended:

Landslide source volume ≤ 500 m^3, $\phi_a = 25^{o}$

Landslide source volume > 500 m^3, $\phi_a = 20^{o}$

These lower-bound values should be sufficiently robust for estimating debris runout distances of OHF using the friction model.

Debris Velocity Ceiling Approach for OHF

6.5 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 likely be on the high side in most cases. This may result in cost and practicability implications for the vast majority of 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; and that the velocity profile of OHF is always lower than that derived using the lower-bound value of ϕ_a.

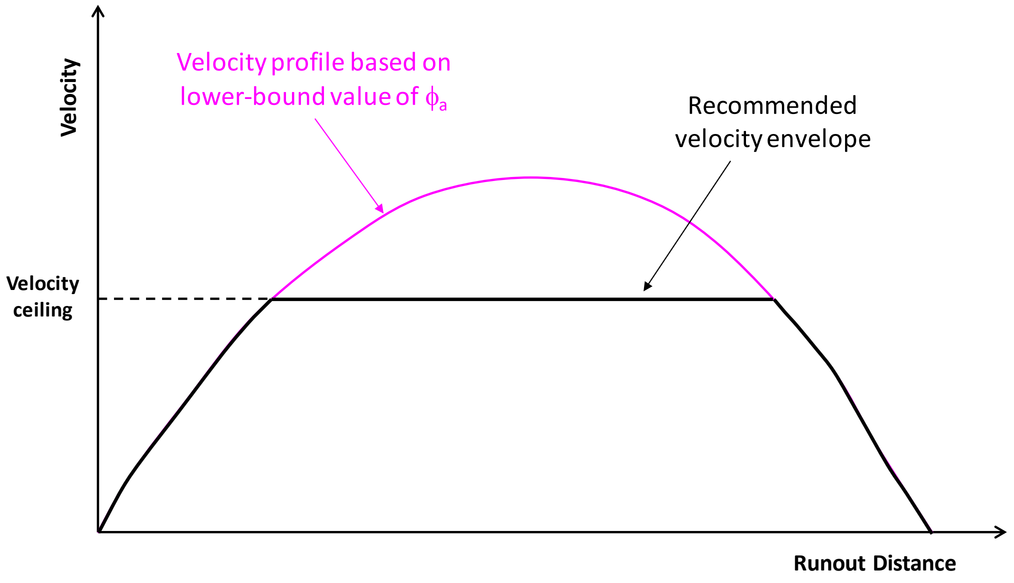
6.6 Based on the results of the additional back analyses using the friction model (see Section 3 in Annex TGN 34B), a more realistic prediction of the maximum debris velocity that could be attained by OHF is presented in Figure B2. As OHF selected for back analyses are of high mobility among the 12,500 OHF in the ENTLI, the velocity ceilings (see Table 1 below) discerned from the calculated maximum frontal velocities for different volume ranges should be representative.

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

Table 1 – Recommended velocity ceilings for different landslide source volumes

Debris Velocity Envelope for Barrier Design

6.7 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 is recommended. The details are illustrated in Figure 1.



Notes:
(1) The velocity ceilings for different landslide source volumes are given in Table 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 B3 in Annex TGN 34B.

Figure 1 – Recommended velocity envelope for design of mitigation measures

Exclusion Criteria for OHF Involving Adverse Site Setting

6.8 Of the 73 OHF, three had maximum back-calculated debris velocities that were higher than the recommended velocity ceilings (see Figure B2). This indicates that the recommended values of velocity ceilings may not be adequate for all types of OHF. A common adverse site setting along the runout paths of the three cases is a continuous steeply inclined ground surface of more than 40° in gradient and 40 m in length on plan (see Figure B3). The presence of such adverse site setting can be conducive to a higher debris velocity (i.e. exceeding the recommended velocity ceiling) as observed in the back analyses. The use of the velocity ceiling approach is therefore not recommended for such topographical setting.

6.9 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 channelised debris flow (CDF) catchments. It is projected that less than 5% of OHF catchments would have limited extent of such adverse setting (i.e. localised areas within the catchment).

Debris Thickness

6.10 Debris impact force on a structure or barrier is related to both the velocity of 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 1 of the TGN). Assuming the discharge rate as calculated from 2d-DMM remains unchanged, the % increase in debris thickness would be proportional to the % reduction in debris velocity (as compared with that calculated using the lower-bound value of ϕ_a) at a given location.

Need for Reliable Digital Terrain Model (DTM)

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

Limitations and Uncertainties in Mobility Modelling

6.12 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 development work is required to examine the effect of deposition on mobility of OHF.

6.13 Debris runout distances of the mapped OHF are mostly shorter than those identified in the ENTLI. For OHF with runout distances exceeding 100 m, the field mapped runout distances are shorter by more than 10% as compared with the corresponding debris trail lengths in the ENTLI.

6.14 The representativeness of the debris mobility assessment for OHF depends critically on the availability of quality field data to calibrate the rheological models and input parameters. The recommendations given in this TGN should be taken as interim recommendations. Further development work will continue.

6.15 If it is considered that site-specific parameters and rheological model rather than those recommended in this TGN should be adopted for assessing the mobility of OHF for a particular hillside, agreement from the GCC should be sought.

7. ANNEXES

7.1 TGN 34A – Landslide Data for Debris Mobility Assessment of OHF

7.2 TGN 34B – Additional Back Analyses of OHF

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Annex TGN 34A – Landslide Data for Debris Mobility Assessment of OHF

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

1.1 OHF debris mobility data reported by Hungr (1998), Ayotte & Hungr (1998), Wong et al (1998) and Franks (1998) were used by Lo (2000). In this review, the original landslide data have been re-examined and the respective authors consulted where appropriate.

1.2 The 16 landslide cases back analysed by Hungr (1998) and Ayotte & Hungr (1998) using the friction model 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.

1.3 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 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.

1.4 According to Wong et al (1998), 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". 'Hydraulic' failures involved debris which had arisen principally as a result of the action of surface running water. 'Mixed' failures refer to debris which was intermediate between 'Gravitational' and 'Hydraulic'. Both 'Gravitational' and 'Mixed' failures have been taken to be OHF for the present purposes.

2. Additional Landslide Data

2.1 About 120 out of 12,500 recent OHF in the ENTLI were of high mobility with runout distances exceeding 100 m. With the assistance of site-specific aerial photograph interpretation (API), a screening exercise had 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).

2.2 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 conducting back analyses.

2.3 In addition to the above 52 OHF (i.e. 6 of which with field mapping) of high mobility, field mapping of 21 nos. of relatively 'less mobile' OHF were also available (most of them with runout distances ranging from 50 m to 100 m). Hence, additional back analyses were conducted for a total of 73 OHF (i.e. 52+21=73) and among which, 27 nos. have field mapping records. In essence, all the mobile OHF in the ENTLI have been considered.

3. Observations of the Mapped 2008 OHF

3.1 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. At present, no velocity data are available for OHF.

3.2 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, 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), whereas the upper-bound exceeds 5 m^3/m (plan distance).

3.3 Debris runout distances of the mapped OHF are mostly shorter than those identified in the ENTLI, particularly for cases of high mobility. 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 more than 10% (average about 20%).

Annex TGN 34B – Additional Back Analyses of OHF

1. Rheological Model used for Back Analyses of OHF

1.1 Additional back analyses were carried out using the friction model to fit the debris runout distances. Where appropriate, fine adjustment of the input parameter (i.e. apparent friction angle ϕ_a) was made with a view to better matching the deposition profile as recorded in field mapping.

2. Updating GEO Report No. 104

2.1 The landslides reported by Franks (1998) and the 'Hydraulic' type failures reported by Wong et al (1998) were excluded (see Section 1 in Annex TGN 34A) from further analysis. Instead, new quality data of OHF were added (see Figure B1), which comprised OHF with field mapping and other OHF that were examined under the GEO's systematic landslide investigation programme (see Table B1). With the inclusion of the additional data, the lower-bound values of ϕ_a for different volume ranges are revised as shown in Section 6.4 of this TGN.

3. Debris Velocity Ceiling Approach for OHF

3.1 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.

3.2 A pragmatic approach is proposed by grouping the velocity data into four volume ranges and selecting the appropriate velocity ceiling for each volume range (see Figure B2).

3.3 The debris runout distances of mobile OHF as recorded by field mapping are generally noted to be shorter than those in ENTLI by more than 10%, with an average of about 20% (see Section 3.3 in Annex TGN 34A). In the back analyses, the use of runout distances based on ENTLI would result in higher debris velocities than those based on field mapping.

3.4 To account for the above observation, supplementary back analyses were carried out for five critical OHF without field mapping of which the debris runout distances were reduced by 10% in the analyses. The results indicated that the maximum debris velocities of these cases would be reduced by 1 to 2 m/s (see Figure B2), giving rise to a velocity ceiling of 9 m/s.

4. Exclusion Criteria for OHF involving Adverse Site Setting

4.1 Of the 52 OHF of high mobility identified by ENTLI, the maximum debris velocities (i.e. >15 m/s) of three cases in the back analyses were higher than the velocity ceilings (see Figure B2).

4.2 Back analyses using the Voellmy model were also carried out for the above 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.

4.3 A common adverse site setting (see Figure B3) involving a continuous steeply inclined ground surface of more than 40^o in gradient and 40 m in length (plan distance) prevailed in the runout paths of all three cases. It is considered that the presence of such adverse setting is conducive to the build-up of high debris velocities. Hence, the use of the velocity ceiling approach is not recommended for such topographical setting.

Location	Reference	Landslide source volume (m^3)	Travel angle (deg)
Tai O San Tsuen No. LS1	GEO Report No. 275	80	35
Tai O San Tsuen No. LS4	GEO Report No. 275	185	34
Tai O San Tsuen No. LS5	GEO Report No. 275	200	34
North Lantau Expressway No. L8	GEO Report No. 272	216	30
North Lantau Expressway No. L11	GEO Report No. 272	34	32
North Lantau Expressway No. L12	GEO Report No. 272	43	39
North Lantau Expressway No. L13	GEO Report No. 272	100	28
North Lantau Expressway No. L14a	GEO Report No. 272	80	36
North Lantau Expressway No. L19	GEO Report No. 272	91	34
North Lantau Expressway No. L34	GEO Report No. 272	30	42
North Lantau Expressway No. L38	GEO Report No. 272	54	30
North Lantau Expressway No. L53	GEO Report No. 272	85	34
Yu Tung Road No. L28	GEO Report No. 271	90	32
Yu Tung Road No. L49	GEO Report No. 271	150	28
Yu Tung Road No. L50b	GEO Report No. 271	30	30
Yu Tung Road No. L51	GEO Report No. 271	30	45
Shek Pik 1 Source D	Landslide Mapping Report No. LS08-0257	16,000	29
Bowen Road	GEO Report No. 214	750	37

Table B1 –OHF examined under GEO’s systematic landslide investigation programme

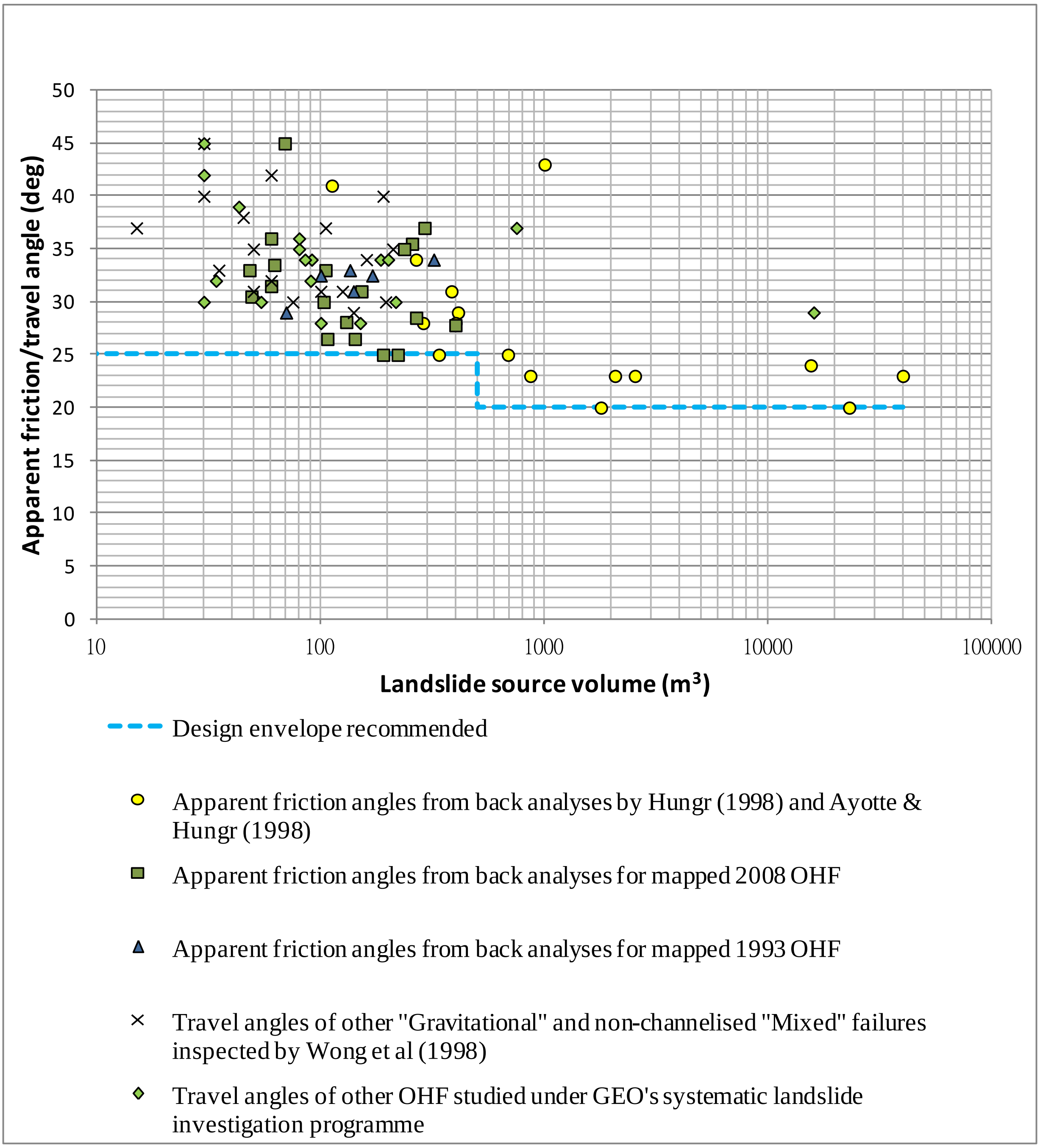

Figure B1 – Recommended apparent friction angle (ϕ_a) of OHF

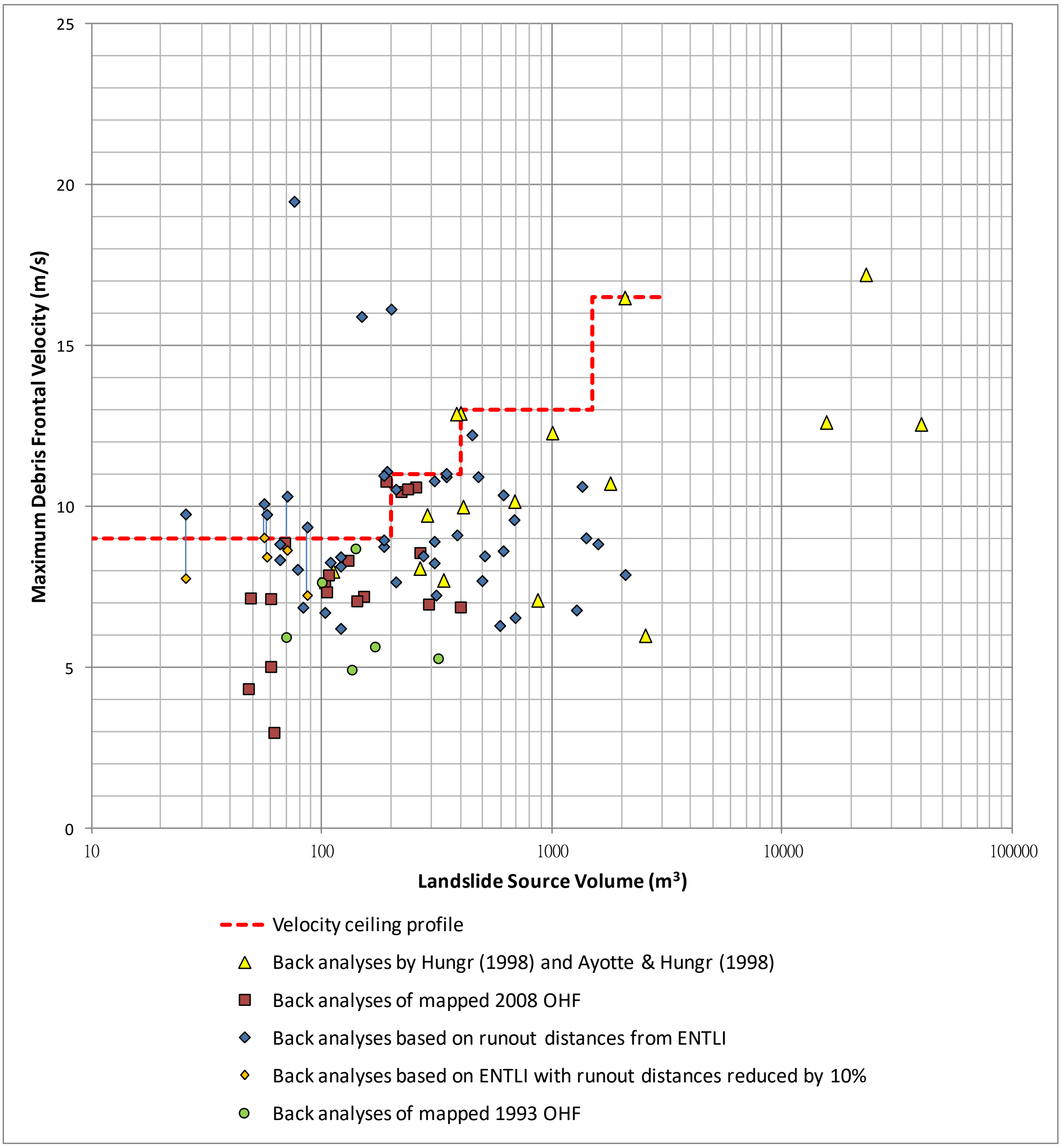

Figure B2 – Maximum debris frontal velocity of OHF

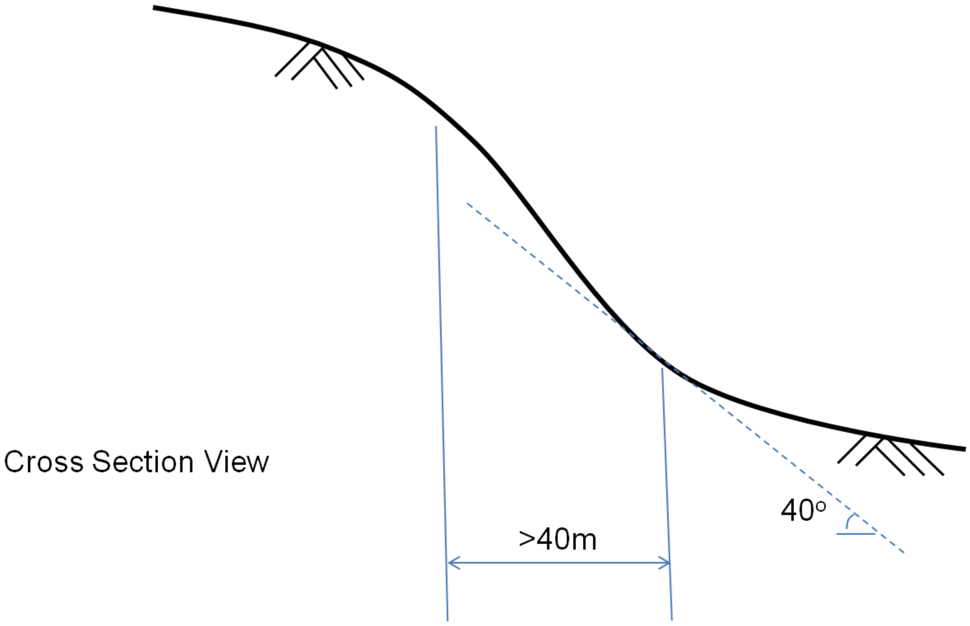

Figure B3 – Adverse site setting where the velocity ceiling approach is not applicable

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