GEO Technical Guidance Note No. 37 (TGN 37)
Guidelines on Empirical Design of Flexible Debris-resisting Barriers for Mitigating Natural Terrain Open Hillslope Landslide Hazards

1. SCOPE

1.1 This Technical Guidance Note (TGN) presents guidelines on use of prescribed flexible barriers in mitigating natural terrain open hillslope landslide (OHL) hazards affecting existing developments under the Landslip Prevention and Mitigation Programme (LPMitP). The guidelines may also be adopted in dealing with OHL hazards under public works projects, private developments and redevelopments, and Housing Department projects.

1.2 Any feedback on this TGN should be directed to the Chief Geotechnical Engineer/Landslip Preventive Measures 2 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 on 16 October 2024.

3. RELATED DOCUMENTS

3.1 Chan, C.H.W., Ting, S.M. & Wong, A.C.W. (2012). *Development of Natural Terrain Landslip Alert Criteria (Special Project Report No. SPR 1/2012)*. Geotechnical Engineering Office, Hong Kong, 68 p.

3.2 Cheng, P.F.K. & Ko, F.W.Y. (2010). *An Updated Assessment of Landslide Risk Posed by Man-made Slopes and Natural Hillsides in Hong Kong (GEO Report No. 252)*. Geotechnical Engineering Office, Hong Kong, 46 p.

3.3 FSJV (2010). *Summary Report on the Identification of June 2008 Natural Terrain Landslides on Lantau Island (Preliminary)*. Fugro Scott Wilson Joint Venture. A Report for the Geotechnical Engineering Office, Hong Kong, 36 p.

3.4 GEO (1984). *Geotechnical Manual for Slopes (Second Edition)*. Geotechnical Engineering Office, Hong Kong, 302 p.

3.5 GEO (2012). *Guidelines on Assessment of Debris Mobility for Open Hillslope Failures (GEO Technical Guidance Note No. 34).* Geotechnical Engineering Office, Hong Kong, 16 p.

3.6 GEO (2024). *Design of Flexible Debris-resisting Barriers Using Energy Approach (GEO Technical Guidance Note No. 56).* Geotechnical Engineering Office, Hong Kong, 5 p.

3.7 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.

3.8 Kwan, J.S.H., Koo, R.C.H. & Ko, F.W.Y. (2016). *A Pilot Study on the Design of Multiple Debris-resisting Barriers (GEO Report No. 319)*. Geotechnical Engineering Office, Hong Kong, 58 p.

3.9 Tattersall, J.W., Devonald, D.M., Hung, R.K.C. & Kwong, R.T.S. (2009). Estimation of ‘design event’ landslide sources for the North Lantau Expressway and Yu Tung Road natural terrain hazard mitigation works study. *Proceedings of the HKIE Geotechnical Division 29th Annual Seminar: Natural Hillsides – Study and Risk Mitigation Measures*. The Hong Kong Institution of Engineers, Hong Kong, pp 141-147.

3.10 Wong, H.N., Ko, F.W.Y. & Hui, T.H.H. (2006). *Assessment of Landslide Risk of Natural Hillsides in Hong Kong (GEO Report No. 191)*. Geotechnical Engineering Office, Hong Kong, 120 p.

4. BACKGROUND

4.1 In Hong Kong, debris-resisting barriers adopted as natural terrain hazard mitigation measures used to be designed by analysis (i.e. analytical design). In 2012, prescribed barriers were introduced for use in mitigation of open hillslope landslide (OHL) hazards affecting roads.

4.2 A number of problems have been encountered in the analytical design of debris-resisting barriers for mitigation of OHL hazards:

(a) Unlike channelised (CD) catchments where the landslide risk can be dealt with by the implementation of risk mitigation measures at the confined outlet of a drainage line, open hillslope (OH) catchments would usually require extensive risk mitigation measures along the full length of their toes. As a result, the costs of the risk mitigation works for OH catchments are much higher than those for CD catchments even though the average landslide risk of OH catchments is lower than that of CD catchments (Using the data of Wong et al (2006), it is estimated that the average landslide risk levels of OH catchments and CD catchments are 2.4×10^{-4} PLL/year and 1.8×10^{-3} PLL/year respectively, i.e. the average risk of OH catchments is about one order of magnitude less than that of CD catchments.).

(b) Knowledge of OHL hazards is limited at present. This includes assessment of the size of the design events, debris mobility modelling as well as debris/barrier interaction. The degree of conservatism would add up and in many cases, lead to onerous requirements which may not be practical to design and build.

(c) Given site constraints, it is often not practicable to provide substantial mitigation works, e.g. rigid barriers, for dealing with OHL hazards.

(d) Even if the design is feasible from a construction view point, the works involved are often so substantial that their physical footprint on the hillside could give rise to environmental concerns and public complaints, in particular when the mitigation measures are conservatively assessed and designed.

(e) The current state of knowledge and technology of flexible barriers, including its structural form and details, maintenance requirements, and short- and long-term field performance, is still under development. Flexible barriers currently available in the market have relatively small structural capacity.

4.3 Hence, there is limited technological capacity and industry support for extensive application of flexible debris-resisting barriers under an analytical design framework at this stage. Given cost-effectiveness consideration in light of the risk level and uncertainties involved, the current state of knowledge and technology, and the need to strike a balance between mitigating risk and minimising disturbance to the environment, adopting empirical design based on use of prescribed flexible barriers is a more practicable approach for mitigation of OHL hazards in general.

4.4 The prescribed flexible barriers referred to in this TGN for mitigation of OHL hazards are based on those that are available in the market. These barriers have been adopted for retention of rock falls and landslide debris in other parts of the world, where the scale of failure is typically greater than that in Hong Kong. In devising the empirical design stipulated in this TGN, a review was carried out on the probability and scale of natural terrain landslides known to have occurred in the Historical Landslide Catchments (HLC) under different rainfall conditions in Hong Kong and on the energy capacity of the barriers. It was found from the review that the energy capacity of the barriers could cope with the vast majority of the OHL in Hong Kong (see Annexes TGN 37 A & B). To further improve the robustness of the empirical use of the prescribed barriers, a set of qualifying criteria has been included in the empirical design.

4.5 Only flexible barriers specified by their energy absorbing capacity are included in the empirical design at this stage. Flexible barriers designed using the force approach are under development stage, and their trial design and use are being considered in selected LPMitP sites. Likewise, possible use of multiple rows of flexible barriers in dealing with more sizeable failures is also being explored (Kwan et al, 2016). It is expected that with further technological development and experience gained from use of novel barrier schemes, additional modules of prescribed barriers may be included for empirical use in future.

5. TECHNICAL RECOMMENDATIONS

Empirical Design Framework

5.1 A natural terrain hazard study (NTHS) should continue to be carried out for a catchment for which prescribed barrier is intended to be used. However, the scope of the NTHS should aim at assessing whether or not the hillside meets the 'react-to-known-hazard' principle in the case of projects under the LPMitP, classifying the types of catchments (viz. CD, topographic depression (TD) and OH, etc.), identifying the types of hazards and the need for mitigation measures, and confirming that the qualifying criteria stipulated in paragraph 5.2 below for the application of the empirical design approach are met. Once the need for mitigation measures is established and the qualifying criteria are satisfied, the energy rating and minimum height of the flexible barrier required to mitigate OHL hazards should be determined based on Table 1. There is no need to determine the design event for the OH catchment concerned.

Qualifying Criteria for Using the Empirical Design Approach

5.2 The empirical design approach should generally only be applied to OH catchments (or sub-catchments) that satisfy the following criteria:

(a) Within a plan distance of 100 m from the affected facilities, no recent landslide with a volume greater than 100 m^3, and no recent landslide with a volume between 50 m^3 and 100 m^3 with debris reaching closer than 20 m on plan from the affected facilities, has occurred on the OH catchment.

(b) Within a plan distance of 100 m from the affected facilities, no continuous steeply inclined ground surface of more than 40° in gradient and 40 m in length on plan along a runout path is present on the OH catchment.

(c) There is no evidence of existing significant signs of distress, continuing hazardous movement or incipient instability within the OH catchment, which could affect a facility covered by the facility types given in Table 1. Appropriate mitigation measures should be designed to address the hazards from such features.

(d) No newly emerged hazardous situation has evolved as a result of the occurrence of new landslide(s) (e.g. landslides which occurred during the course of NTHS), development of new signs of distress and hazardous movement, or exacerbation of existing signs of distress and hazardous movement on the OH catchment, particularly where there is concern of further hillside deterioration leading to instability.

(e) The OH catchment is not susceptible to deep-seated landslide hazards.

5.3 Where a holistic risk mitigation strategy is adopted (Ho & Roberts, 2016), or for emergency works, prescribed flexible barriers may be used irrespective of whether or not the qualifying criteria are satisfied, and it is not necessary to follow Table 1 in determining the required energy rating and minimum height of the prescribed flexible barriers.

Table 1 – Empirical design of prescribed flexible barrier against OHL hazard

Facility	Proximity		
	Very Close (e.g. if angular elevation from the facility is ≥ 30°)	Moderately Close (e.g. if angular elevation from the facility is < 30° and ≥ 25°)	Far (e.g. if angular elevation from the facility is < 25°)
Buildings and sensitive structures(2)	R1 + baffles	R1	R3
Groups 1 & 2 other than buildings and sensitive structures	R1	R2	Nil
Group 3	R2	R3	Nil

Notes:

(1) The facility group and proximity class should be assessed following the guidelines given in GEO Report No. 138 (Ho & Roberts, 2016).

(2) Sensitive structures refer to those facilities including Potential Hazardous Installations, tunnel portal, petrol station, railway platform and MTR exit that may involve severe consequence when affected by landslides, in accordance with the facility classification adopted in GEO Report No. 191 (Wong et al, 2006).

(3) If boulder/rock fall hazards also exist, the kinetic energy of the boulder/rock hitting the barrier should not exceed the energy rating of the barrier, and the corresponding bounce height of the boulder/rock should not exceed the height of the barrier.

(4) R1: 3,000 kJ flexible rock fall barrier with minimum height of 4 m.
R2: 2,000 kJ flexible rock fall barrier with minimum height of 3 m.
R3: 1,000 kJ flexible rock fall barrier with minimum height of 3 m.

(5) 'Baffles' comprise structural steel sections or steel hollow sections filled with concrete placed in rows uphill of the flexible barrier. They are prescribed measures for enhancing the robustness of the mitigation scheme, by reducing the impact force/energy of the landslide debris reaching the barriers and facilitating debris deposition.

(6) A suitable clearance between the barrier and the affected facility should be provided to allow for deformation of the barrier upon hitting by landslide debris/boulder/rock.

(7) The stability of the hillside/slopes below the barrier including the effects of the foundations of the barrier on their stability should be assessed.

Alternatives to Empirical Design

5.4 A designer may choose not to use prescribed flexible barriers based on the empirical approach if other more suitable mitigation schemes are available. For instance, it may be more cost-effective to carry out soil nailing for a small hillside, than the installation of flexible barriers. Also, where it can be shown by analytical design that the OHL calls for less substantial mitigation measures than those based on empirical design, measures based on the analytical design may be adopted.

5.5 Where the empirical design approach is not applicable because the qualifying criteria are not met, the mitigation works for the OH catchment should be designed by other means, with account taken of the site-specific circumstances. Possible mitigation schemes that may be considered include soil nailing, the use of flexible or rigid barrier designed by analysis, and the provision of a hybrid system consisting of prescribed flexible barriers by the empirical method and other engineering measures (e.g. local soil nailing) determined through analytical design.

5.6 When the energy approach is adopted in analytical design of a flexible barrier, the energy capacity of a barrier established by full-scale rockfall (or other single-mass) tests can be adopted for designing a flexible barrier to mitigate landslide hazards from all types of catchments (i.e. CD, TD and OH). The energy capacity of the rockfall barrier needs not be reduced by a scaling factor to account for the differences between rock fall and debris impacts (GEO, 2024).

5.7 Where soil nailing is adopted as the mitigation scheme for an OH catchment, an analytical approach should be adopted for the design of soil nails. Unless there are concerns about known significant hazards involving deeper failures, the following generalised design objectives may be adopted in the hillslope stability analysis or analytical design of soil nails for mitigation of OHL hazards:

(a) demonstrate or provide an adequate factor of safety against failure of the top 2 m of the regolith, in accordance with the design standards given in the Geotechnical Manual for Slopes (GEO, 1984); or

(b) in the absence of reliable information on the soil and groundwater conditions for the stability analysis, provide soil nails to increase the margin of safety against failure of the top 2 m of the regolith by 20% and 40% for circumstances that call for a minimum design factor of safety of 1.2 and 1.4 respectively.

6. STATUS OF OPEN HILLSLOPE CATCHMENTS WITH PRESCRIBED FLEXIBLE BARRIERS DESIGNED BY EMPIRICAL APPROACH

6.1 The use of prescribed flexible barriers based on the empirical design approach in Table 1 should be regarded as Level 1 Protection Measures as described in the GEO Report No. 138 (Ho & Roberts, 2016).

7. ANNEXES

7.1 TGN 37 A – Rationale of Empirical Design of Flexible Barriers for Mitigating Natural Terrain Open Hillslope Landslide Hazards

7.2 TGN 37 B – Probability of Exceeding the Energy Capacity of a 3,000 kJ Flexible Barrier under Different Volumes of Open Hillslope Landslides

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Annex TGN 37 A – Rationale of Empirical Design of Flexible Barriers for Mitigating Natural Terrain Open Hillslope Landslide Hazards

1. Introduction

1.1 The empirical approach is based on the prescription of the volume of the landslide debris that may be discharged from an OH catchment. The aim is not to deal with the most severe debris impact event that would occur on the hillside, but to cope with a sufficiently rare debris impact event. The provision of prescribed flexible barriers to mitigate OHL hazards using this approach represents a reasonable balance among risk mitigation, cost-effectiveness and minimising disturbance to the environment.

2. Capacity of Proprietary Flexible Barrier

2.1 As recommended in GEO TGN No. 56 (GEO, 2024), the energy capacity rating of a 3,000 kJ rock fall barrier in retaining landslide debris is taken as 3,000 kJ.

2.2 According to GEO TGN No. 34 (GEO, 2012), the velocity ceiling of an OHL with a landslide volume of not greater than 200 m^3 is 9 m/s. With this ceiling velocity, the kinetic energy carried by a 37 m^3 mass of landslide debris is about 3,000 kJ.

2.3 When the debris volume exceeds 37 m^3, a 3,000 kJ flexible rock fall barrier may still retain the landslide debris provided that the debris velocity is small such that the energy loading does not exceed 3,000 kJ. For example, if the landslide volume is 50 m^3, the flexible barrier would be able to cope with the OHL provided that the velocity of the debris does not exceed 7.7 m/s. If a 100 m^3 landslide is involved, the corresponding threshold debris velocity is 5.5 m/s.

2.4 An analysis has been carried out to evaluate the probabilities of exceeding the allowable energy loading of 3,000 kJ under different volumes of landslides. The findings are presented in Annex TGN 37 B. The results show that in case a landslide occurs at an OH catchment under a severe rainstorm as heavy as the June 2008 event, the probability of the energy loading of the landslide debris exceeding the energy capacity of a 3,000 kJ flexible barrier is about 19%. This assumes that the landslide will travel long enough to reach the flexible barrier. This is a very conservative assumption as not all landslides would have a sufficiently long run out.

3. Characteristics of Natural Terrain Landslides

3.1 The occurrence of a rainstorm as heavy as the June 2008 event and resulting in a landslide on a particular OH catchment is rare and probably less frequent than once in 100 years. Hence the annual probability of a flexible barrier (3,000 kJ energy rating) anywhere in Hong Kong subject to such a severe rainstorm and then hit by a landslide exceeding its energy capacity is no more than 0.19% (i.e. 0.01 × 19%). This is equivalent to a return period of about 500 years.

3.2 Natural terrain landslides may occur under rainstorms of other intensities. An attempt has been made to estimate the actual annual probability of occurrence of a landslide on an OH catchment. A review of ENTLI data spanning from 1993 to 2009 (17 years) indicates that among the some 9,600 natural terrain landslides recorded over the period, about 1,100 had occurred within the existing 2,534 HLCs (356 HLCs on Hong Kong Island, 1,558 HLCs in Kowloon & the New Territories, and 620 HLCs on outlying islands including Lantau). The average annual probabilities of landslide occurring on an HLC within the three regions are estimated to be 0.6%, 0.9% and 2.4% respectively (see Table A1). With account taken of the uncertainty that the actual number of landslides may exceed that recorded in the ENTLI, the average annual probabilities of landslide occurring on an HLC within the three regions become 1.1%, 1.7% and 4.3% respectively.

3.3 The difference in landslide probabilities for the three regions is related to the spatial and temporal variations in rainfall intensity of the individual rainstorm hitting Hong Kong during the observation period.

3.4 Besides calculations of the actual probability, the theoretical annual probability of landslide occurring on an HLC has been estimated based on the methodology given in Appendix B of GEO Report No. 191 (Wong et al, 2006). The theoretical annual probabilities, using the latest natural terrain landslide-rainfall correlation (Chan et al, 2012), were found to be 2.0%, 1.8% and 3.8% for HLCs located within Hong Kong Island, Kowloon & the New Territories, and outlying islands including Lantau respectively (see Table A2). The results are broadly comparable with the actual landslide probabilities given in paragraph 3.2 above.

3.5 As shown in Annex TGN 37 B, the annual probability of having a landslide hit exceeding the energy capacity of a flexible barrier (3,000 kJ rating) installed at an HLC anywhere in Hong Kong is lower than 1%. The corresponding return period of the debris impact event is more than 100 years.

3.6 Because of the conservative assumptions made in the probability estimates (e.g. the peak frontal velocity obtained from back analysis of the some 70 mobile OHL cases are taken as the impact velocity), the calculated notional return periods given in paragraphs 3.1 and 3.5 are on the low side. The notional return periods could be several times longer if less conservative assumptions are made, e.g. some of the less mobile OHL cases are taken into account in assessing the probability distribution of frontal velocity and/or possible deposition of debris along the trail are taken into account in assessing the impact energy. That means the use of a 3,000 kJ flexible barrier for mitigation of OH hazards would be able to deal with a debris impact event with a return period of several hundred years.

4. Use of Proprietary Flexible Rock Fall Barrier for Mitigation of OHL Hazards

4.1 The above analyses indicate that by installing a 3,000 kJ rock fall barrier to retain OHL, the probability of it being overwhelmed by landslide debris is not very high, the return period being in the order of hundreds of years. Taking into account the low probability of failure, the cost-effectiveness of the mitigation measures and the availability of proprietary products in the market, it is considered appropriate to use 4 m high 3,000 kJ rock fall barriers as prescribed barriers. The minimum height of a 3,000 kJ rock fall barrier in the market is 4 m. Based on previous design experience, the typical retention volume of a 10 m wide panel of such a flexible barrier is in the range of 150 m^3 to 250 m^3.

4.2 Since the landslide risk of individual OH catchments would vary depending on the type of facilities affected and their proximity to the hillside, the energy rating of the flexible barrier selected to mitigate the OHL hazard should be commensurate with the level of landslide risk involved in order to ensure cost-effectiveness. It is recommended that, for the general cases (e.g. a hillside located moderately close to a building), a 3,000 kJ flexible barrier should be provided to mitigate the OHL hazard. For OH catchments posing a lower landslide risk (e.g. those affecting Group 3 facilities), a flexible barrier with a smaller energy rating and lower height can be used. A 2,000 kJ flexible barrier of 3 m high is considered appropriate. For the more risky situations (e.g. a hillside located very close to a building), additional prescribed measures by construction of baffles to reduce the impact energy of landslide debris on the flexible barrier should be provided.

4.3 For those natural hillsides with OHL hazard far from the affected facilities, no mitigation works are required in principle as the facilities are located beyond the travel angle of 25°, which is the lower bound apparent friction angle of OHL with a landslide volume not greater than 500 m^3 (the empirical design is only applicable to OH catchments with no recent landslides larger than 100 m^3 within a distance of 100 m from the affected facility, as stipulated in the qualifying criteria). However, for those natural hillsides affecting buildings or sensitive structures, it would be prudent to install a notional barrier of 1,000 kJ as a precautionary measure even if the buildings or structures are at a distance slightly beyond the area covered by the travel angle of 25°.

4.4 Although the estimated probability of exceeding the energy capacity of the prescribed barrier is not high, it should be noted that this is only an average value. The probability of exceedance at individual sites could be significantly higher than the average value if the OH catchment concerned is very susceptible to landslides. In this regard, qualifying criteria should be stipulated in order to screen out the more ‘susceptible’ OH catchments; hence the recommendation in paragraph 5.2 of this TGN.

5. The Alternative of Soil Nailing

5.1 Besides the use of prescribed flexible barriers, a designer may adopt alternative mitigation measures such as soil nailing, if it is found to be more cost-effective or environmentally acceptable to do so. The design of soil nails should aim to reduce the likelihood of OHL on the hillside. In this regard, it is noted that the natural hillsides in Hong Kong are susceptible to rain-induced, shallow failures. Field observations have revealed that failures typically occur within 0.5 m to 2 m of the hillside surface. For example, more than 99% of the natural terrain landslides occurring in Lantau due to the 7 June 2008 rainstorm have a maximum depth of failure not greater than 2 m at the source areas. Therefore, unless there is clear evidence that deeper landslides will occur on the OH catchment, the design of soil nails only needs to cater for shallow failures within the top 2 m of the regolith.

Table A1 – Summary of landslides recorded in ENTLI for the period from 1993 to 2009

Year	No. of natural terrain landslides	No. of HLCs with landslides			Annual probability of landslides (%)		
		Hong Kong Island	Kowloon & New Territories	Lantau & other islands	Hong Kong Island	Kowloon & New Territories	Lantau & other islands
(A)	(B)	(C1)	(C2)	(C3)	(D1=C1/356)	(D2=C2/1,558)	(D3=C3/620)
1993	1,702	0	37	60	0	2.37	9.68
1994	806	3	22	7	0.84	1.41	1.13
1995	157	2	7	1	0.56	0.45	0.16
1996	98	1	8	3	0.28	0.51	0.48
1997	361	0	17	0	0	1.09	0
1998	386	1	7	0	0.28	0.45	0
1999	935	2	32	34	0.56	2.05	5.48
2000	910	1	26	0	0.28	1.67	0
2001	298	0	14	2	0	0.90	0.32
2002	66	0	1	1	0	0.06	0.16
2003	308	0	18	3	0	1.16	0.48
2004	26	0	0	0	0	0	0
2005	243	3	11	5	0.84	0.71	0.81
2006	86	2	8	4	0.56	0.51	0.65
2007	135	1	2	5	0.28	0.13	0.81
2008	2,997	21	32	127	5.90	2.05	20.48
2009	62	0	2	0	0	0.13	0
			Average		**0.61**	**0.92**	**2.39**
			Adjusted Value (Average/Recognition Factor) Note (2)		**1.1**	**1.7**	**4.3**

Notes:

(1) The actual number of historical landslides that can be observed from detailed interpretation of the available low-level aerial photographs exceeds that recorded in the ENTLI. A recognition factor, which is the ratio of the number of landslides recorded in ENTLI to the actual number of landslides identified from detailed interpretation of low-level aerial photographs, has been applied to the calculation of the landslide probabilities. Depending on the volume of landslides, the suggested recognition factor for ENTLI varies from 55% to 100% (Cheng & Ko, 2010).

(2) By applying a recognition factor of 55%, the average annual probabilities of landslide occurring on an HLC within the three regions (i.e. Hong Kong Island, Kowloon & New Territories, and outlying islands including Lantau) are increased to 1.1%, 1.7% and 4.3% respectively.

Table A2 – Rainfall scenarios and landslide frequencies

Rainfall scenario	Normalised 24-hour rainfall	Mean annual frequency of occurrence	ENTLI landslide density (No./km^2)
A	≤ 0.10	F_a = 0.8130	D_a = 0.0396
B	> 0.10 - 0.20	F_b = 0.4785	D_b = 0.4955
C	> 0.20 - 0.30	F_c = 0.0608	D_c = 8.8946
D	> 0.30 - 0.35	F_d = 0.0035	D_d = 77.5691

Notes:

(1) The annual theoretical landslide frequency on a catchment of area, A, is given by $[F_aD_a + F_bD_b + F_cD_c + F_dD_d]A$.

(2) The total areas of HLCs on Hong Kong Island, Kowloon and New Territories, and outlying islands including Lantau are 3.482 km^2, 13.729 km^2 and 11.979 km^2 respectively. Thus the corresponding annual theoretical landslide frequencies, based on Note (1) above, are 3.766 no./year, 14.849 no./year and 12.956 no./year.

(3) By dividing the theoretical landslide frequencies in Note (2) above by the corresponding number of HLCs, the annual theoretical landslide probabilities become 1.1% (3.766/356), 1.0% (14.849/1,558) and 2.1% (12.956/620) respectively.

(4) By applying a recognition factor of 55% (see Note (1) in Table A1), the average annual probabilities of landslide occurring on an HLC within the three regions (i.e. Hong Kong Island, Kowloon & New Territories, and outlying islands including Lantau) are increased to 2.0%, 1.8% and 3.8% respectively.

Annex TGN 37 B – Probability of Exceeding the Energy Capacity of a 3,000 kJ Flexible Barrier under Different Volumes of Open Hillslope Landslides

1. A 3,000 kJ flexible barrier will be able to resist the impact of a landslide provided that the kinetic energy carried by the debris hitting the barrier is not greater than 3,000 kJ. Using 3,000 kJ as the limit, the variation between the volumes of landslides and the corresponding threshold impact velocities is shown in Table B1.

Table B1 – Variation between volume and threshold impact velocity for a 3,000 kJ flexible barrier

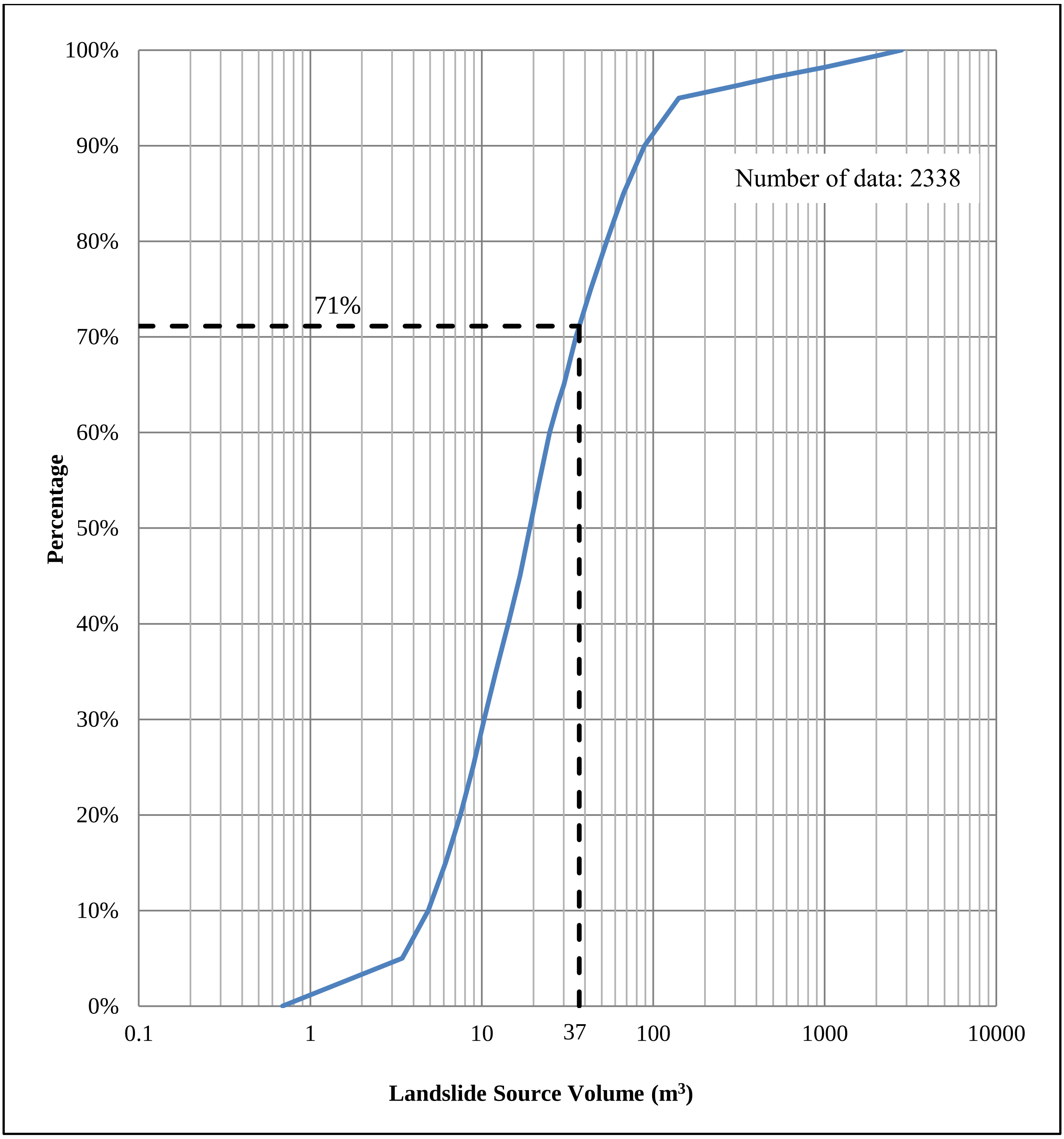
Volume of landslide	Threshold impact velocity
37 m^3	9.0 m/s
40 m^3	8.7 m/s
45 m^3	8.2 m/s
50 m^3	7.7 m/s
70 m^3	6.5 m/s
100 m^3	5.5 m/s
200 m^3	3.9 m/s
500 m^3	2.4 m/s

2. The distribution of the source volume of natural terrain landslides that occurred in Lantau under 7 June 2008 rainstorm is shown in Figure B1. It can be seen that about 71% of the landslide volumes are less than 37 m^3.

3. Based on the results of back analyses of 73 OHL cases given in GEO TGN No. 34 (GEO, 2012), the distribution of the maximum frontal velocities of the landslide debris is shown in Figure B2. The maximum frontal velocities are used in the assessment of the variation of the kinetic energies of different volumes of landslides hitting a flexible barrier. This is a conservative approach because the flexible barrier is usually installed in a relatively gentle area at the toe of a hillside where deceleration may occur before the landslide debris reaches the barrier. That means the debris velocity upon impact with the flexible barrier would be less than the maximum frontal velocity. Also, the 73 OHL cases selected for back-analyses in GEO TGN No. 34 (GEO, 2012) represent only the most mobile landslides among the entire population of 12,500 OHL recorded in the ENTLI.

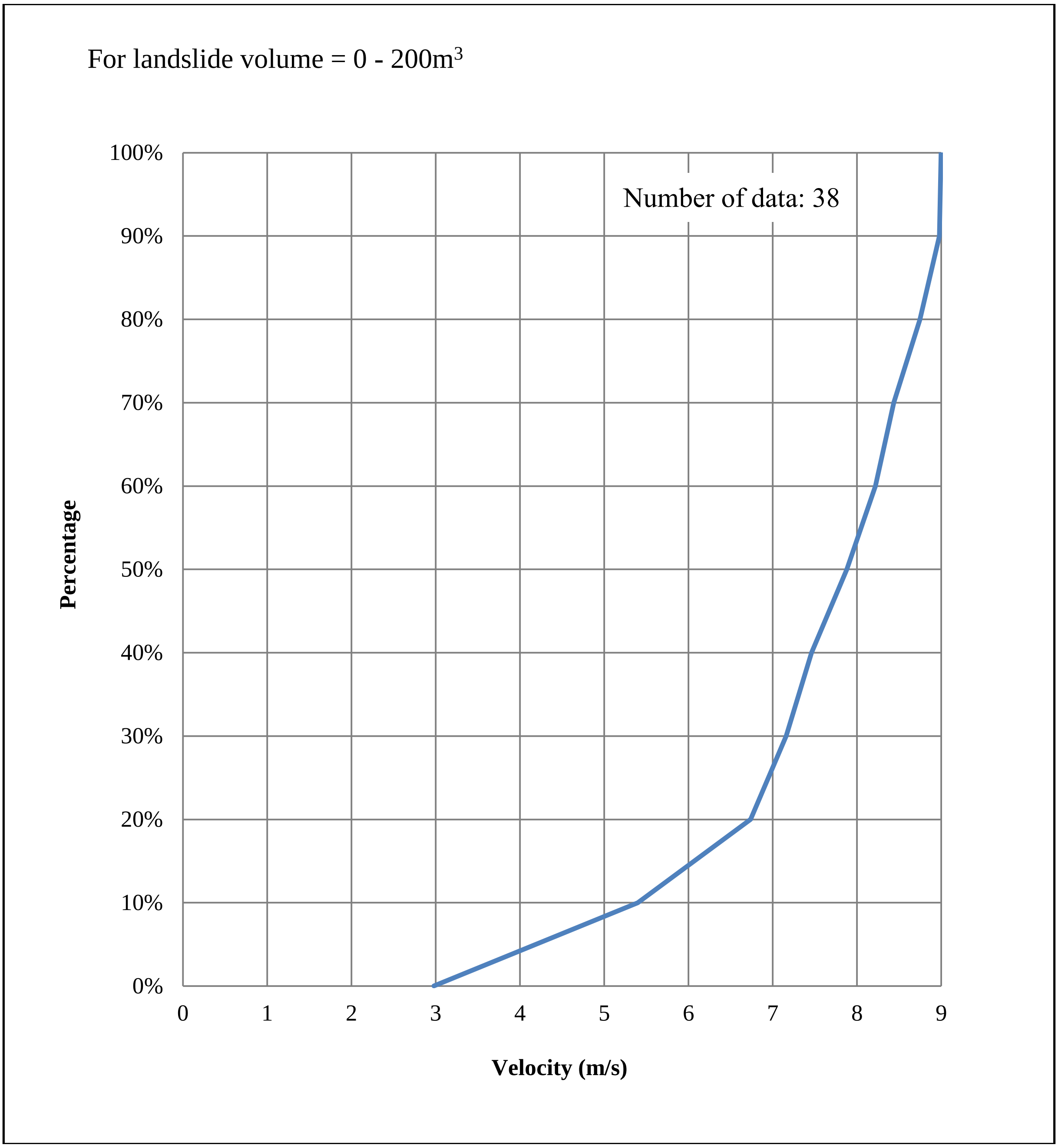
4. If a natural terrain landslide occurs on an OH catchment, the probability that its kinetic energy will exceed 3,000 kJ can be determined from the volume distribution of the landslide shown in Figure B1 and the velocity distribution given in Figure B2. For example, the probability of having a landslide volume less than 37 m^3 is 71% and the probability that the landslide has a maximum velocity greater than 9.0 m/s (i.e. threshold velocity corresponding to 37 m^3 landslide in Table B1) is 0% because of the velocity ceiling for OHL recommended in GEO TGN No. 34 (GEO, 2012). That means the probability of having a landslide volume less than 37 m^3 with the kinetic energy of the landslide debris exceeding 3,000 kJ is 0%. For a landslide volume between 37 m^3 and 45 m^3 (average volume being about 40 m^3), the probability of its occurrence is about 5%. The probability that the debris velocity will be higher than 8.7 m/s (i.e. threshold velocity corresponding to 40 m^3 landslide in Table B1) is about 23%. Therefore, the probability of having a landslide volume between 37 m^3 and 45 m^3 that will carry a kinetic energy in excess of 3,000 kJ is 1.2% (i.e. 5% × 23%). Using this approach, the exceedance rates (i.e. assuming the occurrence of a natural terrain landslide, the conditional probability that its volume is of a given value and the kinetic energy of its debris will exceed 3,000 kJ) for different volumes of landslides have been derived and the results are presented in Figure B3.

5. The cumulative exceedance rate covering all different volumes of landslides is about 19%. As the annual probability of occurrence of landslides on an HLC is about 1.1% to 4.3% (see paragraph 3.2 of Annex TGN 37 A), that means the annual probability that a landslide will occur on an HLC and carry an energy loading greater than 3,000 kJ upon impact with the flexible barrier is 0.21% to 0.82%. The average annual probability of the event is considered lower than 1% (i.e. [0.21 + 0.82]/2).



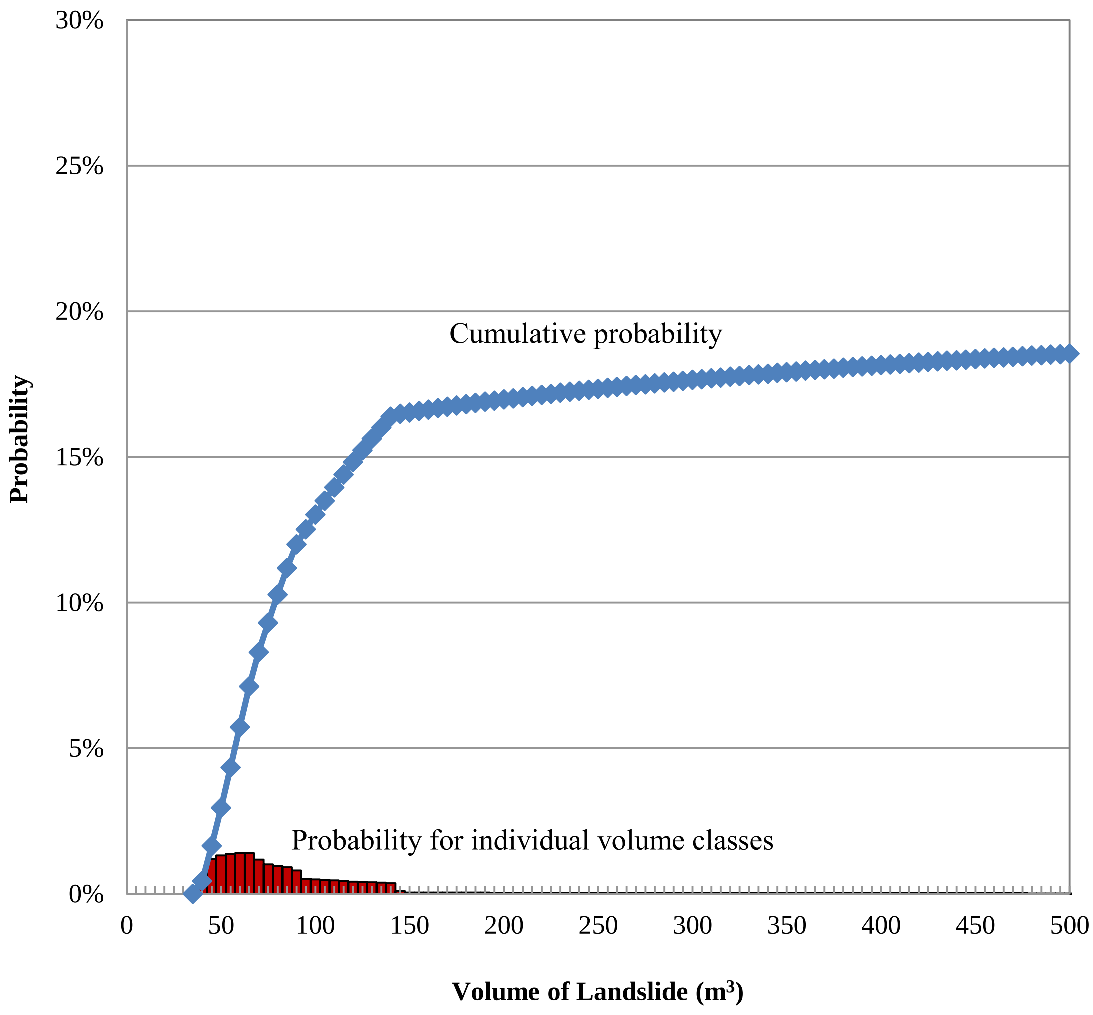
Note: The landslide source volume is estimated based on the plan area of source from API (FSJV, 2010) and the correlation between the plan area and detached volume of source (Tattersall et al, 2009).

Figure B1 – Cumulative distribution of landslide source volumes in Lantau due to 7 June 2008 rainstorm



Note: Only distribution of velocities for landslide volume less than 200 m^3 is shown.

Figure B2 – Cumulative distribution of maximum frontal velocities based on back analyses of 73 OHL cases



Note: For landslides with a volume greater than 500 m^3, their contribution to the cumulative probability of exceedance is less than 1%.

Figure B3 – Probability of landslides with impact energy exceeding 3,000 kJ