A Review on the Design of Rigid Debris-resisting Barriers

GEO Report No. 339

J.S.H. Kwan, R.C.H. Koo & C. Lam

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

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This report was originally produced in March 2016
as GEO Technical Note No. TN 1/2016

First published, December 2018

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Preface

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W.K. Pun
Head, Geotechnical Engineering Office
December 2018

Foreword

This Technical Note presents a review on the design guidance of rigid debris-resisting barriers based on the comments provided by Professor Oldrich Hungr. The study was carried out by Dr J.S.H. Kwan with assistance of Mr R.C.H. Koo and Dr C. Lam under my supervision. Professor P. Cui of the Institute of Mountain Hazards and Environment, China provided useful information on the field measurement of debris flow impact load on rigid structures. The Drafting Unit of the Standards and Testing Division assisted in formatting this report. All contributions are gratefully acknowledged.

H.W. Sun
Chief Geotechnical Engineer/Standards and Testing

Abstract

This Technical Note presents a review on the prevailing design guidance of rigid debris-resisting barriers in accordance with Professor Hungr's comments and suggests updates to GEO Report No. 270. The suggested updates pertain to the beneficial effects of self weight of impact debris in stability assessment (para. 5.1(b) of GEO Report No. 270), superposition of the debris flow impact load and boulder impact load (para. 4.2 of GEO Report No. 270), the assumption of simultaneous impacts by several boulders on barriers (para. 2.1(b) of GEO Report No. 270) and debris mobility assessment (para. 4.4(a) of GEO Report No. 270). Suggestions pertaining to assessment of design groundwater conditions and consideration of three-dimensional effects in stability assessment are also made. The suggestions aim to produce more rational and cost-effective design solutions.

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1 Background

Professor Oldrich Hungr has been engaged to review the design of an LPMit rigid debris-resisting barrier from a perspective of value engineering. In addition to comments on the site-specific assumptions made in the design, he provided a number of comments on the design guidelines recommended by GEO Report No. 270 (Kwan, 2012). His full comments on the design guidelines are reproduced in Appendix A. The salient points of the comments are summarised in Items (a) to (d) below. In light of Professor Hungr's comments, an additional point pertaining to debris mobility assessment is identified (see Item (e)).

(a) Self weight of the impacting debris

The recommendation made by para. 5.1(b) of GEO Report No. 270 (i.e. the beneficial effects of the self-weight of the impacting debris be ignored in geotechnical stability checking) should be better rationalised.

(b) Downward thrust by debris flow

The beneficial effects of the downward thrust acting on the basin floor slab at the junction of the inclined channel and the basin floor slab due to the change in debris flow direction can be considered in geotechnical stability assessment.

(c) Superposition of the debris flow impact load and boulder impact load

Given that the fluid thrust multiplication factor (i.e. dynamic pressure coefficient, α) of 2.5 already allows for a certain amount of particle impacts, the recommendation to combine the fluid thrust and the boulder impact load for design is likely very conservative.

(d) Simultaneous impacts by several boulders on barriers

The recommended use of boulder impact line load should be reviewed because impacts of individual large boulders would need to be precisely synchronized in order to achieve the effect as recommended.

(e) Consideration of realistic topographic profile in debris mobility assessment

Some rigid barriers comprise sub-horizontal debris basin, on which debris flows will slow down before impacting on the barriers. The profile of the sub-horizontal debris basin instead of the pre-construction ground profile should be adapted in the debris mobility analysis.

Items (a) to (e) have been considered in detail, and they are discussed in Sections 2.1 to 2.5 respectively. Professor Hungr’s comments on the site-specific assumptions made for the design of the barriers reviewed by him are also noteworthy, and they are outlined in Section 2.6. Recommendations to adopt the comments for enhancing the prevailing design guidance are made in order to reduce conservatism in current design, and further technical development work are proposed.

2 Discussion

2.1 Self Weight of the Impacting Debris

The recommendation of para. 5.1(b) of GEO Report No. 270 (Kwan, 2012) was made on the basis of the notion that the self weight of the flowing debris is a surcharge live load and so its beneficial effects should be ignored in the design of retaining structures. Section 7.1 of Geoguide 1 has been revisited in the light of Professor Hungr’s comment. According to Section 7.1 of Geoguide 1, surcharge may result from traffic load, footing load and loads from stockpiling goods. However, the self weight of soil to be retained is not taken as surcharge. As such, it is considered more appropriate to take the self weight of impacting debris as dead load and its beneficial effect should be considered in design. It is recommended that para. 5.1(b) of GEO Report No. 270 should be updated.

2.2 Downward Thrust by Debris Flow

The concept of taking into account downward thrust of debris flow is rational. The beneficial effects of the downward thrust have been studied in detail for 3 rigid barriers designed under LPMitP (see Appendix B). It is noted that contributions of the downward thrust in providing sliding resistance and restoring moment are not significant comparing with the effects given by the barrier weight. In most cases, the downward thrust will contribute to 1% - 2% increase in the stabilizing forces. An exception is noted where the debris routing channel is 45° inclined. In this case, the downward thrust brings about a 4% to 5% increase in the stabilizing forces. However, debris routing channels are normally shallowly inclined to avoid debris flow from displaying an excessive projectile motion.

In practice, the downward thrust acting on the debris basin floor slab is dependent on the debris velocity and affected by many factors, e.g. obstruction by debris deposition. The downward thrust is thus highly variable and dynamic in nature. In view of the uncertainty involved and the little gain, it is considered prudent to ignore the potential beneficial effects of the transient downward thrust in the design of rigid barriers.

2.3 Superposition of the Debris Flow Impact Load and Boulder Impact Load

The dynamic impact pressure acting on a barrier is calculated using the hydrodynamic equation $p = \alpha\rho v^2$ (p = dynamic impact pressure; α = dynamic pressure coefficient; ρ = debris flow density; and v = debris velocity). Cui et al (2015) indicated that the dynamic pressure coefficient (α) reported by various researchers varies widely from 0.45 to 5. The α-value could represent the difference in flow regimes and proportions of granular composition, i.e.

the value could have allowed for a certain amount of particle impacts. Field data of debris flow impact load on rigid structures reported by Du et al (1987) and Hu et al (2011) have been reviewed. A dynamic pressure coefficient α = 2.5 fits the average impact pressure. Figure 2.1 shows the measured data with the flume test results by Cui et al (2015) provided in the same plot. A recent communication with Cui (2015) has been made to learn that in the river where the load measurements by Du et al (1987) and Hu et al (2011) were carried out, normally, the diameter of boulders can be up to 0.5 m.

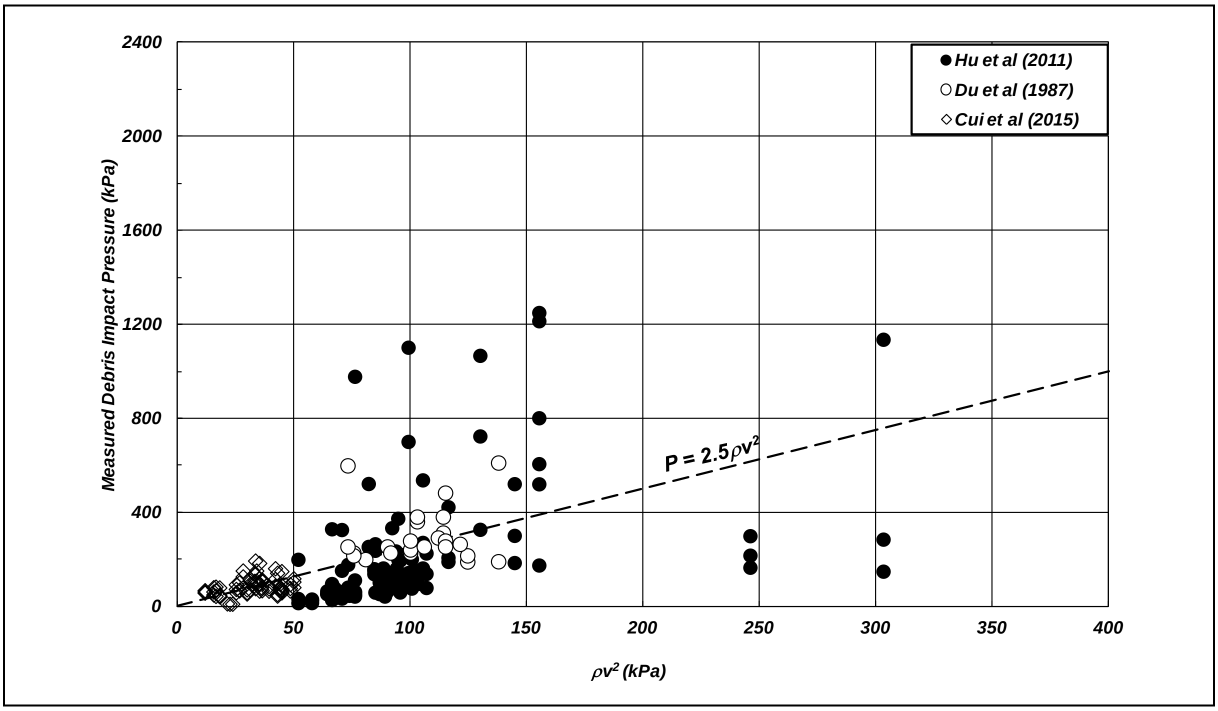

Figure 2.1 Debris Impact Pressure

Based on the above review, it is considered that the use of α = 2.5 would account for impact loads induced by boulders of diameter up to 0.5 m. Superposition of debris flow impact load and boulder impact load will not be required, if the diameter of the largest entrainable boulder is less than 0.5 m. Figure 2.1 shows that there is a large scatter of the measured impact pressures. Hu et al (2011) reported that extreme impact pressures were caused by the impacts of large boulders as observed on site. Therefore, should impact by boulders of diameter larger than 0.5 m is considered likely, design impact load comprising debris flow impact load and boulder impact load should be adopted.

Para. 2.1(b) of GEO Report 270 recommends the use of baffles to reduce the boulder impact load when there exists abundant of boulders along the debris runout path. In present practice, baffles are installed prescriptively but their effects in the respect of load reduction are not considered in design. Appendix C presents an illustrative design example of boulder baffles for reference. With the provision of baffles, superposition of the boulder impact load and debris flow impact load may not be necessary and potential optimization in the structural design of rigid barriers can be achieved.

2.4 Simultaneous Impacts by Several Boulders on Barriers

Para. 2.1(b) of GEO Report No. 270 recommends the consideration of boulder line load only if there are abundant boulders perched along stream course or potential debris flow path and where simultaneous impact by several boulders cannot be ruled out. It is agreed that in most situations, it will be too conservative to estimate boulder impact load based on this onerous assumption. As such, it is suggested to issue supplementary guidance to clarify that simultaneous impact by several boulders need not be assumed in order to avoid undue conservatism. If there are abundant boulders perched along the stream course or potential debris flow path with diameters larger than 0.5 m, boulder impact scenarios to reflect the actual site conditions (e.g. impact load corresponding to an appropriate spacing of boulders over a certain portion of the barrier wall) can be applied in the design.

Professor Hungr's comments also mention that the effects of boulder impacts are transient, and impulses delivered by major boulder impacts is likely to be consumed by the inertia of the massive wall (see para. A.2 of Appendix A). Collaborations with the University of Melbourne have been initiated to study along this line. A preliminary study indicates that displacement approach (i.e. allowing the barrier to be displaced during debris impact to avoid designing the barrier and its foundations for a large resistance capacity) could be adopted to bring about further optimisation in the geotechnical design of rigid barriers. The results will be reported separately when the study is completed.

2.5 Consideration of Realistic Topographic Profile in Debris Mobility Assessment

When carrying out debris mobility analysis, the design profile of the landslide runout path, including the portion within the debris retention zone, should be considered in the analysis.

2.6 A Preliminary Assessment of Implications of Updated Guidelines

Rigid barrier designs in two LPMit projects have been repeated using the above updated guidelines and the prevailing guidance promulgated by TGN 44. The study calculates the mass of barriers required based on geotechnical stability assessment. The mass of barrier calculated using the updated guidelines and the prevailing guidance is reduced by about 60% when compared with the design following the recommendations of GEO Report No. 270. It should be noted that since the structural design requirements were not considered in the assessment and assumptions on various factors e.g. barrier geometry were made, the reduction could be over estimated. The actual amount of reduction would be dependent on site-specific conditions, including the design impact scenario. Appendix D presents details of the study.

2.7 Other Issues

In addition to the comments on the design guidance recommended in GEO Report No. 270, Professor Hungr gave comments on the site-specific assumptions made in the design of the barriers reviewed by him. The following two remarks are made in light of those comments on the site-specific issues:

(a) The assessment of design groundwater condition could have significant implication on the design, since it pertains to the determination of the uplift pressure acting on the base of the debris basin. Underground drainage provisions should be made as necessary. It should be noted that the groundwater conditions assumed in the worked example given in GEO Report No. 270 were selected arbitrarily and should not be regarded as suggested values for design of mitigation measures.

(b) Rigid barriers may comprise lateral walls (or wing walls), integrated structural with barrier basin. Consideration of three-dimensional effects e.g. self weight and frictional resistance on wing walls should be made in geotechnical stability assessment of barriers as appropriate.

3 Recommendations

The following recommendations are proposed to incorporate Professor Hungr's comments in the current design guidelines for enhancement of design cost-effectiveness:

(a) The beneficial effects of the self weight of the impacting debris should be considered in geotechnical stability checking.

(b) The design impact pressure of debris flow should be calculated based on $\alpha = 2.5$, and this would include the effects of debris flow impact and impact of boulders of diameter up to 0.5 m. If there exists boulders larger than 0.5 m diameter in the debris flow, design impact load comprising debris flow impact load and boulder impact load should be considered.

(c) Boulder line load is only valid when there are simultaneous impacts by several boulders. This design scenario need not be considered to avoid undue conservatism. If there are abundant boulders perched along the stream course or potential debris flow path with diameters larger than 0.5 m, boulder impact scenarios to reflect the actual site conditions (e.g. impact load corresponding to an appropriate spacing of boulders over a certain portion of the barrier wall) can be applied in the design. Boulder baffles as illustrated in Appendix C can be used to screen out large boulders at the debris flow front, and consideration of boulder impacts on the stem of a rigid debris-resisting barrier would not be required. For isolated large boulders in subsequent phases, designers should consider their potential impacts on the barrier on a case-by-case basis. The provision of baffles could be considered in the design option assessment to deliberate whether their use could achieve cost savings.

(d) When carrying out debris mobility analysis, the design profile of the landslide runout path, including the portion within the debris retention zone, should be considered in the analysis.

(e) The design groundwater conditions should be duly assessed based on relevant monitoring records, and appropriate ground model and seepage analysis as necessary. When significant groundwater pressure acting on the barrier is anticipated, suitable drainage provision may be provided for more cost-effective design.

(f) Consideration of three-dimensional effects e.g. frictional resistance on wing walls should be made in geotechnical stability assessment of barriers as appropriate.

4 Further Work

Technical development work on (a) the use of composite structures comprising baffles and rigid barriers, and (b) the use of displacement approach for geotechnical design of rigid barriers, is being undertaken with a view to drawing up revised design guidance for further optimisation of the design of rigid barriers.

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Appendix A

Professor Hungr's Comments on the Design Guidelines Recommended by GEO Report No. 270

Contents

A.1 Geotechnical Stability Assessment: Weight of Flowing Debris

We question the recommendation in Paragraph 5.1(b) of GEO Report No. 270 that the weight of flowing debris should not be taken into account. The floor of the basin is horizontal (or stepped-horizontal), while the entry face of the basin is steeply sloped. Therefore, the entering debris will at first deliver a vertical impact on the floor of the basin and create a hydraulic jump, before proceeding forward towards the collision with the stem of the barrier. Because of the abrupt change in inclination of the velocity vector, the flow will continue to exert a vertical dynamic force at the same point, in addition to the static force corresponding to the weight of the debris. These vertical dynamic and static forces will be beneficial to both sliding and overturning stability. This should again be better rationalized.

A.2 Boulder Impact Load

The sliding and overturning stability calculations are carried out per m width of the barrier and the boulder force is added to the dynamic thrust force of the debris. This implies that there is one boulder impacting simultaneously for each metre of barrier width. This is not considered likely, even if many boulders are concentrated in the front. The boulder impact, as estimated by the Hertz equation, is very transient (Hu et al, for example, measured boulder impacts as peaks a fraction of a second in duration). The impacts of individual large boulders would need to be precisely synchronized, to achieve the effect assumed in the design. In fact, a large proportion of each of the brief impulses delivered by major boulder impacts is likely to be consumed by the inertia of the massive wall and will exert little influence on the sliding or overturning force resultant, which needs to be sustained over a longer period. Also, the fluid thrust multiplication factor of 2.5 already allows for a certain amount of particle impacts, averaged over a period of time. The procedure for combining fluid thrust and boulder impacts used in the design is likely very conservative and should be better rationalized.

Appendix B

Beneficial Effects of Downward Thrust

The contribution of downward thrust to the sliding resistance and restoring moment of rigid barriers has been assessed using fluid mechanics principles. Rigid barriers at three locations, namely, Shek Pai Wan Road, Yu Tung Road and St Joan of Arc Secondary School have been considered. The effects of downward thrust corresponding to the first phase, an intermediate phase and the last phase of debris impacts were compared with the stabilizing forces provided given by the weight of barrier and debris retained behind barrier.

The three barriers were selected for their different dimensions and design impact scenarios as detailed below:

Case	Design Volume (m^3)	Barrier Height (m)	Barrier Width (m)	Barrier Length (m)	Inclination of Debris Routing Channel	Design Total No. of Impact Phases
Shek Pai Wan Road	300	5.7	9	13	45^o	8
Yu Tung Road (C30)	3,300	7	24	24	15^o	3
St Joan of Arc Secondary School	620	5	16	9	30^o	3

The results show that the increases in sliding resistance and restoring moment are generally less than 2% so the effect of downward thrust can be considered marginal (see Table B1).

The only exception to the above is the first impact phase for the Shek Pai Wan Road barrier, where the sliding resistance and restoring moment increase by 5.2% and 3.6% respectively when downward thrust is considered. This is due to the relatively high downward thrust angle 45° (i.e. the inclination of the debris routing channel). In this case, debris flow might display a projectile motion from the crest of the debris routing channel.

Table B1 Beneficial Effects of Downward Thrust

Case	No. of Impact Phases	Design Debris Depth (m)	Design Debris Velocity (m/s)	Resisting Force Given by Barrier and Debris Weight		Increased Resisting Force Due to Downward Thrust		Increased Percentage with Downward Thrust (%)	
				Sliding Resistance (kN)	Restoring Moment (kNm)	Sliding Resistance (kN)	Restoring Moment (kNm)	Sliding Resistance	Restoring Moment
Shek Pai Wan Road	1st	0.7	7.0	2,153	62,757	2,266	65,025	5.2	3.6
	4th	0.6	6.0	3,200	75,150	3,266	76,653	2.1	2.0
	8th	0.4	5.0	4,714	98,316	4,746	99,295	0.7	1.0
Yu Tung Road (C30)	1st	2.5	7.6	37,963	813,083	38,374	830,275	1.1	2.1
	2nd	2.5	6.9	66,763	1,158,683	67,102	1,172,854	0.5	1.2
	3rd	2.0	4.9	95,563	1,504,283	95,700	1,510,000	0.1	0.4
St Joan of Arc Secondary School	1st	2.0	5.6	8,336	131,600	8,514	134,442	2.1	2.2
	2nd	2.0	5.0	13,808	156,224	13,950	158,490	1.0	1.5
	3rd	1.0	3.0	19,280	180,848	19,305	181,256	0.1	0.2

Appendix C

An Illustrative Design Example of Boulder Baffles

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C.1 Background

When boulders are engulfed to form part of a debris flow, a boulder front would be developed. Boulder impact load and debris flow impact load should be allowed in the design of the rigid debris-resisting barriers for this scenario.

Overseas experience shows that arrays of baffles are capable of filtering large hard inclusions including boulders from debris flows. In local practice, baffles are installed prescriptively. The effects of baffles in the respect of impact load reduction are not considered.

It is suggested that with the provision of appropriately designed baffles within the debris retention basin, boulders at the debris front could be screened out, and consideration of boulder impacts on the stem of a rigid debris-resisting barrier would not be required. Baffles can be placed outside the footprint of the barrier to reduce the horizontal loads acting on the barrier. The choice of the baffle location should be made with consideration given to site conditions, constructability and future maintenance requirements.

This Appendix presents an illustrative design example of boulder baffles installed within the debris retention basin.

C.2 Conditions Considered

In this example, it is assumed that a rigid barrier is to be constructed to mitigate a debris flow hazard. The rigid barrier comprises a sub-horizontal debris retention zone. There exists an abundant of perches boulders of diameter up to 1 m along the debris runout path. They can be potentially engulfed by the debris flow to develop into a boulder front. The design impact velocity is 10 m/s. An array of baffles is proposed to screen out boulders at the debris front.

C.3 Configuration of the Baffle Array

Figure C1 shows a schematic configuration of a baffle array for debris flow mitigation. Table C1 summarises the clearance of baffles recommended for practice in other regions. The recommended clearance in Mainland China and Canada is 1.5 to 4.0 times the maximum diameter of the hard inclusions (d_{max}). In Japan and Taiwan, the maximum clearance should be limited to $2d_{\text{max}}$. For 1 m diameter of boulders, the clearance of baffles (S_h) in this example can be taken as 1.5 m.

S_h is larger than the design boulder diameter (1 m). Two rows of baffles installed in a staggered configuration are required. The spacing between the two rows of baffles (S_r) is taken as 1.5 m.

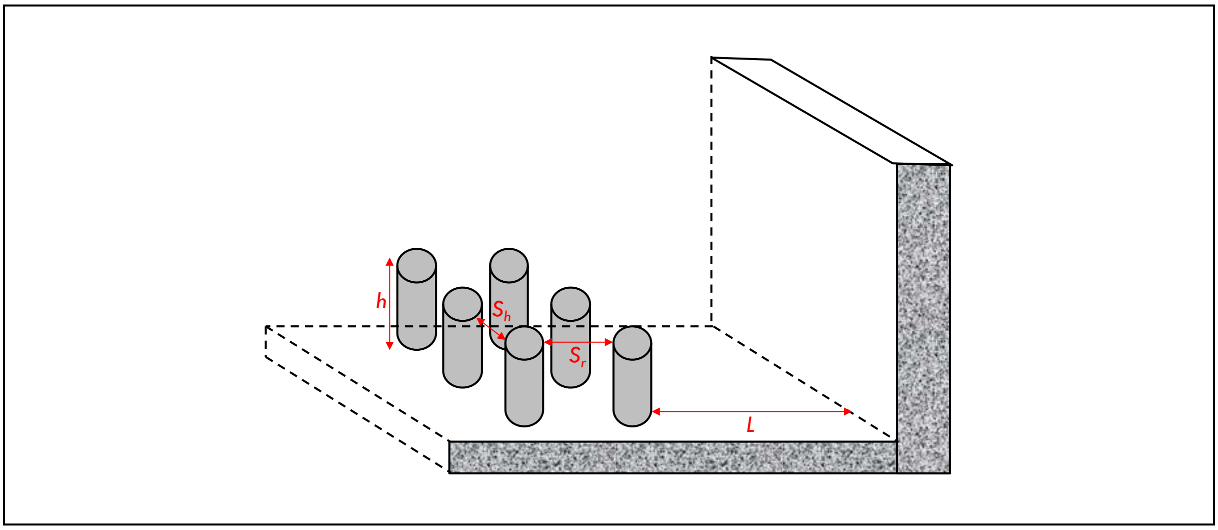

Figure C1 Configuration of Baffles

Table C1 Clearance of Baffles Adopted in Practice of Other Places

Design Practice	Clearance of Baffles (S_h)
China (MLR, 2004) Canada (VanDine, 1996)	$1.5\ d_m \le S_h \le 4.0\ d_m$
Japan (NILIM, 2007) Taiwan (SWCB, 2005)	$S_h \le 2.0\ d_m$

Notes: (1) d_m is the diameter of the largest boulder in debris flows.
(2) MLR (2004) and SWCB (2005) specify that the blockage of the baffles should be in the range of 20% to 60% of the barrier width.

Boulders usually travel near the top of debris flows due to vertical segregation of materials of different grain size that occurs during the debris transportation. The baffles should be sufficiently high to intercept the boulders. Baffles of at least 1.5 m high are deemed appropriate (i.e. $h \ge 1.5$ m).

It is anticipated that boulders at the frontal portion will be brought to rest by the baffles and form a deposition plug to help stopping the other hard inclusions. Debris flow travels from behind may ride on the plug and launch a ballistic flight. The clearance between baffles and the barrier is determined based on the horizontal travel distance of the ballistic flight. For debris flow velocity of 10 m/s, the horizontal travel distance is 1.8 m. The clearance (L) can thus be taken as 2 m.

C.4 Sizing of Baffles

Chan et al (1986) designed a boulder fence using steel square hollow sections (SHS) infilled with concrete. The design considered that the kinetic energy of boulders be dissipated by a plastic hinge formed at the base of the SHS when subject to the boulder impact. Load tests were carried out to study the maximum angular distortion of the SHS infilled with concrete that should be adopted in the design. Results of a more recent experimental study of the maximum angular distortion by Soundararajan & Shanmugasundaram (2008) are consistent with the findings of Chan et al (1986).

The energy dissipation by the development of a plastic hinge of a SHS can be calculated based on the following equation:

$$E_d = M_p\ \theta \quad \text{(C.1)}$$

where E_d = energy dissipated (in kJ)
M_p = plastic moment of the hinge (in kNm)
θ = angular distortion (in radian).

Based on the results of Chan et al (1986) and Soundararajan & Shanmugasundaram (2008), the maximum angular distortion before significant loss in the moment capacity of the SHS infilled with concrete can be taken as 0.35 (i.e. 20^o).

The kinetic energy of a 1 m diameter boulder travelling at 10 m/s is 67 kJ. Using Equation C.1 and $\theta = 20^o$, it can be shown that a plastic hinge formed at the base of the SHS of dimensions 200 mm x 200 mm x 16 mm can dissipate 80 kJ. The formation of the plastic hinge in the SHS is adequate to dissipate the kinetic energy of the boulder.

Effects of debris flow impact on the SHS are insignificant. Conservatively assuming that the debris flow thickness is 1 m, the bending moment (M) induced by the debris flow impact calculated using Equation C.2 is 50 kNm, which is less than M_p of the SHS (220 kNm).

$$M = \alpha \rho v^2 A\ l \quad \text{(C.2)}$$

where α = dynamic pressure coefficient (= 2.5)
ρ = density of debris flow (taken as 2 Mg/m^3 in this example)
v = debris impact velocity (it is 10 m/s in this example)
A = impacting area (it is 0.2 m^2 in this example)
l = moment arm (it is 0.5 m in this example).

C.5 Geotechnical Stability Assessment

With the provision of the boulder baffles, the following two separate design scenarios should be considered:

(a) sliding failure that may be induced by the boulder impact on baffles; and

(b) sliding failure and overturning failure that may be induced by the debris flow impact on the barrier.

With reference to para. C.5(a), the disturbing force considered in the checking of the sliding failure can be determined based on the magnitude of the impact force large enough to form the plastic hinge (= M_p/height of impact). Assuming the impact would occur at the mid-point of the baffles, the force is 293 kN. Baffles are installed at a spacing of 1.7 m, the disturbing force per metre run is 172 kN/m.

If baffles are not provided, the scenario stated in para. C.5(a) is not relevant, and consideration of superposition of debris flow impact load and boulder impact load will be required for assessing the geotechnical stability of the barrier (c.f. consideration of the debris flow impact load only as stated in para. C.5(b)).

C.6 Other Design Considerations

Detailing, e.g. bracings or other connections between individual baffles and drainage channels running between the rows of baffles for discharge of water from the debris trapped by baffles, to enhance the robustness of the design should be formulated as part of the detail design.

While baffles can help screen out large boulders at the debris flow front, it is good practice, for design robustness, to consider on a case-by-case basis the potential impacts from isolated large boulders in subsequent phases on the barrier in design.

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Appendix D

A Preliminary Assessment of Implications of Updated Guidelines

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D.1 Background

The implication of the updated guidelines on barrier sizing has been assessed. For the assessment, the ground profiles of two LPMit natural terrain mitigation works sites, known as sites A and B, were used to form the basis of assessment. For each site, it was assumed that a rigid barrier is to be constructed near the outlet of the drainage channel to mitigate a debris flow hazard. The minimum required barrier mass to satisfy the geotechnical stability requirements was calculated separately following (i) the guidelines given in GEO Report 270, and (ii) the updated guidelines presented in this TN and TGN 44.

D.2 Assumptions

The following assumptions have been made for the purpose of the assessment:

(a) The barrier's geometry (including base width) and design debris volume follow the conforming design (see Figure D1).

(b) The barrier's stem wall, side walls, and base slab have the same thickness. Their self weights are considered.

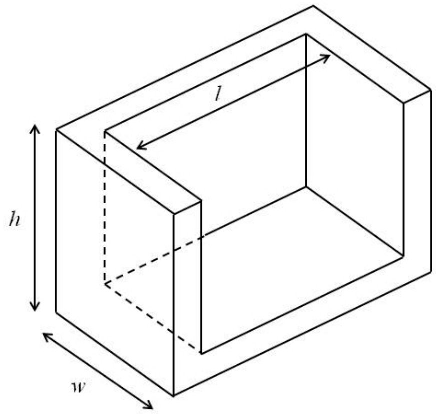
(c) Uplift pressure due to groundwater is not considered.

(d) The friction angle (ϕ) between concrete and soil is 34°.

(e) A partial factor of 1.2 is applied to tan ϕ.

(f) A load factor of unity is applied to the design debris impact loads.

(g) Impact of a boulder of diameter 1.0 m is considered in the design.



Location	h (m)	w (m)	l (m)	Debris Volume (m^3)
Site A	6.5	13.0	9.0	300
Site B	8.2	31.2	22.0	3,300

Figure D1 Geometry of Barriers and Design Debris Volume Considered in Assessments

D.3 Assessments

Table D1 summarises the frontal debris velocity and thickness generated with and without incorporating a sub-horizontal debris basin into the debris mobility analyses. It can be seen that with consideration of a sub-horizontal basin, a reduction in the frontal debris velocity and a slightly higher debris thickness are obtained. The changes pertain to the anticipated slowing down of landslide debris as they travel across the debris basin. The assessment has been carried out with consideration given to the 3D effects including the weight of the wing wall.

Table D1 Frontal Debris Velocity and Thickness

Location	Ground profile	Frontal debris velocity (m/s)	Frontal debris thickness (m)
Site A	sub-horizontal debris basin **not** considered	7.0	0.7
	sub-horizontal debris basin considered	4.0	0.9
Site B	sub-horizontal debris basin **not** considered	8.5	2.5
	sub-horizontal debris basin considered	6.2	2.9

For each site, the minimum required barrier mass to satisfy the geotechnical stability requirements was established based on design approaches tabled below (Table D2).

Table D2 Design Approaches

Design Approach	GEO Report No. 270	TGN 44	Updated guidelines recommended by this TN	Remarks
1	✓			Design debris impact velocity calculated **without** the consideration of sub-horizontal debris basin
2		✓	✓	Design debris impact velocity calculated **with** the consideration of sub-horizontal debris basin

Table D3 summarises the minimum barrier masses required to satisfy geotechnical stability requirements for the two sites (the barrier masses include mass of barrier wall, wing wall and base slab). It can be seen that optimization of the required masses can be achieved if the recommendations given in TGN 44 (debris velocity attenuation) and the updated guidelines presented in this TN are adopted. It should be noted that only geotechnical stability requirements have been considered in this assessment. The structural requirements are not completely reflected by this study. However, with the use of Approach 2 (Table D2), the structural requirements can also be optimised.

Table D3 Minimum Required Barrier Mass

Location	Design Approach	Minimum Required Barrier Mass (kg)
Site A	1	486,000
	2	176,000
Site B	1	4,120,000
	2	1,405,000

D.4 References

GEO (2015). *Assessment of Landslide Debris Impact Velocity for Design of Debris-resisting Barriers (TGN 44)*. Geotechnical Engineering Office, Hong Kong, 4 p.

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