Review of Rockfall Incidents Occurring under Dry Weather

GEO Report No. 370

R.C.T. Wai, K.S.P Lam & R.W.H. Lee

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 December 2022
as GEO Landslide Study Report No. LSR 2/2021

First published, February, 2024

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Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond W M Cheung
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February 2024

Foreword

This report presents the findings of a review of rockfall incidents occurring under dry weather that were reported to the Government in the past two decades. Lessons learnt from the notable incidents in recent years and areas that deserve attention in rock slope engineering practice in relation to the observations from the review are highlighted.

The review was carried out by Mr Roland C.T. Wai, Mr Kevin S.P. Lam and Mr Ryan W.H. Lee of the Landslip Preventive Measures Division 2 under the supervision of Mr Patrick K.S. Chau initially and later Ms Florence W.Y. Ko. Assistance was provided by AECOM Asia Company Limited, the 2019 to 2021 landslide investigation consultants. All contributions are gratefully acknowledged.

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Abstract

In Hong Kong, on average about 300 landslides are reported to the Government every year, among which rockfall incidents constituted about one-tenth of the reported landslides. The majority of rockfall incidents, similar to other types of landslides, are rain-induced. Meanwhile, rockfalls have from time to time occurred under dry weather with little tell-tale sign. Aggravated by the dense urban settings in Hong Kong, some of these incidents resulted in serious/significant consequence or rendered 'near-miss' events with the potentially severe consequence narrowly avoided. Along with the generally low alertness or perception to landslide risk by the public under dry weather, the respective risk of rockfalls should not be overlooked. An improved understanding on this type of event would therefore be useful for examination of the adequacy of the relevant slope engineering practice.

This report presents the findings of a review of the rockfall incidents occurring under dry weather between 2001 and 2020 to provide insights on their characteristics, in particular the probable triggers, causes and modes of failure when under dry weather. The notable incidents in recent years are presented to shed light on the lessons learnt. It is noteworthy that while the rockfalls are generally local and not sizeable, they could also be consequential. The adverse consequence of rockfall events could have been minimised should there be proper provisions to mitigate the risk concerned. The review findings reiterate the importance to have proper provisions to mitigate the landslide risk associated with rockfall events as a good practice in slope safety management.

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1 Introduction

In Hong Kong, on average about 300 landslides are reported to the Government every year, among which rockfall incidents (herein defined as rockfalls or rockslides occurring on man-made slopes or natural hillsides disregarding the scale of failures) constitute about one-tenth of the reported landslides. In some cases, notable consequences had been resulted exacerbated by the dense urban settings in Hong Kong. For example, in 2001, a rockfall incident at Castle Peak Road where a van traveling along the busy highway was hit by a small piece of fallen rock debris. The driver lost control of the van and crashed into the slope resulting in significant vehicle damage and injury of the driver and a passenger (MGSL, 2005). In 2015, a rockfall incident at Stanley Gap Road where a tour bus traveling along the road was hit by a small rock block. The rock block broke and punched through the window of the tour bus leading to injury of four passengers (Section 2.2).

The risk arising from rockfall events has been well recognised. The understanding on rockfall and the rock slope engineering practice in Hong Kong has been continuously improved particularly through studies of rockfall incidents by the Geotechnical Engineering Office (GEO) over the years. The characteristics of rockfall, the landslide risk management framework adopted and the prevailing rock slope engineering practice in Hong Kong were summarised in Ho et al (2017). Further advices and technical recommendations on enhancing the rock slope engineering practice taking due cognizance of the lessons learnt and findings from landslide studies were presented in GEO (2020) and Ho & Lau (2007).

In the past decade, fortunately, Hong Kong experienced a period with no fatal landslides although from time to time there had been landslides resulted in varying degrees of damage and social disruption. In these relatively uneventful years, 'near-miss' cases, that could have resulted in more serious consequences, came more readily to our attention. Some of these cases involved rockfall incidents under dry weather. Unfavourably, these incidents with no apparent trigger or little tell-tale sign occurred at time when people's alertness or perception to landslide risk is generally low. An improved understanding on this type of event would be useful for examination of the adequacy of the relevant slope engineering practice.

This report presents the findings of a review of rockfall incidents occurring under dry weather that were reported to the Government in the last two decades (viz. between 2001 and 2020). The key objectives of the present review are as follows:

(a) to share the lessons learnt from the notable rockfall incidents in recent years that occurred under dry weather,

(b) to diagnose landslide data and review published information and file records on the rockfall incidents that occurred under dry weather to provide insights on their characteristics including the probable triggers, causes and modes of failure, and

(c) to highlight the areas deserving particular attention in rock slope engineering practice in relation to the observations from the review.

2 Notable Rockfall Incidents Occurring under Dry Weather

2.1 General

Rockfall incidents have from time to time been reported to the Government under dry weather. In this Section, five notable cases in recent years are presented which either resulted in serious/significant consequences (Sections 2.2 and 2.3) or rendered 'near-miss' events with the potentially severe consequences narrowly avoided (Sections 2.4 to 2.6). These incidents all occurred at time without rain or with little rain. The documentation below provides insights on the rockfall incidents and the lessons learnt are also highlighted.

2.2 The 19 Feburary 2015 Rockfall at Stanley Gap Road near Chung Hom Kok Road, Stanley (Incident No. 2015/02/1659)

At about 5:00 p.m. on 19 February 2015, a rockfall incident occurred on a 6 m high rock cut slope (Feature No. 15NE-A/C425) above Stanley Gap Road near Chung Hom Kok Road (Figure 2.1a). The incident occurred under dry weather and no rain was recorded preceding it. The rockfall, with an estimated failure volume of about 0.05 m^3, involved the detachment of several rock blocks. Most of them were deposited on the carriageway while one rock block punched through the window of a tour bus travelling along the road (Figure 2.1b). As a result, four passengers on board were injured by the broken window glass fragments. The incident was reported by the mass media.

The fallen rock blocks originated from the bare rock face of a subvertical rock cut slope above Stanley Gap Road. Along the affected section of the road, there was no pedestrian pavement or footpath. The rockfall debris was largely deposited on the carriageway. As observed from the landslide inspection, mature trees with extensive network of roots were growing over and above the failure location and the progressive tree root growth had penetrated into the apertures of a number of rock joints. It is evident that root wedging action destabilized the rock blocks by opening up the joints of the near-surface rock mass rendering them more susceptible to local detachment. Detached rock blocks were also observed on other parts of the slope, some of which were perching on the rock face adjacent to the failure location (Figure 2.1c).

This incident highlights that rockfalls occurring on slopes adjoining vulnerable facilities (e.g. heavily-trafficked roads) could result in severe consequence, even for failure of small scale. Root wedging action could destabilize the rock blocks on slope face increasing the susceptibility of local detachment.

2.3 The 20 July 2010 Rockfall behind Somerset, No. 67 Repulse Bay Road (Incident No. 2010/07/0968)

At about 11:15 a.m. on 20 July 2010, a rockfall incident occurred on a 40 m high soil and rock cut slope (Feature No. 15NE-A/C233) behind Somerset, No. 67 Repulse Bay Road (Figures 2.2a and 2.2b). The incident occurred under dry weather and no rain was recorded preceding it. The fallen rock block, with an estimated failure volume of about 0.03 m^3, dislodged from about 35 m above ground level travelling downslope over a plan distance of about 30 m and hit a car parked in the open car park at the slope toe. While the car was damaged, no casualty was reported as a result of the incident.

The slope is sizeable and comprises three slope batters. The detached rock block was sourced from a bare rock face, being 45° inclined, near the crest of the slope. Along the trajectory path of the fallen rock block as inferred from the impact marks, the slope surface was primarily covered with shotcrete (Figure 2.2c). From the landslide inspection, closely-jointed weathered rock mass (Grade III/IV) with the growth of mature trees and vegetation were noted over the rockfall source location. This failure was probably attributed to the root wedging action by the nearby trees.

As generally observed from rockfall cases, it is not uncommon that the presence of trees, shrubs and slope furniture (e.g. handrails and fences) may serve as energy dissipators against the motion of rockfalls. In this case, the slope surface along the rockfall trajectory path was primarily covered with shotcrete which in favour the rolling and bouncing of the fallen rock block, as well as the building up of kinetic energy along the fall. Meanwhile, energy dissipators were limited along the rockfall trajectory path. With this setting, the rock block detached from its source area at height travelled over a long distance reaching the open car park at the slope toe.

This incident highlights the possible rendering of long travel distance and high energy of rockfalls associated with source areas at height. Rockfall motion could also be aggravated by the smooth slope surface (e.g. shotcrete cover) and the lack of energy dissipators along its trajectory path.

2.4 The 26 June 2019 Rockfall at Argyle Street, Mong Kok (Incident No. 2019/06/2456)

At about 6:30 p.m. on 26 June 2019, a rockfall incident occurred on a 19 m high soil and rock cut slope (Feature No. 11NW-D/C16) at Argyle Street, Mong Kok (Figure 2.3a). There was no rain at the time of failure. The rockfall with a failure volume of approximately 4 m^3 originated from the bare face of the lower rock batter, adjacent to another rockfall incident that occurred in 2018 (Incident No. 2018/08/2208 with a failure volume of about 0.005 m^3). The debris, comprising rock fragments and some vegetation, was largely deposited on the pedestrian pavement and some of it covered part of a road lane. Rock fragments with size up to 1.5 m in diameter were recorded. As a result, two road lanes, the pedestrian pavement and the bus stops at slope toe were temporarily closed. No casualty was involved. The incident was reported in the media.

The rockfall involved a planar sliding failure from a sub-vertical rock cut batter over an adversely orientated sliding plane dipping out of the slope at about 75°. Vegetation with extensive root growth was noted at the source area prior to the failure (Figure 2.3b). Post-landslide inspection observed seepage on the failure scar which was probably associated with the precedent heavy rainfall (viz. Amber Rainstorm Warnings were issued in the evening of 25 June 2019 and in the morning of 26 June 2019 and the rolling 2-day rainfall preceding the incident was about 60 mm). The failure was probably caused by the development of cleft water pressure along the sliding plane attributable to the subsurface flow from upslope. The penetration of roots into the joint apertures, as evidenced on the scar, could have progressively wedged open the adversely orientated rock joints allowing enhanced water ingress.

The incident was notable in that it occurred on a sizeable steep cut slope (19 m high and 85 m long) along a heavily-trafficked road overlooking a number of busy bus stops (located intermittently over a continuous length of about 50 m) during rush hours. Fortunately, the failure did not result in any casualty under such dense urban setting and failure timing. The incident highlights the landslide risk posed by sizeable slopes with the presence of a persistent length of facilities of heavy usage along the slope toe. Given the vulnerable setting, even local failures may lead to severe consequences.

2.5 The 15 July 2020 Rockfall at Woh Chai Street, Shek Kip Mei (Incident No. 2020/07/2723)

At about 6:20 p.m. on 15 July 2020, a rockfall incident occurred on a 50 m high soil and rock cut slope (Feature No. 11NW-B/C39) at Woh Chai Street, Shek Kip Mei (Figures 2.4a and 2.4b). The incident occurred under dry weather and no rain was recorded preceding it. The rockfall incident, with an estimated failure volume of about 0.06 m^3, involved the detachment of small rock blocks from a 50° inclined bare face at the lower rock batter. The rock fragments with a maximum size of about 0.5 m by 0.5 m by 0.25 m were deposited on the pedestrian pavement covering an extent of at about 2.5 m from the slope toe outside an exit of the Shek Kip Mei MTR station. As a result, the affected section of pedestrian pavement and the exit of the MTR station were temporarily closed. No casualty was involved.

Post-landslide inspection revealed that a number of trees and extensive vegetation were growing over and above the failure location (Figure 2.4b) and tree roots were noted on the failure scar. The joints of the rock mass at the failure location could have been opened up by tree root action. Root wedging action had played a key contributory role in this failure.

The subject portion of the slope abuts the pedestrian pavement of varying width (from 2 m to 4 m) with bus stops, a mini-bus stop and an MTR station exit (Figure 2.4c). Although the scale of failure is small, the incident could have resulted in more serious consequences if the rockfall is sourced from a higher slope portion where rock blocks falling with higher energy may reach the carriageways; or if the rockfall is sourced from the area right above the bus/mini-bus stops, located within metres away from the present rockfall location (where a recess rendered a wider pavement at the MTR station exit area), with a narrower pavement. This incident highlights that a slight difference in site settings or rockfall source locations could significantly increase the chance of rendering severe consequences.

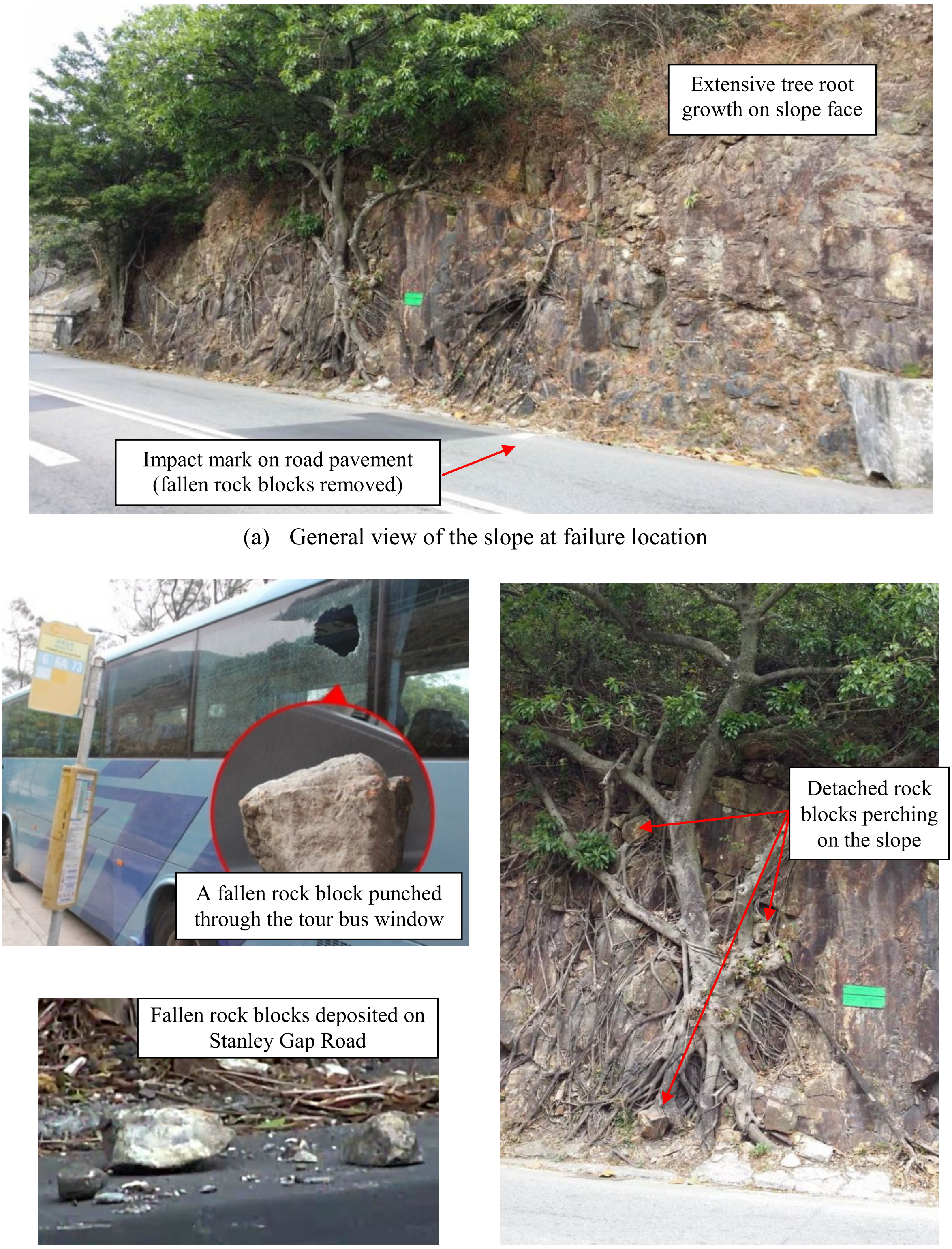
2.6 The 2018 and 2019 Rockfalls at South Bay Road (Incident No. -)

Between December 2018 and February 2019, four rockfall events were reported at South Bay Road (Figure 2.5a) with the fallen debris, comprising rock fragments as well as construction and demolition materials, deposited and scattered along a road section of about 80 m long (Figures 2.5b and 2.5c). Though the exact time of failures is not known, the rockfalls were reported under dry weather within the dry season. No significant consequence was resulted from these rockfall events.

The affected section of South Bay Road is abutted by a 10 m high rock cut slope (Feature No. 15NE-A/C100), above which being the natural hillside with a height of about 35 m. A low-rise residential building on a building platform is located at the crest of the hillside. The source locations of the rockfalls are not known. They probably sourced from the hillside with extensive rock outcrops while the cut slope was covered with rock mesh in a fair condition.

The discrete rockfall events affected a substantial length of South Bay Road. In particular, the debris deposited over a 30 m long road section instead of an isolated location in one of the events, differing from the typical observations on rockfall disposition. Wild boars' activities were evidenced on the hillside above the cut slope. Any rock blocks and other materials perched on the hillside could have fallen off with the crossing of the wild boars rendering debris scattered along the road. The activities of wild boars could have constituted to a moving trigger for the rockfalls.

The rockfall events serve as a reminder that rockfall under dry weather may involve other less common triggers, such as the activities of wild animals on slopes.

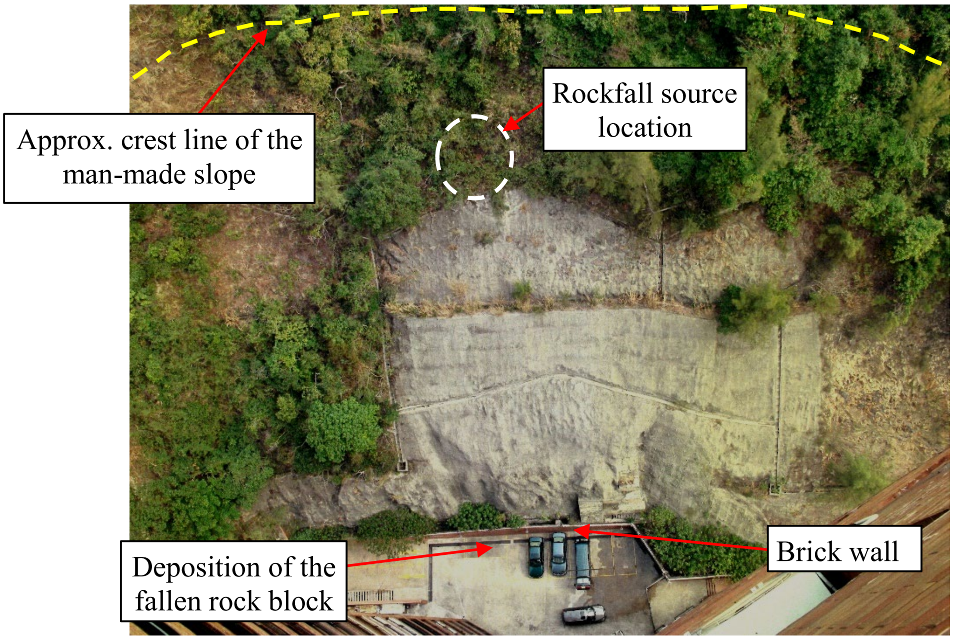


(a) General view of the slope at failure location

(b) Views of fallen rock blocks and the damaged tour bus

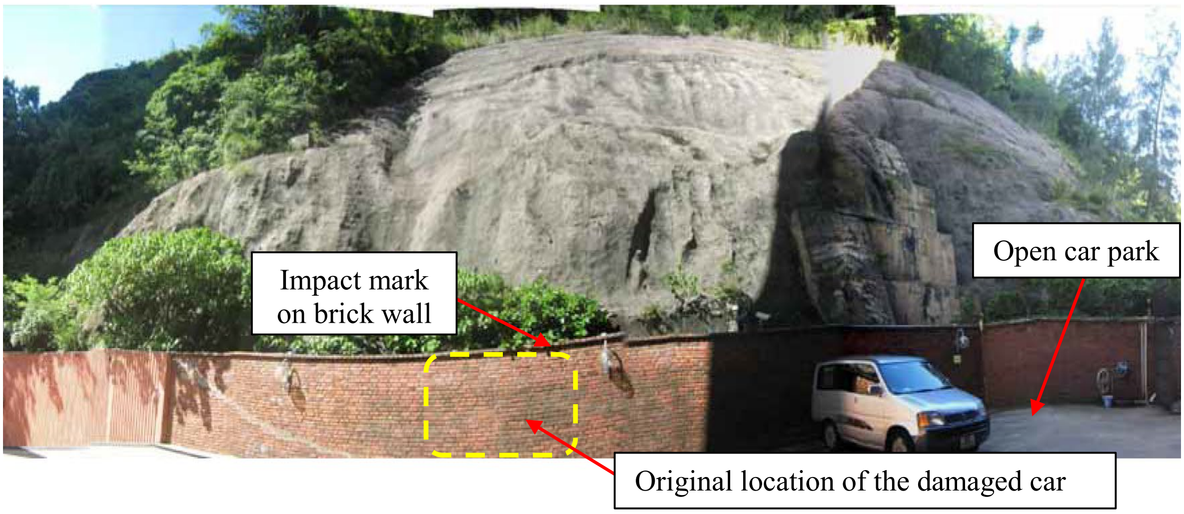
(c) Close-up view of the slope face with the growth of a mature tree

Figure 2.1 Views of the 19 Feburary 2015 Rockfall at Stanley Gap Road near Chung Hom Kok Road, Stanley (Incident No. 2015/02/1659)



(a) Aerial view of the slope showing the failure location

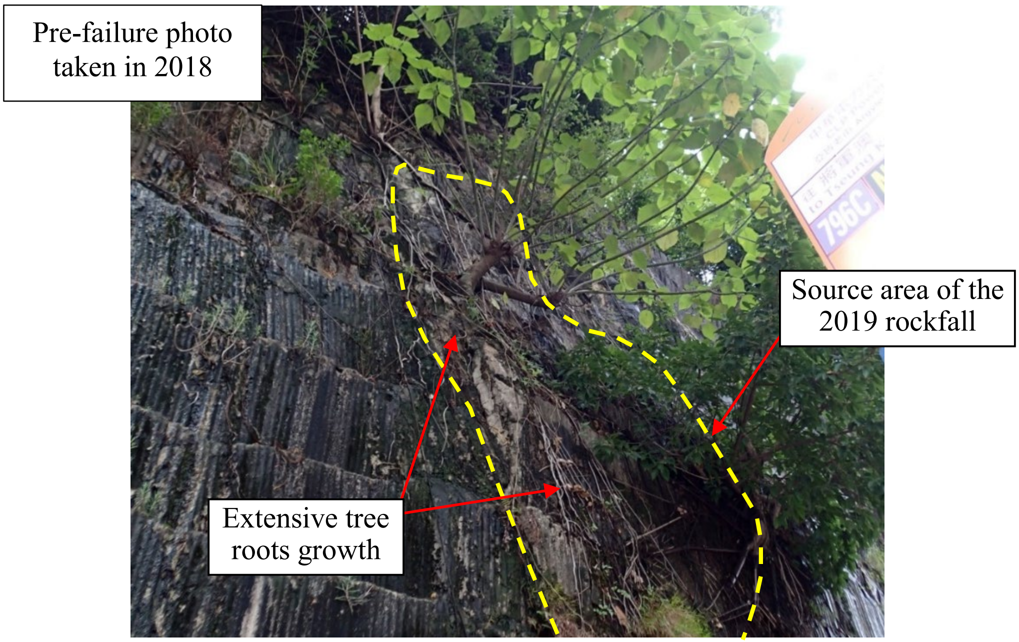
(b) View of the fallen rock



(c) General view of the slope and facility at the slope toe

Figure 2.2 Views of the 20 July 2010 Rockfall behind Somerset, No. 67 Repulse Bay Road (Incident No. 2010/07/0968)

(a) General view of the rockfall

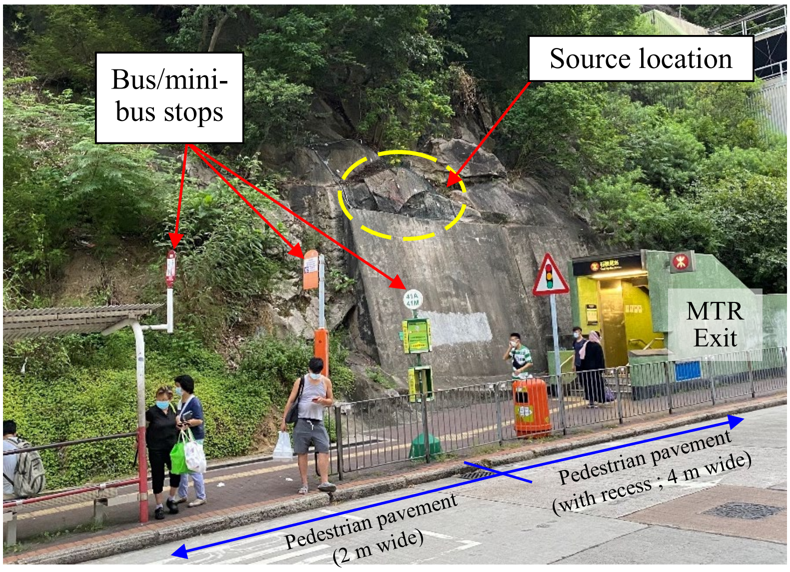


(b) Conditions of the source location prior to the failure

Figure 2.3 Views of the 26 June 2019 Rockfall at Argyle Street, Mong Kok (Incident No. 2019/06/2456)

(a) Temporary closure of the affected section of pedestrian pavement and the MTR station exit

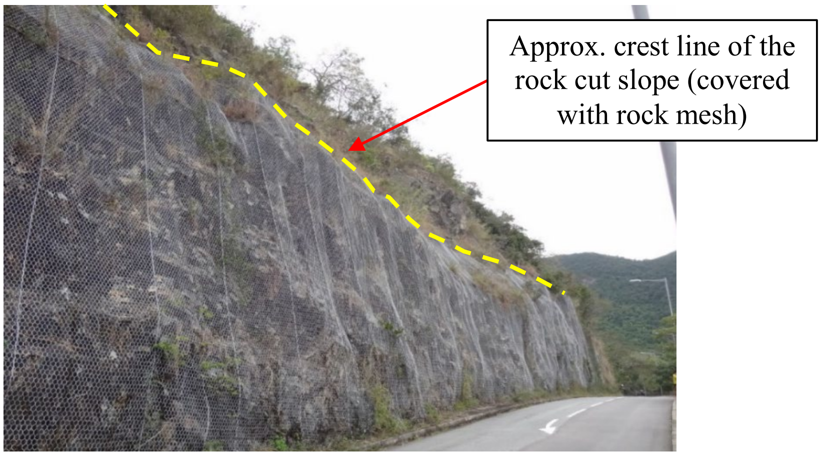
(b) General view of the rockfall



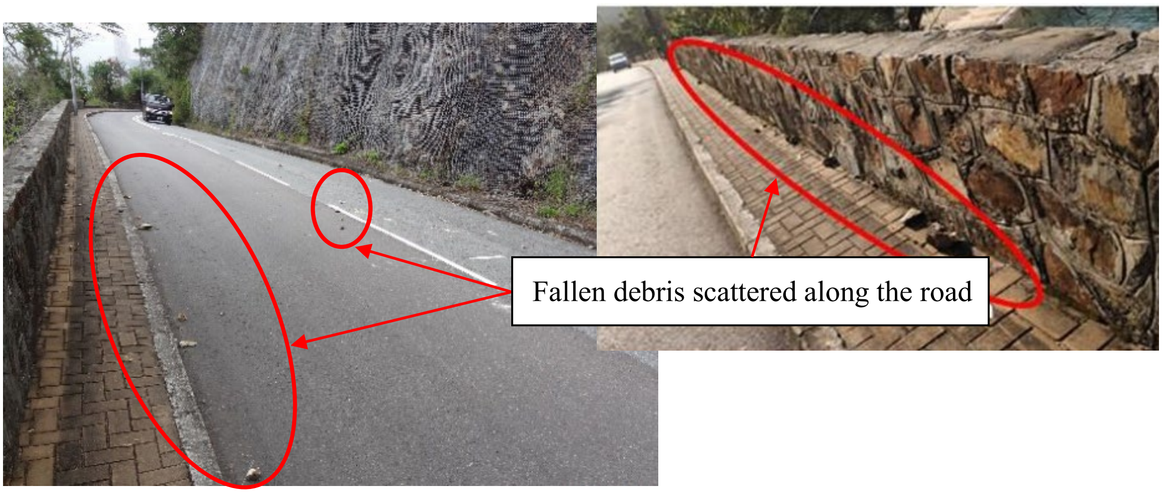
(c) General view of the facilities at the slope toe

Figure 2.4 Views of the 15 July 2020 Rockfall at Woh Chai Street, Shek Kip Mei (Incident No. 2020/07/2723)

(a) Aerial view of the site



(b) General view of the slope above the road



(c) Views of the debris deposition at the slope toe

Figure 2.5 Views of the 2018 and 2019 Rockfalls at South Bay Road

3 Diagnosis of Rockfall Incidents Occurring under Dry Weather

3.1 General

A review of rockfall incidents occurring under dry weather between 2001 and 2020 has been conducted with a view to acquiring a better understanding on their characteristics. The methodology adopted in identifying the relevant cases for review is presented in Section 3.2. The statistics compiled and observations made from the review are presented in Sections 3.2 to 3.5. The review has mainly focused on the following aspects:

(a) facilities affected and consequences of the incidents (Section 3.3),

(b) probable triggers, causes and modes of failures (Section 3.4), and

(c) incidents on registered man-made slopes (Section 3.5).

The present review is based primarily on a desk study, which comprises a systematic examination of all the available records and published information. The sources of information include the slope information system, the relevant landslide incident reports, inspection notes and records prepared or collated by the landslide investigation (LI) consultants engaged by the GEO under the systematic LI programme. It should be noted that most cases covered under this review were not the subject of previous detailed investigations and hence some relevant information may not be readily available. Notwithstanding this, the present overall review has allowed a broad appreciation of the key areas that deserve attention.

For boulder fall incidents, there is generally a lack of information of the source locations and conditions for assessing the characteristics of the failures. This precludes a representative diagnosis and hence boulder fall incidents are not covered in the present review.

3.2 Data Screening, Statistics Compiled and Incidents Reviewed

Between 2001 and 2020, about 4,400 landslides were reported to the Government. Among these landslides, failure dates were known in some 2,950 incidents, of which 245 (about 8%) were rockfall incidents. For these 245 rockfall incidents, the amount of rainfall preceding the incidents has been collated in order to identify those cases occurring under dry weather. In the present context, rockfall incidents with known failure dates and found to have experienced rolling 3-day rainfall preceding the incidents as being less than 10 mm based on the respective nearest rainguages, are regarded as having occurred under dry weather. Others are regarded as cases with the effect of rainfall cannot be adequately ruled out. Based on this data screening methodology and criterion, 42 cases occurring under dry weather have been identified for the review. It should be noted that the effects of rainfall on slopes may sometimes be influenced by complicated site hydrogeology inducing varying groundwater responses (e.g. delay response). The adoption of the above 'dry weather' screening criterion is considered suitable for the purpose of an overall diagnosis under the current review.

The breakdown of the reported landslide incidents is shown in Figure 3.1. A list of the 42 rockfall incidents occurring under dry weather is given in Appendix A and the salient review findings are presented in Sections 3.3 to 3.5.

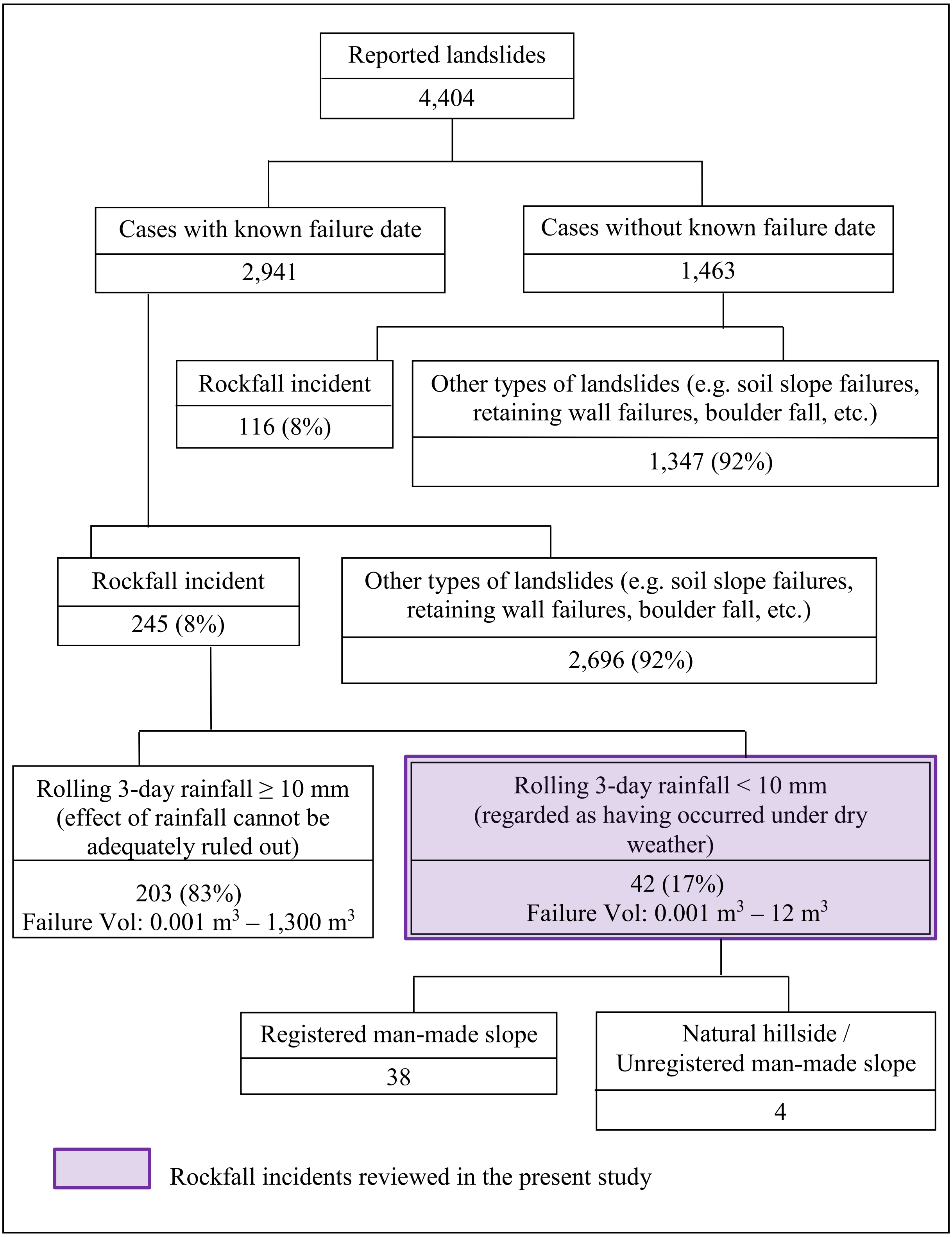


Figure 3.1 Breakdown of Reported Landslide Incidents between 2001 and 2020

A plot on the annual percentage of rockfall incidents occurring under dry weather among the total number of rockfall incidents is shown in Figure 3.2. Rockfall incidents occurring under dry weather have been reported from time to time over the years. On average, these have constituted about 17% (42 out of 245) of the rockfall incidents which is slightly higher than the respective figure (about 13%) compiled for the other types of landslides (e.g. soil slope failures, retaining wall failures, boulder fall, etc.).

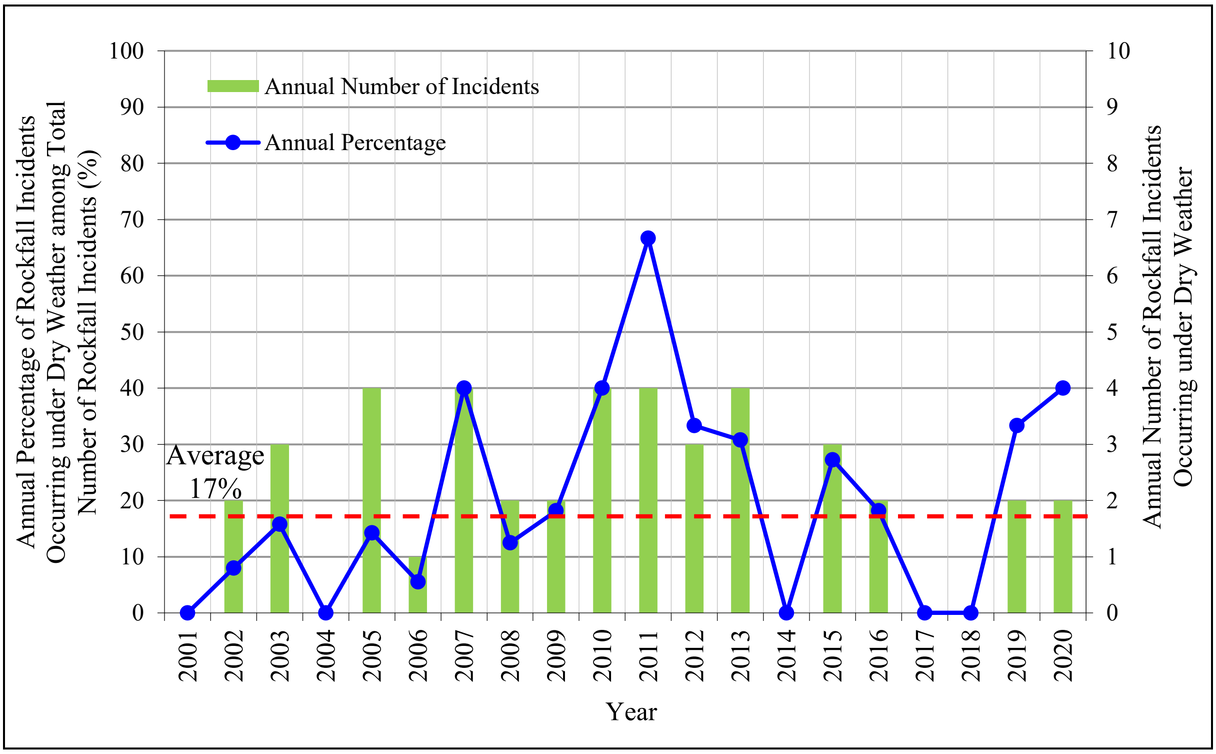


Figure 3.2 Yearly Statistics of Rockfall Incidents Occurring under Dry Weather

In terms of failure volume, all these 42 rockfall incidents that occurred under dry weather are minor in scale with volume up to 12 m^3. The scale of failures is generally smaller than that of the cases with the effect of rainfall cannot be adequately ruled out, for which the failure volume could be up to 1,300 m^3. For dry weather cases, it is worth noting that the majority of the incidents involved local detachment of small rock blocks with a volume of less than 1 m^3 (about 85%). Figure 3.3 presents the volume distribution of these 42 incidents.

Most of the incidents involved registered man-made slopes. Of the 42 incidents, 38 (about 90%) occurred on registered man-made slopes, two occurred on unregistered man-made slopes and two occurred on natural hillsides. A diagnosis of the incidents on registered man-made slopes is presented in Section 3.5.

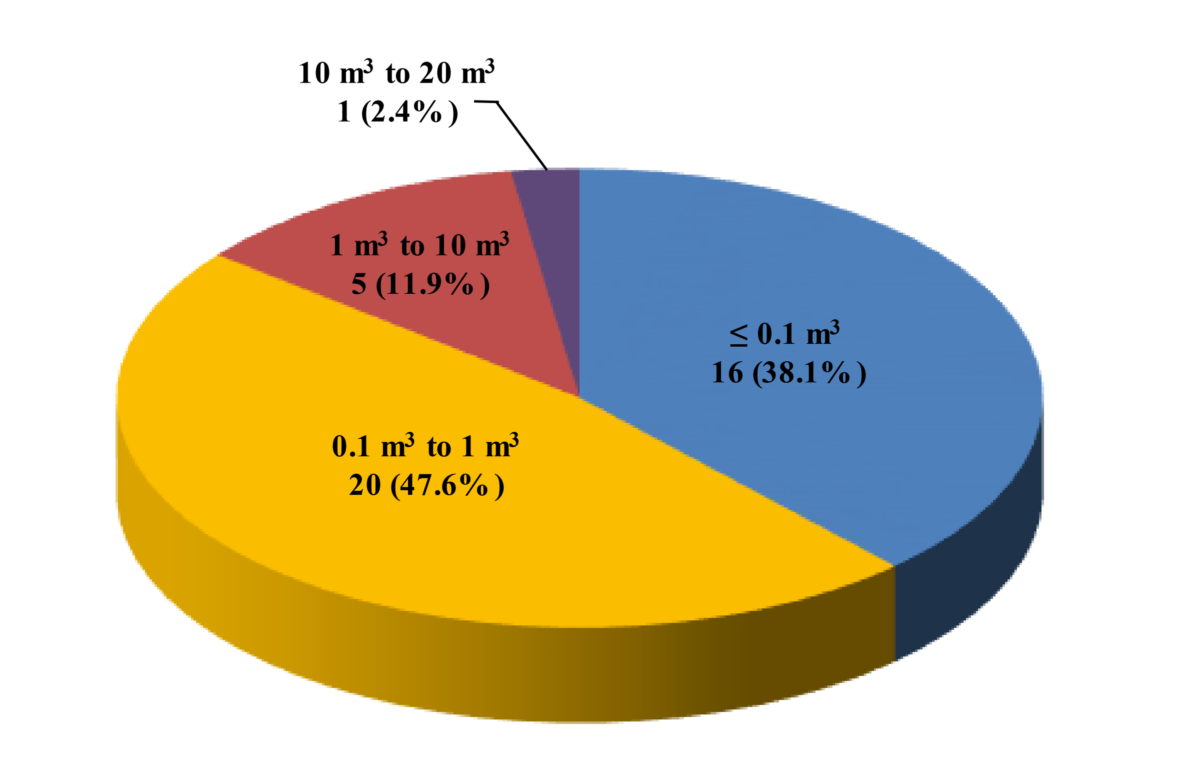


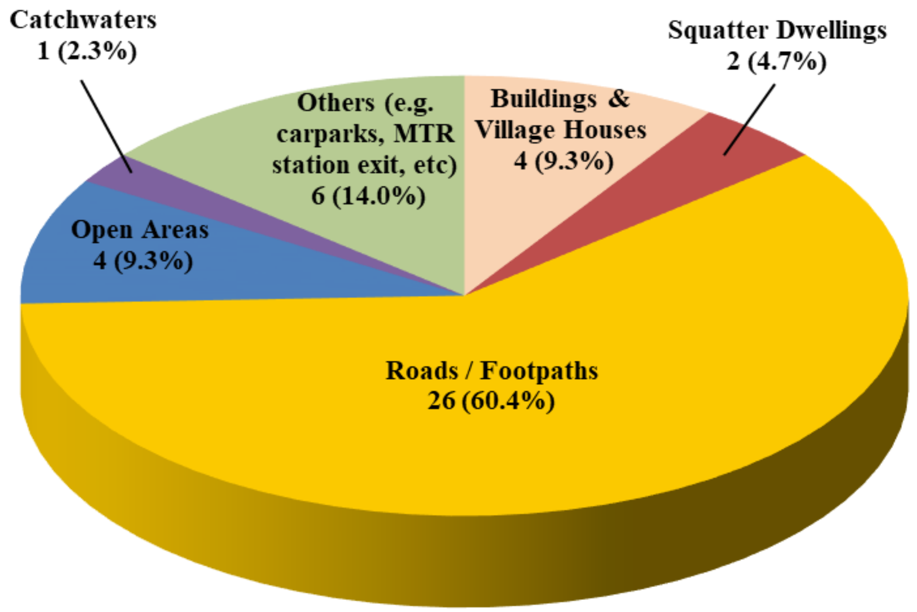
Figure 3.3 Volume Distribution of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020

3.3 Facilities Affected and Consequences of Incidents

Of the 42 rockfall incidents occurring under dry weather, more than half of them (about 60%) affected roads and footpaths, about one-seventh affected buildings, village houses and squatters, and the remaining cases affected open areas, catchwaters, MTR station exit, carparks, tennis courts and remote areas. The types of facilities affected are shown in Figure 3.4.

With regard to the consequences of the incidents, one led to injuries of four passengers on a tour bus (Section 2.2), one resulted in damage of a parked car (Section 2.3), three resulted in temporary closure of roads with varying degrees of traffic disruption while the other 37 cases did not give rise to any significant public nuisance or notable consequences.

It is noteworthy that apart from the one resulted in casualty, about half of the cases (viz. 22 cases) occurred on the slopes overlooking facilities of moderate to high vulnerability (viz. consequence-to-life (CTL) Categories 1 & 2). These are 'near-miss' cases which could have resulted in severe consequences. The other 19 cases occurred on the slopes overlooking facilities of lower vulnerability (viz. CTL Category 3). The 42 rockfall incidents, with grouping based on their actual/potential consequences in a board sense, are listed in Appendix A.



Note: A given rockfall incident may affect more than one type of facility.

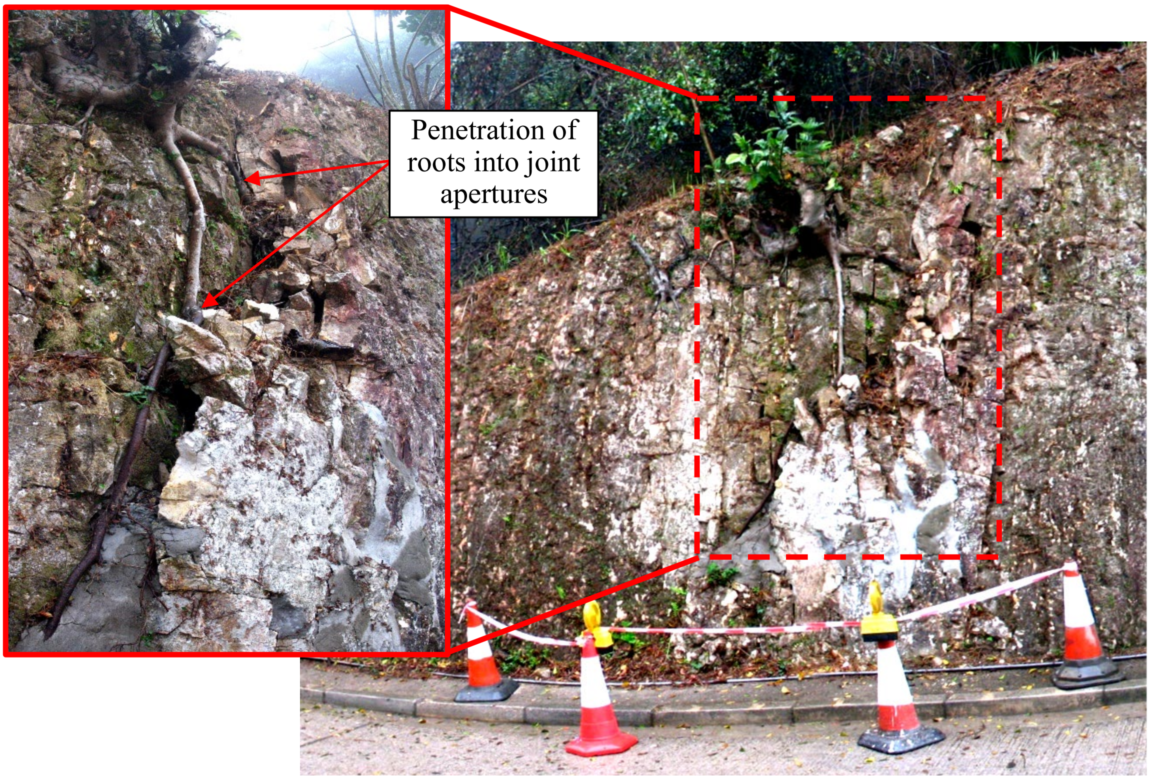
Figure 3.4 Breakdown of Rockfall Incidents Occurring under Dry Weather by Types of Affected Facilities

3.4 Probable Triggers, Causes and Modes of Failures

Of the 42 rockfall incidents occurring under dry weather, 40 originated from bare rock faces with varying degrees of trees or vegetation growth and the remaining two originated from the rock faces covered by shotcrete or chunam. The present diagnosis reveals that the rockfalls were typically controlled by adverse geological features (e.g. adversely orientated rock joints, heavily-jointed rock mass, infill of weak materials along joints, opened joints, etc.).

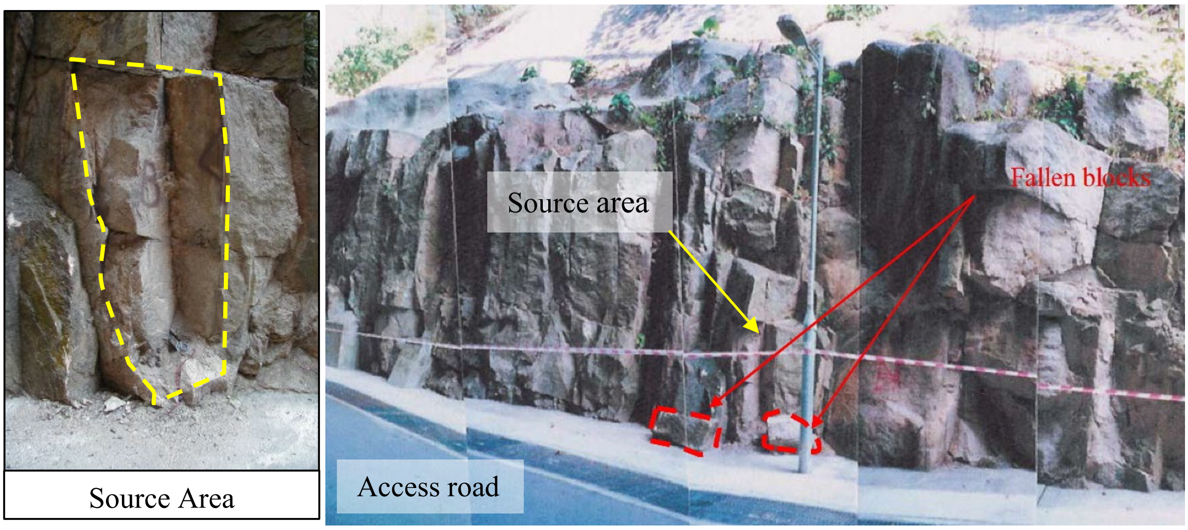
Almost all these rockfall incidents (41 out of 42) were likely triggered by root wedging action of the trees or vegetation growing on the rock face. The penetration of roots into adversely orientated rock joints over more weathered or closely jointed rock within a strong rock mass were generally observed. Examples of the rockfall incidents on bare rock faces probably triggered by the wedging action of tree roots are given in Figure 3.5. One incident occurred on a bare rock face without any vegetation. The case probably involved loosening of rock blocks at a metastable state prior to failure which could be sensitive to external disturbance (see Figure 3.6). Other possible non-rain triggers for rockfall, such as leakage/burst of water mains or disturbance by animal/human activities, are not identified in the 42 cases reviewed.

(a) Rockfall on a rock cut slope near Section 4 of Hong Kong Trail, Middle Gap in 2012



(b) Rockfall on a rock cut slope at the access road leading to 76 Peak Road in 2005

Figure 3.5 Examples of Rockfalls Incidents on Bare Rock Faces Probably Triggered by Wedging Action of Tree Roots



Rockfall on a rock cut slope at Hong Kong Stadium in 2002

Figure 3.6 Rockfall on a Bare Rock Face without Vegetation

As regard the failure modes, the majority of the cases involve ravelling (viz. detachment of loosened rock fragments or blocks locally from the slope face), accounting for about 80% of the cases reviewed. The rest involve kinematic instabilities with varying types and degrees of structural control (viz. 3 planar sliding failures, 3 wedge failures and 3 toppling failures).

3.5 Incidents on Registered Man-made Slopes

Among the 38 rockfall incidents involving registered man-made slopes, almost all occurred on bare slope surface (36 out of 38) while two occurred on slopes covered with rock mesh at the time of incidents. In these two incidents with rock mesh, the rockfall debris, with failure volume of about 1.8 m^3 and 3 m^3 respectively, was fully retained by the mesh. Having compared with the present conditions, it is noted that surface protection measures have generally been provided following the incidents. Currently, more than half of the slopes with rockfall incidents on bare slope surface (24 out of 36; about 65%) have been covered with either rock mesh or hard cover at the source locations and their vicinity. As yet, no recurrent rockfall cases have been reported on these slopes subsequent to the provision of the surface protection measures.

In terms of the engineering status of the slopes, 11 (about 30%) occurred on engineered slopes[1] and the other 27 (about 70%) occurred on non-engineered slopes. The percentage of cases involving engineered slopes is apparently high. Among the 11 cases on engineered slopes, one occurred on a slope that was upgraded in 2006, with the detached rock debris fully

[1] Engineered slopes refer to those slopes with geotechnical engineering input and submissions processed by the slope safety system as conforming to the required safety standard.

retained by the rock mesh. For the other 10 cases, they all occurred on bare slope surface and these slopes were upgraded before the early 2000s prior to the promulgation of the relevant good practice in managing the risk of minor rockfall (GEO, 2002 & 2003). Further diagnosis is presented in Section 4.

4 Discussion

The rockfall incidents in Hong Kong, similar to other types of landslides, are mostly rain-induced. Rockfall incidents occurring under dry weather, which constituted about 17% of the reported rockfall incidents (i.e. roughly one out of five incidents), have been reported from time to time over the years.

The present review on the 42 rockfall incidents occurring under dry weather reveals that they are typically minor in scale (about 85% with failure volume ≤ 1 m^3 with the largest one up to 12 m^3) and mostly involved ravelling type failure (about 80%). Even the rockfalls are not sizeable, they could also be consequential, e.g. the injury case at Stanley Gap Road in 2015 (Section 2.2) and the car damage case behind No. 67 Repulse Bay Road in 2010 (Section 2.3). In addition, 'near-miss' cases are not uncommon under the dense urban setting in Hong Kong. It is noted that around half of the reviewed cases involved CTL Categories 1 and 2 slopes with a relatively high potential to give rise to severe consequences.

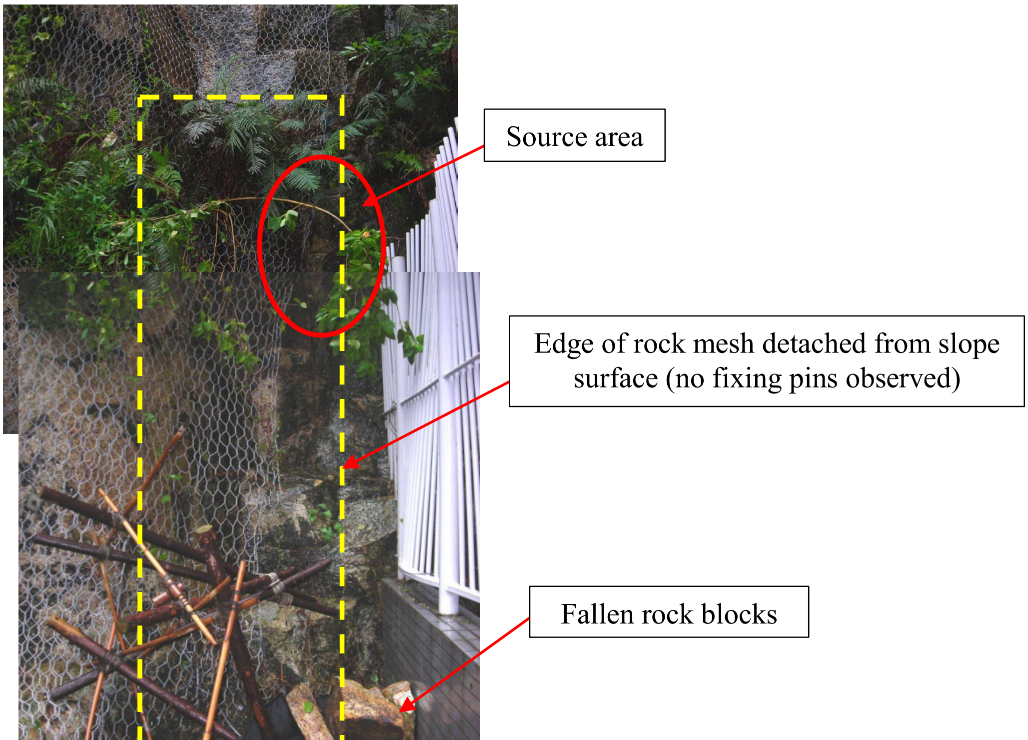
The potential hazard of root wedging action was manifested in the cases reviewed. Such action could destabilise the loose rock blocks on rock face regardless of the weather conditions. Penetration of tree roots could also lead to the opening up of rock joints (see Figure 3.5b for example) making them more susceptible to water ingress under rainfall and rendering progressive deterioration. Based on the cases reviewed, bare rock faces with tree or vegetation growth have shown to be fairly vulnerable to minor rockfalls under dry weather. Almost all cases were triggered by root wedging action on bare rock faces where the destabilisation effect on rock blocks is typically confined within the locality of the root network and in this respect the rockfalls under dry weather are generally local and shallow.

Given the trigger, there may be practical difficulties to guard against these rockfall events in design, e.g. root network may not be visible for appraisal on its impact and the development of which could change with time. Hence, the adoption of a pragmatic approach (e.g. provision of rock mesh, rockfall fence/barrier, rock trap and buffer zone) is recommended to mitigate the potential consequence induced by minor rockfalls when opportunities arise, in particular for slopes adjoining vulnerable facilities (e.g. village houses, bus stops, busy roads or footpaths) (GEO, 2020). For roadside slopes particular in urban areas where verge at the slope toe is generally absent, the provision of rock mesh on unprotected rock faces is considered to be a simple and effective means to retain minor rockfalls (Figure 4.1) therefore averting any potential severe consequences and traffic disruption. The two cases reviewed with rock mesh fully retaining the rockfall debris are good examples to showcase the protection. Apart from provision, the robustness of fixing details of rock mesh, e.g. provision of a bottom wire rope and adequate fixing pins, is important to ensure the reliability of the rock mesh protection for proper containment. Figure 4.2 shows examples of past incidents with rock blocks falling out of rock mesh which shed light on the rooms for improvement that have been incorporated in GEO (2020).

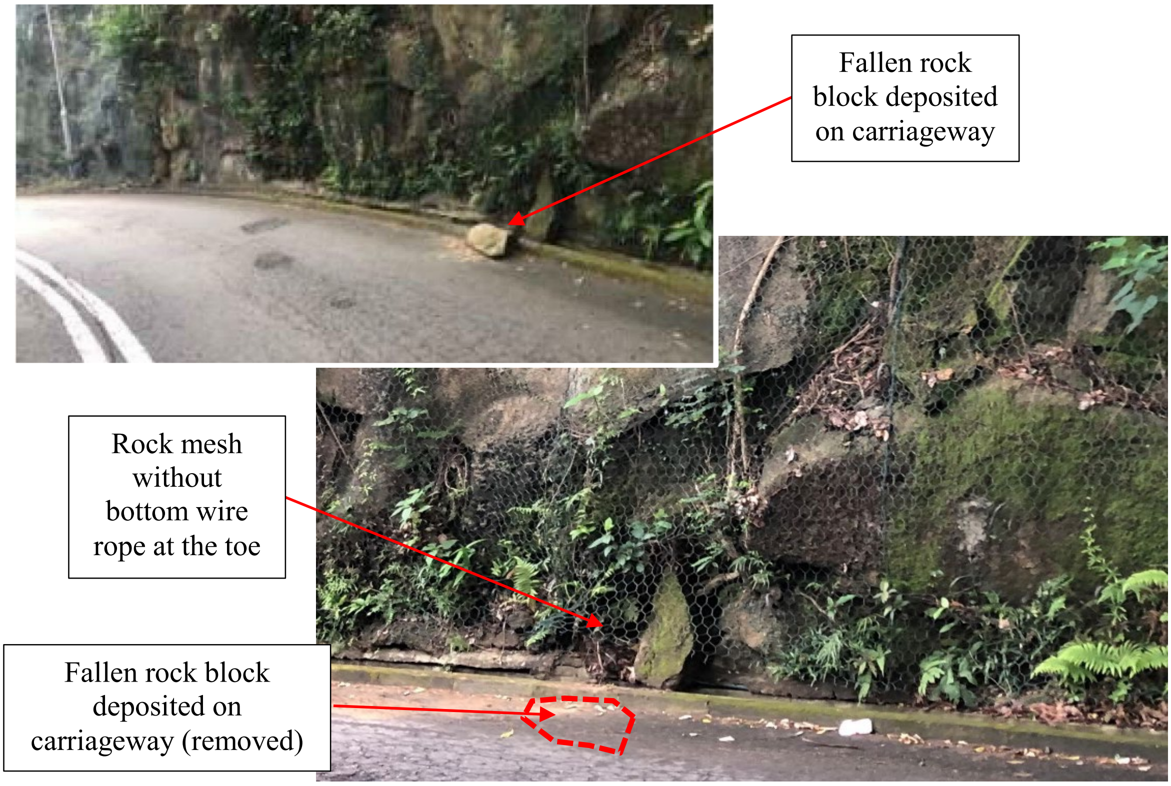
(a) Rockfall on a rock cut slope near the junction of Island Road and Repulse Bay Road in 2021

(b) Rockfall on a rock cut slope at No. 156 Kau Pui Lung Road, To Kwa Wan in 2021

Figure 4.1 Examples of Rockfall Incidents with Debris Retained by Rock Mesh



(a) Rockfall on a rock cut slope near Mansion Street, Quarry Bay in 2012 (Lee et al, 2015)



(b) Rockfall on a rock cut slope at the junction of Tai Hang Road and Mount Butler Road in 2019 (Kong et al, 2022)

Figure 4.2 Rockfall Incidents with Rock Blocks Falling out of Rock Mesh

As mentioned in Section 3.5, the percentage of cases involving engineered slopes for rockfall incidents occurring under dry weather is apparently high. Ho et al (2017) suggests that in practice, the basic and simple rock mechanics principles are generally found to be adequate for the routine problems posed by the typical range of rock slope hazards encountered locally. However, experience has shown that the application of theory to practice in managing landslide risk can sometimes be fraught with difficulty, especially in respect of minor detachments. This is reflected by a relatively high percentage of rockfall incidents involving engineered slopes. In addition, potential time-dependent changes (e.g. growth of unplanned vegetation) are also liable to be contributory factors to minor rockfalls on engineered slopes. Given the observations, the profile of some 250 landslides as identified to have occurred on engineered slopes between 2001 and 2020 has been reviewed and about 30% of which is found to have involved minor rockfalls. This reveals the potential room for reducing the associated landslide hazard from the failures of engineered rock slopes by the application of the aforesaid mitigation measures against minor rockfalls in a pragmatic manner.

Given the local influence, root wedging action alone may not be a sufficient condition to trigger large scale rock slope failures. Notwithstanding that it could increase the likelihood of large scale failures under rainfall. In the massive failure on a rock cut slope below Tsing Yi Road in 2017 (failure volume of about 1,300 m^3), root wedging action was found to have played a key contributory role in the failure. The growth of vegetation was observed to be substantial over the decade before the incident. As noted on the scar, the tree roots had penetrated to a considerable depth (> 10 m) within the rock mass which could have wedged open the rock joints promoting water ingress. This could have exacerbated the development of cleft water pressure in the jointed rock mass under the very intense rainfall, causing the failure (Wai et al, 2022a & 2022b). In light of the above, dealing with existing trees and other vegetation on bare rock face in an appropriate manner during slope upgrading and maintenance works (viz. routine and preventive slope maintenance) is important to the continued stability of rock slopes. Guidances on slope maintenance are given in GEO (2021).

From a human perspective, people's alertness or perception to landslide risk is generally low at time of dry weather and the taking of personal precautionary measures to reduce the exposure to landslide risk is normally not expected. In this connection, the landslide risk associated with rockfall events under dry weather could be elevated to some extent. This reiterates the importance to have proper provisions where possible to mitigate the relevant risk as a good practice in slope safety management.

5 Conclusions

Rockfall incidents have from time to time occurred under dry weather. These incidents could result in severe consequences exacerbated by the dense urban setting in Hong Kong. Notable incidents in recent years as presented in this report provide insight on their characteristics and shed light on the lessons learnt. From the review conducted, the risk of rockfalls under dry weather associated with root wedging action by tree or vegetation growth on rock face was manifested. As a good practice in slope safety management, the importance of proper provisions where possible to mitigate the landslide risk associated with rockfall events is highlighted.

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Appendix A

List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020

Table A1 List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020 (Sheet 1 of 5)

Casualty case - 1 no.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (Refer to Note 1)	CTL Category (Refer to Note 1)	Consequence
2015/02/1659	Stanley Gap Road near Chung Hom Kok Road	15NE-A/C425	0.05	Road	2(b)	2	Four passengers on board of a tour bus injured and tour bus damaged

'Near-miss' cases - 22 nos.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (Refer to Note 1)	CTL Category (Refer to Note 1)	Consequence
2020/07/2723	Near Shek Kip Mei MTR Station Exit B1, Shek Kip Mei	11NW-B/C39	0.063	Pedestrian Pavement; Others (Bus Shelter & MTR Station Exit)	1(b)	1	Temporary closure of an exit of Shek Kip Mei MTR station and the adjoining pedestrian pavement
2020/05/2616	Lee Wing Street, Ap Lei Chau	15NW-A/CR18	0.03	Office	1(a)	1	-
2019/08/2482	Near Rhine Terrace, Castle Peak Road, Sham Tseng	6SE-C/C18	1.8	Road	3	2	-
2015/04/1662	Behind Chung Shan Terrace No. 23 Castle Peak Road, Kwai Chung	11NW-A/C120	1	Residential building	1(a)	1	-
2015/02/1658	Opposite of Serenity Place, To Lok Road, Tsueng Kwan O	11NE-D/C141	0.3	Road	1(b)	1	One lane of To Lok Road temporarily closed
2013/10/1458	Wan Poon Path, Sai Kung	12NW-C/C507	0.6	Footpath	3	2	-
2013/07/1412	Slope to the East of Lamp Post No. V5540, Tung A, Sai Kung	Unregistered cut (4.8 m high)	0.5	Village house	1(b)	1	-

Table A1 List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020 (Sheet 2 of 5)

'Near-miss' cases - 22 nos.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (refer to Note 1)	CTL Category (refer to Note 1)	Consequence
2013/05/1283	House No. 313, Tan Kwai Tsuen, Yuen Long	6NW-C/C265	1.8	Village house	1(b)	1	-
2012/06/1185	No. 115, Repulse Bay Road	15NE-A/C74	< 0.1	Others (carpark)	3	2	-
2012/05/1178	So Kwun Wat Tsuen, Tuen Mun	6SW-C/C178	0.5	Squatter dwelling	1(b)	1	-
2011/09/1128	Behind Block C of North Point Central Building, 278-288 King's Road	11SE-A/CR160	0.2	Residential building	1(a)	1	-
2010/07/0968	Somerset, No. 67 Repulse Bay Road	15NE-A/C233	0.01	Others (carpark)	3	2	Car damaged
2009/07/0888	Feature 11NE-A/C497, Shatin Pass Road, Wong Tai Sin (Near Lamp Post AB6055)	11NE-A/C497	0.01	Road	3	2	-
2008/10/1211 (WSD/2008/10/1/K)	North Side of Ma Yau Tong Salt Water Reservoir	11NE-D/C191	0.2	Road	1(b)	1	Access road temporarily closed
2007/09/0067	42 MacDonnell Road	11SW-B/C85	0.04	Road	1(b)	1	-
2007/09/0066	The Methodist Lee Wai Lee College, Kwai Shing Circuit	7SW-C/C67	0.5	Pedestrian pavement	3	2	-
2007/05/0008	Hong Hing Road, Sau Mau Ping, Kowloon (Opposite to Sau Mau Ping Police Station)	11NE-C/C62	0.03	Road	3	2	One lane of Hong Hing Road temporarily closed
2005/11/0561	Above Tennis Court of Hiu Ming Street, Kwun Tong	11NE-D/C44	0.125	Others (tennis court)	3	2	-

Table A1 List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020 (Sheet 3 of 5)

'Near-miss' cases - 22 nos.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (refer to Note 1)	CTL Category (refer to Note 1)	Consequence
2005/07/0245	Near 12 - 14 Wong Nai Chung Gap Road	11SW-D/C373	0.1	Road	2(b)	2	-
2003/04/1007 (LandsD/KT/2003 / 04/0001)	Slope No. 11NW-A/C697, Kau Wa Keng San Tsuen	11NW-A/C697	0.5	Squatter dwelling	1(b)	1	-
2003/02/0003	Between Hong Lee Road Rest Garden and Kung Lok Road	11NE-C/FR99	< 1	Pedestrian pavement	3	2	Pedestrian pavement temporarily closed
2002/05/0034	66-68 Kennedy Road (Vehicle Access Ramp)	11SW-D/C627	0.003	Others (carpark)	3	2	-

Table A1 List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020 (Sheet 4 of 5)

Low potential consequence cases - 19 nos.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (refer to Note 1)	CTL Category (refer to Note 1)	Consequence
HyD/K/2019/12/0032	Shatin Pass Road	11NE-A/C916	0.15	Road	4	3	-
2016/10/1926	Pak Tam Road, Sai Kung	8NW-D/C9	0.15	Pedestrian pavement	4	3	Pedestrian pavement temporarily closed
2016/02/1796	Po Lam Road North, Tseung Kwan O	12NW-C/C210	0.1	Footpath	4	3	-
2013/05/1347	Shatin Pass Road	11NE-A/C351	2	Road	4	3	Shatin Pass Road (one lane road) temporarily closed
AFCD/2012/08/0015	Near Stage 4 of the Hong Kong Trail, Middle Gap	Unregistrable cut (< 3 m high)	1	Access road	4	3	Part of access road fenced off
2011/11/1141	Lugard Road near lampost 14613	Natural hillside	0.06	Access road	5	3	-
2011/09/1126	Bus Terminal at Lei Tung Estate	15NW-B/C92	0.001	Footpath	4	3	Minor footpath temporarily closed
HyD/K/2011/07/0007	Shatin Pass Road, between Lamp Poles no. AF0645 & AF0646	11NE-A/C284	3	Road	4	3	-
2010/12/1085	Harlech Road, The Peak	11SW-C/C307	0.3	Access road	4	3	-
2010/03/0937	Shau Kei Wan High Level Fresh Water Service Reservoir (S/R) No.2, Yiu Hing Road, Hong Kong	11SE-A/C348	12.5	Open area	4	3	-
ArchSD/SKW&IS-S /2010/02/0003	Hong Kong Museum of Coastal Defence	11SE-B/CR272	0.018	Others (remote area)	5	3	

Table A1 List of Rockfall Incidents Occurring under Dry Weather between 2001 and 2020 (Sheet 5 of 5)

Low potential consequence cases - 19 nos.

Incident No.	Location	Feature No. (if any)	Failure Volume (m^3)	Slope Toe Facility	Toe Facility Group (refer to Note 1)	CTL Category (refer to Note 1)	Consequence
2009/05/0868	HK Chinese Women's Club College, No. 2B Tai Cheong Street, HK (Area 13)	11SE-A/C1	1	Open area	4	3	-
2009/01/0839	Cape Collinson Path	Natural hillside	1	Access road	4	3	-
WSD/2007/8/1/HK	Adjoining Peng Chau Service Reservoir Access Road	10SE-A/C6	1.5	Footpath	5	3	-
2006/02/0572	Opposite No.8 Pak Pat Shan Road	15NE-A/C187	1	Pedestrian pavement	4	3	Pedestrian pavement temporarily closed
2005/10/0556	On slope 11SE-D/C542 at the Branch Road Leading from Cape Collinson Road to Sin Sai Wan	11SE-D/C542	0.04	Access road	4	3	-
2005/02/0075	Access Road Leading to Orient Crest (76 Peak Road)	11SW-D/C1633	0.006	Pedestrian pavement	5	3	Pedestrian pavement temporarily closed
WSD/2003/6/4/NTE	Kei Ling Ha Catchwater CH2250	8NW-C/CR101	0.5	Catchwater	4	3	-
2002/02/0006	East of Hong Kong Stadium	11SE-C/CR29	< 0.5	Access road	4	3	-

Notes:
(1) Facility group and CTL category for facilities at slope toe are classified in accordance with the GEO Technical Guidance Note No.15.
(2) 42 rockfall incidents are grouped based on their actual/potential consequences in a broad sense. The following grouping criteria are adopted:
i) casualty case - case resulting in fatality or injury.
ii) 'near-miss' case - case not resulting in casualty and occurred on the slope with toe facilities being Group 1, 2 or 3 facilities (viz. CTL Cat.1 & 2).
iii) low potential consequence case - case not resulting in casualty and occurred on the slope with toe facilities being Group 4 or 5 facilities (viz. CTL Cat.3).

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