Review of the Practice on Slope Surface Drainage Management

GEO Report No. 359

R.W.H. Lee & R.H.C. Law

Geotechnical Engineering Office
Civil Engineering and Development Department
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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 WM Cheung
Head, Geotechnical Engineering Office
December 2022

Foreword

This Technical Note presents the findings of a review of the current practice on slope drainage management and its influence on slope performance with particular reference to the lessons learnt from the relevant landslide studies and the published guidance documents. Areas that deserve attention in managing slope surface drainage at various stages of a project cycle are highlighted.

Mr Ryan W.H. Lee and Ms Rachel H.C. Law of the Landslip Preventive Measures Division 2 prepared this Technical Note under initially the supervision of Dr Dominic O.K. Lo and subsequently my supervision. Fugro (Hong Kong) Limited, the 2016 to 2018 landslide investigation consultants, provided general support. All contributions are gratefully acknowledged.

H. W. Sun
Chief Geotechnical Engineer/LPM2

Abstract

The vast majority of the landslides in Hong Kong are triggered by rainfall. Surface drainage commonly provided on man-made slopes aims to prevent surface erosion and reduce infiltration. It plays an important role to avert slope instability. However, inadequate management of surface drainage could hamper its efficiency and often results in uncontrolled surface water flow contributory to landsliding.

This Technical Note provides insights on the importance of slope surface drainage management under the dense urban settings in Hong Kong from the landslide perspective. Selected landslides involving inadequately managed surface drainage are presented to shed light on the key lessons learnt on various drainage aspects. It is noteworthy that inadequate surface drainage maintenance could exacerbate and lead to sizeable landslides even on engineered slopes. A review of landslide records over the years suggests that some landslides might have been averted had there been proper surface drainage maintenance.

With reference to the observations from landslide studies and the published guidance documents, the areas that deserve particular attention in managing the surface drainage on slopes at various stages of a project cycle, from design, construction to maintenance, are highlighted. Examples of good practice and inadequacy are presented for the ease of reference of the practitioners with a view to promoting further enhancement of the practice.

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1 Introduction

In Hong Kong, landslides are mostly rain-induced and surface water is a common cause of instability. Surface drainage is generally provided on man-made slopes to collect surface runoff from the slope and its upslope catchment. Whilst slope surface drainage serves to reduce infiltration and erosion, it could result in uncontrolled surface flow contributing to landslides if the drainage performance is not as intended. In some cases, cascading failures may result exacerbated by the dense urban settings in Hong Kong, e.g. overflow from catchwater due to blockage by landslide debris.

The association of landslides with surface water is well recognised and the understanding has been further improved through landslide studies conducted by the Geotechnical Engineering Office (GEO) over the years. General guidance of slope drainage design and detailing was promulgated in GCO (1984). The effect of some adverse environmental factors including road drainage and geometry potentially leading to uncontrolled or concentrated surface flow was emphasised by Au & Suen (1991, 2001a & 2001b). The importance of road drainage was highlighted by the fatal landslide which occurred at Shum Wan Road in 1995 (GEO, 1996) and the lessons learnt were promulgated in GEO (2017a). Hui et al (2007) presented 11 landslides that occurred between 1997 and 2003 notably involving inadequate surface drainage provisions and identified some typical inadequacies and areas requiring attention in the design and detailing of surface drainage on slopes as observed in practice. Recommendations on the requirements and technical aspects of maintenance were summarised in GEO (2018a).

The effectiveness and performance of surface drainage are principally governed by the adequacy of its provision (e.g. design and detailing) and maintenance, which are collectively referred to as 'surface drainage management' in the present context. On this subject, a review has been conducted and the pertinent findings are presented in this report. The scope of the review comprises:

(a) Diagnosis of data on landslides to provide insights on the characteristics of landslides involving inadequate slope maintenance, particularly surface drainage maintenance (Section 2),

(b) Review of the study findings and lessons learnt from selected incidents involving inadequate surface drainage management (Section 3),

(c) Consolidation of the areas deserving particular attention in slope surface drainage management at various stages of a project cycle from design, construction to maintenance (Section 4).

For item (c) above, the areas deserving particular attention in slope surface drainage management as noted from various published guidelines and references together with the lessons learnt from landslide studies have been embraced. Much related information presented in Hui et al (2007) has been incorporated in this report. Illustrative examples of good practice and inadequacy are presented for the ease of reference of the practitioners and to promote further enhancement of the practice.

2 Diagnosis of Data on Landslides

2.1 General

As part of the systematic landslide investigation (LI) programme, the LI consultants engaged by the GEO have examined every reported landslides and conducted landslide studies on selected cases. For each landslide involving registered man-made slope, the LI consultants also assess the state of maintenance of the slope surface drainage and surface protection as revealed by landslide inspections and conduct assessment to diagnose if inadequate slope maintenance is a key contributory factor to failure. Data obtained from the LI process allow a holistic assessment of the trend and characteristics of landslides.

In the current review, the assessment data as compiled by the LI consultants have been examined with a view to correlating slope performance to the adequacy of surface drainage maintenance. The pertinent review findings are presented in this Section. These provide insight on the overall state of slope maintenance (Section 2.2) and the characteristics of landslides involving inadequate slope maintenance, particularly surface drainage maintenance (Section 2.3).

2.2 Overall State of Slope Maintenance

Among the 60,000 man-made slopes registered in the Catalogue of Slopes, there is broadly an equal share of engineered and non-engineered slopes (engineered slopes refer to those slopes with geotechnical engineering input and submissions processed by the slope safety system as conforming to the required safety standards). The annual failure rates of the two groups of slopes over the years are plotted as 15-year rolling average in Figure 2.1 to smooth out the annual fluctuations primarily associated with rainfall.

As shown in the figure, the failure rates of engineered slopes are about one-seventh of those of non-engineered slopes illustrating the contribution of engineering input in landslide risk reduction. The failure rates of engineered and non-engineered slopes have both been contained which suggests a satisfactory overall state of slope maintenance in retarding deterioration. Routine maintenance, that upkeeps the condition of the prevailing surface drainage and surface protection provisions on slopes (GEO, 2018a), could have a key role to play and the trend also suggests a continuous general improvement in this respect. Apart from routine maintenance, preventive maintenance which typically entails the use of prescriptive measures to enhance the surface drainage and surface protection of slopes (GEO, 2009) has been undertaken on some of the non-engineered slopes and this also contributes to containing and to certain extent combating the risk of landslides. All in all, these observations shed light on the significant contribution of maintenance to slope performance, reaffirming its importance as one of the key elements in slope safety management.

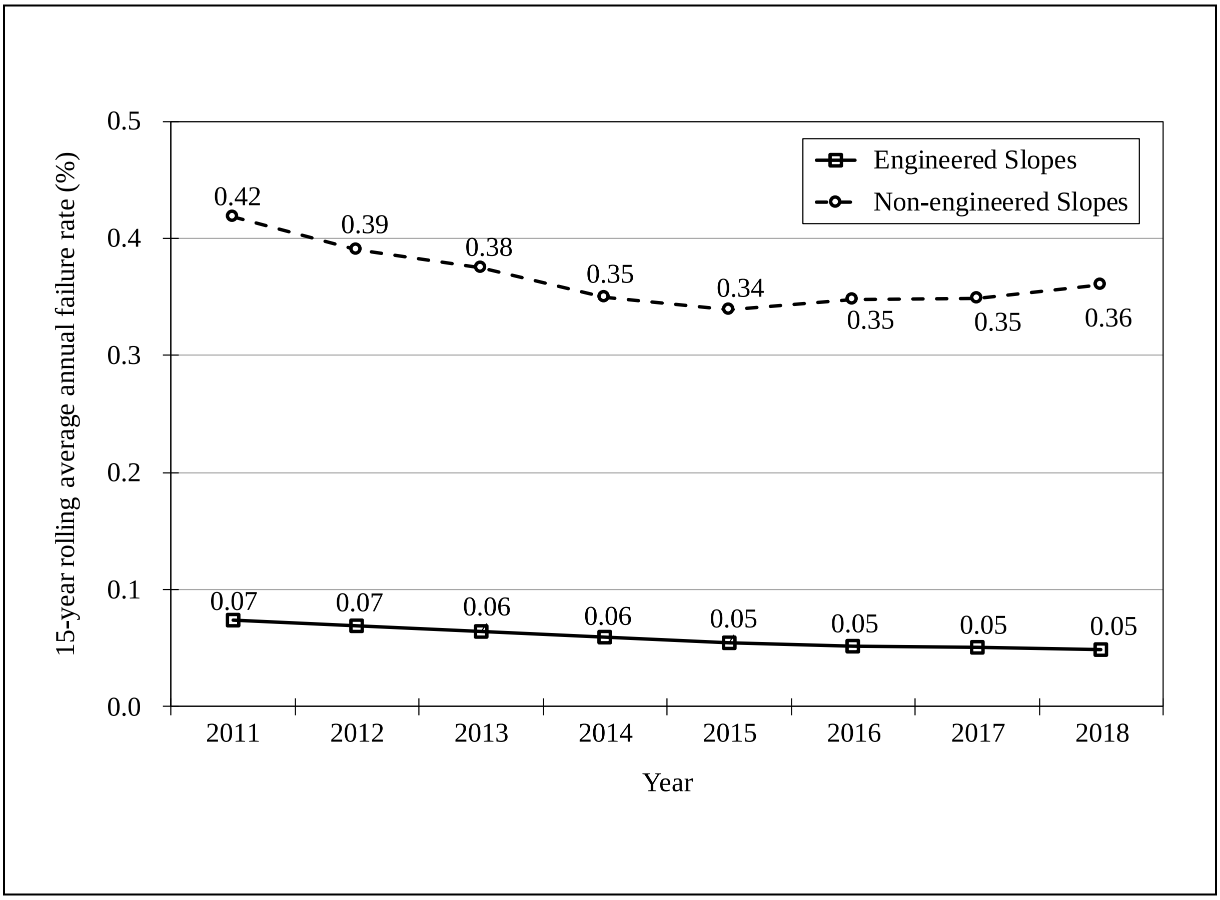


Figure 2.1 Annual Failure Rates of Registered Man-made Slopes

2.3 Characteristics of Landslides Involving Inadequate Slope Maintenance

The assessment records in diagnosing whether inadequate slope maintenance is a key contributory factor to failure for some 1,850 landslides that occurred on registered man-made slopes between 2005 and 2018 have been reviewed. The compiled statistics are presented in Table 2.1.

About 17% of the landslides were diagnosed as landslides involving inadequate slope maintenance as a key contributory factor to failure (abbreviated as ‘lack of maintenance (LoM) landslides’ hereafter), about one-third of which (viz. 5% of the landslides) involved inadequate surface drainage maintenance, typically blockage or damage of surface channels giving rise to concentrated flow and additional water ingress. The other two-third LoM landslides showed no sign of inadequate surface drainage maintenance but involved inadequately maintained surface protection. In respect of major landslides with failure volume $\geq 50\ m^3$, a lower percentage (viz. 10% of the major landslides) was diagnosed as LoM landslides, yet a high proportion of which involved inadequately maintained surface drainage. The statistics support the common observations that maintenance generally plays a more significant role in small-scale landslides (Lo et al, 1998). While major landslides are often associated with inherently adverse hydrogeological conditions and site settings, it is worth noting that inadequate surface drainage maintenance could exacerbate and lead to sizeable landslides (refer to the ex-Turret Hill Quarry landslide in Section 3.2.1).

Table 2.1 Landslides on Registered Man-made Slopes Involving Inadequate Slope Maintenance as a Key Contributory Factor to Failure between 2005 and 2018

Registered Man-made Slopes with Landslides (2005-2018)			
	All Slopes	Engineered Slopes	Non-engineered Slopes
All Landslides			
LoM landslides	17% (317 / 1,849)	38% (69 / 183)	15% (248 / 1,666)
LoM landslides involving inadequate surface drainage maintenance	5% (100 / 1,849)	21% (38 / 183)	4% (62 / 1,666)
Major Landslides (i.e. failure volume ≥ 50 m^3)			
LoM landslides	10% (14 / 134)	30% (3 / 10)	9% (11 / 124)
LoM landslides involving inadequate surface drainage maintenance	8% (11 / 134)	30% (3 / 10)	6% (8 / 124)

Notes:
(1) ‘LoM landslides’ denote landslides diagnosed as involving inadequate slope maintenance as a key contributory factor to failure.
(2) Values in brackets present derivation of the percentages, e.g. ‘(69 / 183)’ denotes 69 out of the 183 landslides on engineered slopes are diagnosed as LoM landslides.
(3) Engineering status of slope refers to that at the failed slope portion.

Table 2.1 also shows that landslides could occur on engineered slopes due to inadequate surface drainage maintenance. The percentages of LoM landslides may serve to indicate that up to 21% and 4% of the landslides on engineered slopes and non-engineered slopes respectively might have been averted had there been adequate maintenance to the surface drainage provisions. The relatively high percentage for engineered slopes may be attributed to the fact that engineered slopes generally possess a higher margin of safety against instability as the inherent instability factors, e.g. steep gradient or adverse hydrogeological settings, should have been tackled or catered for. As such, landslides on engineered slopes are more likely to be associated with inadequate maintenance. Therefore, the importance of maintenance should not be underemphasised by the engineering status of slopes.

Figure 2.2 shows the failure volume distribution of landslides on man-made slopes for different types of failure, irrespective of the slope engineering status. As compared with the overall figure, LoM landslides tend to be of smaller scale, viz. about 70% with failure volume ≤ 5 m^3. For those LoM landslides involving inadequately maintained surface drainage, about 60% and 40% are slope failures and washouts respectively. Whilst the washouts are of minor scale, the slope failures are notably larger in scale in particular some 20% are major landslides with failure volume ≥ 50 m^3 which could give rise to more significant consequences under the dense urban settings.

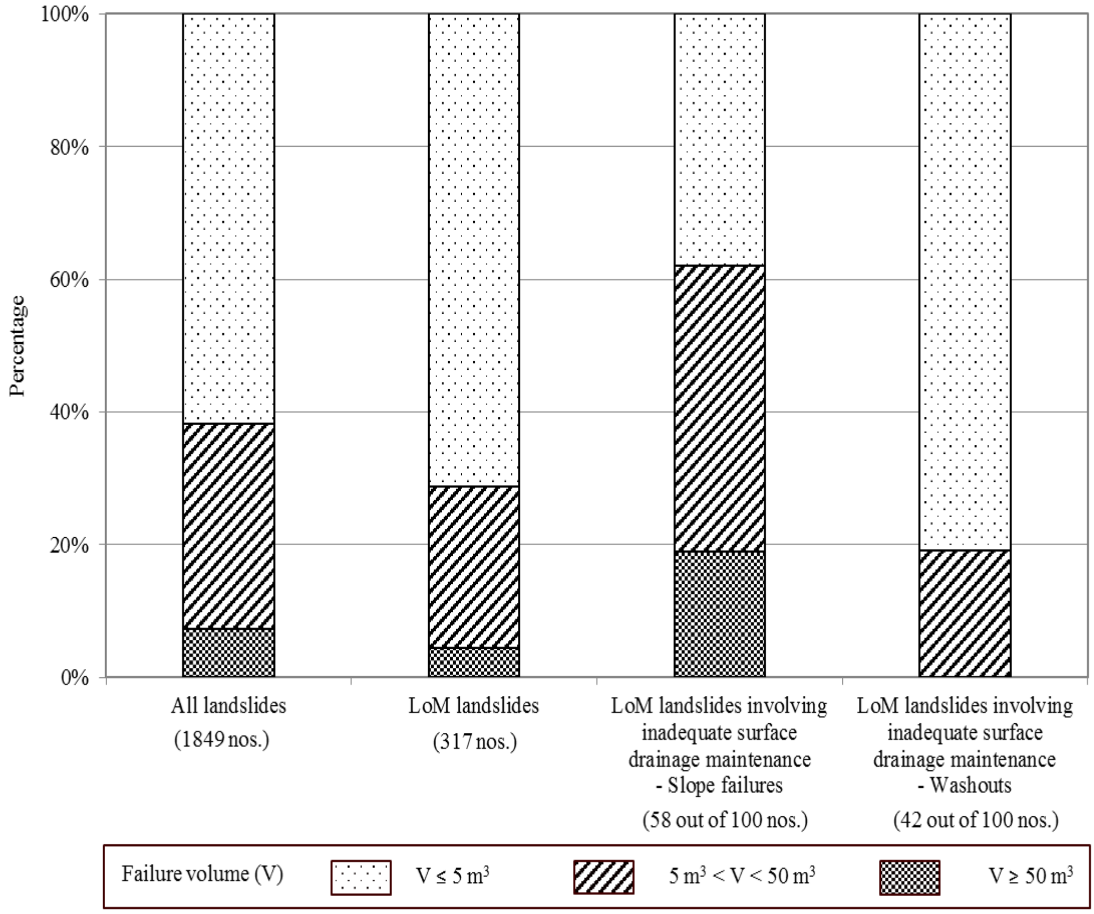


Figure 2.2 Failure Volume Distribution of Landslides on Registered Man-made Slopes between 2005 and 2018

3 Notable Incidents Involving Inadequate Surface Drainage Management

3.1 General

Apart from maintenance, drainage provision (e.g. design and detailing) is another important aspect of drainage management. In this section, case studies comprising four landslides primarily on engineered slopes and a flooding incident involving inadequate surface drainage management over the past decade are presented. These provide insight on some specific aspects of surface drainage management that are important to slope performance. Reference can be made to Hui et al (2007) for other relevant landslides in earlier years.

The sources of information referred to in this section primarily include the relevant landslide incident reports, inspection notes and records prepared or collated by the LI consultants engaged by the GEO under the systematic LI programme.

3.2 The Incidents

3.2.1 Rockslide at Ex-Turret Hill Quarry in August 2015

A major rockslide with a failure volume of about 150 m^3 occurred on a rehabilitated rock cut slope (Feature No. 7SE-A/C506) at the ex-Turret Hill Quarry, Shatin (Figure 3.1). The debris partially inundated an industrial training site at the slope toe. The rainstorm that triggered the landslide was severe with a return period of about 170 years, representing the record highest 1- to 3-hour duration rainfall experienced by the slope since the quarry rehabilitation was completed in 1994. The landslide involved the lowest 60° inclined slope batter being traversed by a shear zone and was associated with blocked and overwhelmed slope surface drainage.

According to the eye-witness, there was continuous heavy surface flow overtopping the failure location. The slope comprises ten batters and is sizeable, viz. 620 m long by 180 m high. No maintenance access was available. A post-landslide inspection over limited accessible areas observed substantial blockage of channels and notably many channel sections were buried by soil with vegetation which suggested that the channels had been silted up for some time. The heavy surface flow at the time of the landslide was likely the runoff from the upslope catchment overtopping the blocked berm channels. Besides, overflow was observed from the 750 mm stepped channel above the failure location which was overwhelmed, attributable to the aeration under rapid flow leading to bulking of the flow volume that was not accommodated in the design requirement prevailing at the time. Apart from infiltration through the slope surface, the overflow from the blocked and overwhelmed drainage rendered ponding over the unpaved berm at the crown of the scar where it was a local low point along the berm and coincided with the shear zone. The ponding promoted enhanced infiltration into the shear zone elevating the water pressure within the highly permeable fractured rock mass and consequently resulted in the landslide.

The incident highlights that inadequate drainage management in combination with other unfavourable factors, viz. adverse geological conditions and site settings, can lead to sizeable landslides. The importance of providing proper maintenance access over the slope and regular maintenance to drainage services cannot be over-emphasised. Besides, the incident serves as a reminder of the possible insufficient drainage capacity of stepped channels designed in the early days when aerated flow was not considered (GEO, 2006). Where opportunities arise such as in Engineer Inspections, necessary preventive maintenance works can be recommended to improve any deficiency in the drainage measures and maintenance access.

3.2.2 Washout below Pak Wan Street in July 2010

A major washout with a failure volume of about 150 m^3 occurred on a fill slope (Feature No. 11NW-B/FR5) at Pak Wan Street, Sham Shui Po (Figure 3.2). The incident undermined a section of pedestrian pavement and resulted in temporary closure of one lane of Pak Wan Street. The rainstorm that triggered the incident was severe with a return period of about 100 years for a 2-hour duration. At the time of the incident, upgrading works was in progress on the slope and a temporary 60° cut covered with tarpaulin sheets and shotcrete was formed at the failure location.

The slope was situated below Pak Wan Street where the road sloped towards the slope before reaching a road bend at the slope crest. At about 50 m upslope from the slope, there was a stormwater inlet at the roadside feeding the surface flow from a 4 m wide open channel into a 1 m diameter underground pipe. Immediately preceding the incident, eye-witnesses reported that there was substantial spillage at the stormwater inlet rendering Pak Wan Street becoming a conduit with significant overland flow. Although roadside gullies were present, they were overwhelmed. The adverse topographical settings, viz. road sloping towards the slope coupled with the presence of road bend, promoted the development of high-velocity flow overtopping the road kerb at the bend onto the subject fill slope and consequently resulted in the washout failure.

The permanent drainage as part of the upgrading works for the subject fill slope had not been constructed at the time of the incident. Although the drainage performance was yet to be tested, the designer had taken the opportunity to review the adequacy of the drainage design. From the review, it was noted that the original design had underestimated the catchment area for the crest channel design. Eventually, the size of crest channel was increased from 300 mm to 450 mm wide. While the drainage capacity of the channel was not to accommodate the subject severe overland flow, an upstand was incorporated in the crest channel to guard against possible overshooting of flow onto the slope in light of this incident.

The incident showcases an example of cascading failures under the dense urban settings where severe overland flow could trigger a sizeable landslide. The incident also highlights the importance of appreciating adverse topographical settings and their implications, e.g. sloping roads acting as conduits channelising high-velocity flow and possible spillage at road bends, which may warrant particular attention in slope drainage design. Where a slope could be subjected to the impact of overland flow fed by surface catchment well beyond the immediate upslope area, precautionary measures such as the provision of upstand or baffle wall at the slope crest should be recommended. Moreover, the incident serves to remind that the catchment area for surface channel design should be cautiously assessed.

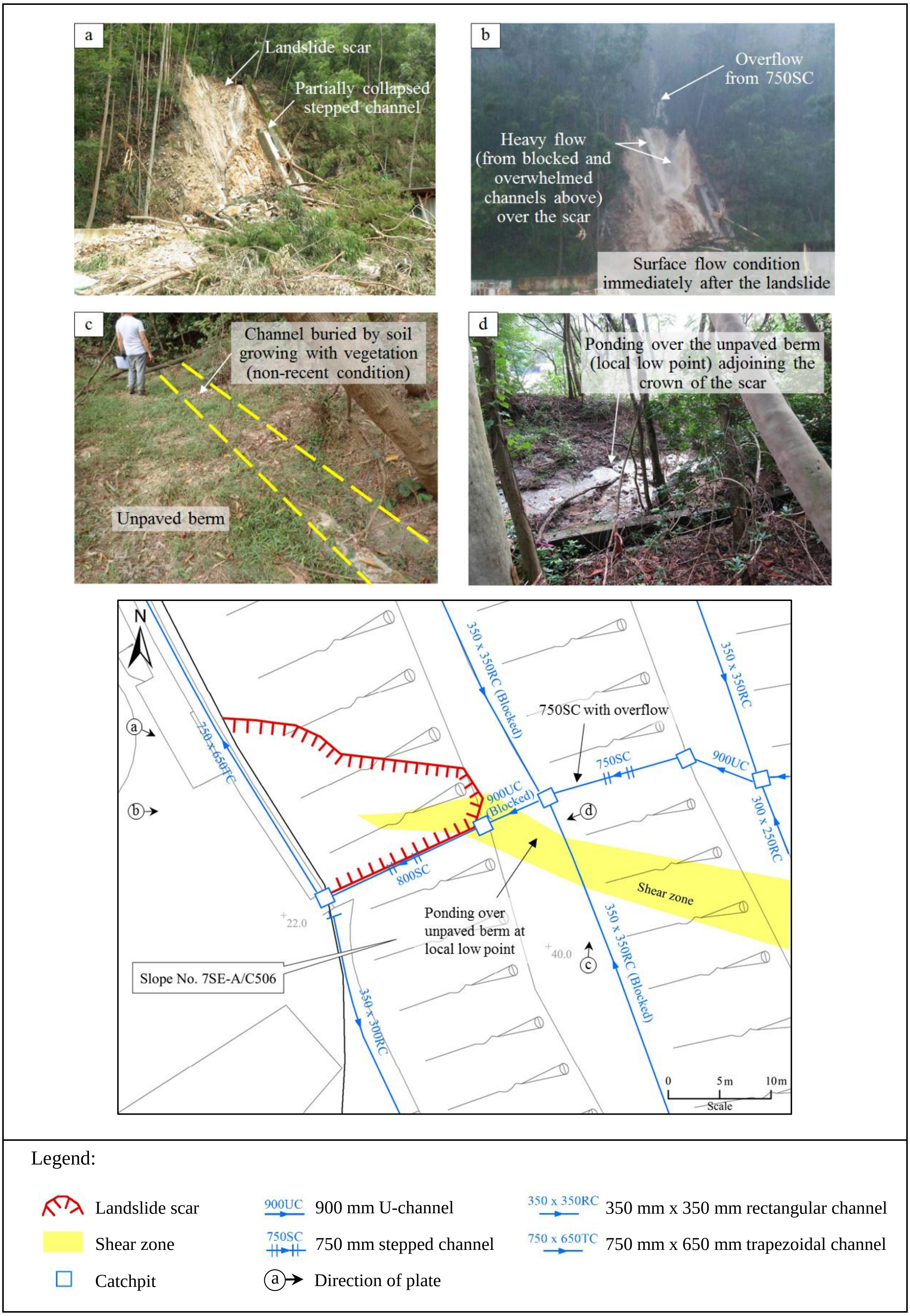


Figure 3.1 Rockslide at Ex-Turret Hill Quarry in August 2015

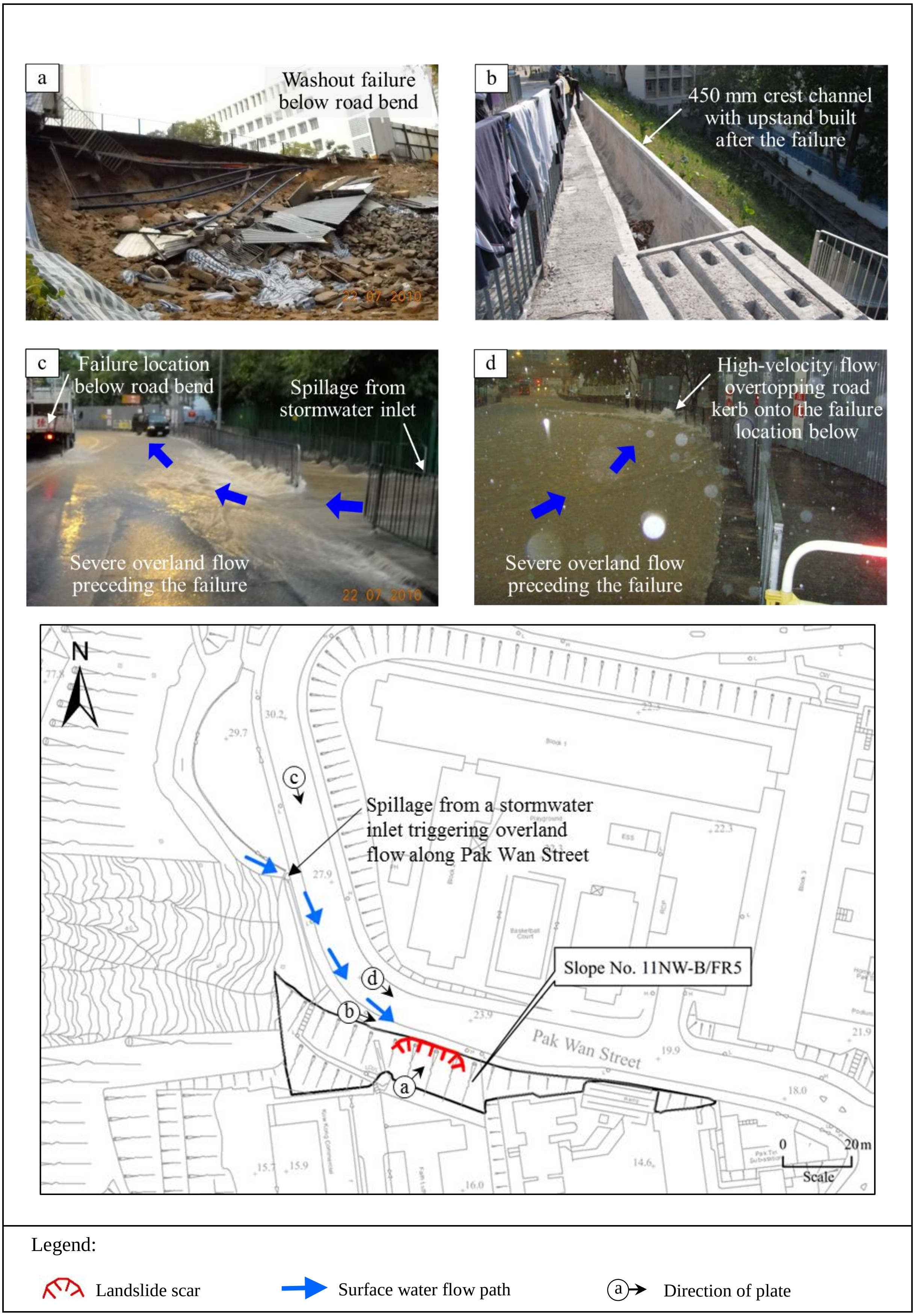


Figure 3.2 Washout below Pak Wan Street in July 2010

3.2.3 Flooding at Haven of Hope Hospital in July 2010

The incident involved overland flow resulting in flooding which inundated substantial areas within the Haven of Hope Hospital, Tseung Kwan O (Figure 3.3). It was fortunate that the incident did not result in any landslide. The rainfall preceding the incident was intense, with a return period of about 10 years. The overland flow originated from a culvert inlet that received surface flow from a 2 m wide open channel. The post-incident inspection revealed that the 300 mm high inlet opening installed with a trash grille was completely blocked by soil debris.

The provision of trash grille offers benefit in avoiding blockage of downstream drainage services and facilitating maintenance at convenient locations. However, it may also inadvertently create a spot susceptible to blockage and hence overflow, particularly at drainage inlets as in this incident. In lieu of increasing the frequency of unblocking the trash grille, the blockage-induced impact may be averted by judiciously locating and sizing the trash grille as illustrated in the drainage improvement measures implemented following this incident. As part of the measures, the trash grille originally installed at the culvert inlet was set back upstream and a series of trash grilles were installed within the open channel further upstream to increase the solid retention capacity. The top of trash grilles was set to be below the channel sidewalls to confine the flow to overtop within the channel when the grilles were blocked. Other post-incident drainage improvement measures included enlargement of the culvert inlet opening to increase the flow capacity and extension of the headwall surrounding the inlet to provide additional freeboard to attenuate the peak flow. These improvement measures judiciously provided are good references in drainage detailing which greatly enhance the flow efficiency and hence minimise the likelihood of overflow onto adjacent ground.

3.2.4 Washout at Tai Lam Correctional Institution in April 2009

A minor washout with a failure volume of about 10 m^3 occurred on a soil cut slope (Feature No. 6SW-D/C439) at Tai Lam Correctional Institution, Tuen Mun (Figure 3.4). The rainfall preceding the incident was not intense, with a return period of less than 2 years. The slope was upgraded in 2004 and the failed portion, being 50° inclined, was installed with soil nails and covered with erosion control mat and wire mesh.

Immediately above the eroded area, a 275 mm U-channel running along the slope berm received the flow from an orthogonal 300 mm stepped channel forming a T-junction. The junction imposed an abrupt change in flow direction yet no flow containment measures were provided. Overshooting of flow from the 300 mm stepped channel at the T-junction resulted in the incident. Besides, a review conducted by the LI consultants following the landslide revealed that the drainage capacity of the surface channels was underestimated in the design. In particular, the design did not account for the continuation of the surface channels from the adjoining slope. The size of actual catchment was several times larger than that considered in the design.

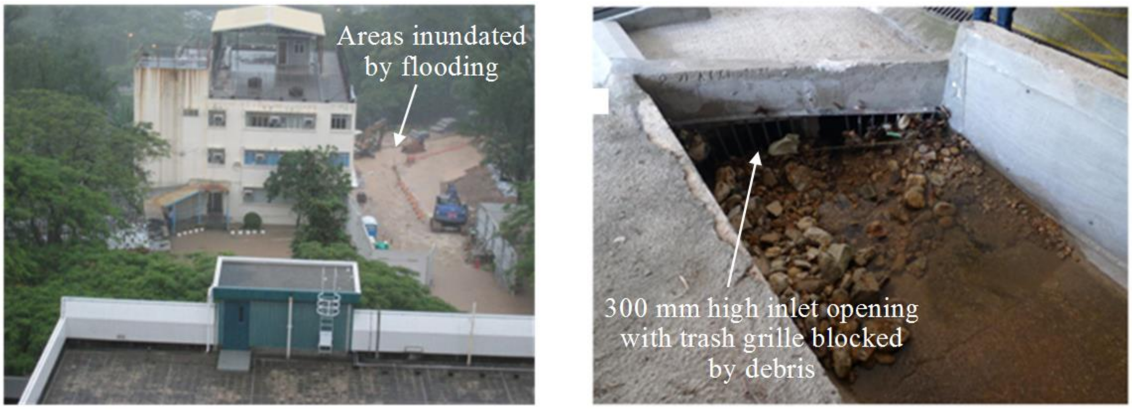
The incident highlights the importance of proper detailing at the junction of surface channels to avoid spillage due to an abrupt change in flow direction, e.g. by provision of proper containment measures such as a catchpit or a baffle wall. The size of catchment for surface channel design should be properly assessed giving due regard to any possible sources of water diverted from outside the slope. The incident also emphasises that even engineered slopes provided with robust structural support and adequate surface protection measures are liable to failure if there is deficiency in drainage detailing.

3.2.5 Washout below Robinson Road in June 2017

A minor washout with a failure volume of about 1 m^3 occurred on a soil cut slope (Feature No. 11SW-A/CR81) below Robinson Road, Mid-levels (Figure 3.5). The rainfall preceding the incident was not particularly intense, with a return period of about 5 years. The slope was upgraded in 1989 and 2013. The failure occurred on the locally unsupported portion near the slope crest, being 40° inclined, that was covered with shotcrete. At the time of the incident, construction for a school redevelopment project was in progress at the toe area of the slope. Although the scale of failure is small, it could result in notable consequence had the school been in use.

The incident involved erosion of a local strip of ground aside a 900 mm down-the-slope U-channel. The eroded area was immediately below (< 1 m) the outlet of a cross-road drain that conveyed flow largely from the hilly areas above Robinson Road. The cross-road drain had a relatively gentle fall (approx. 5°) while the 900 mm U-channel followed the slope profile with an overall gradient of about 40°. Adjoining the upper part of the eroded area, the channel section was particularly shallow, viz. a depth of 400 mm comparing with the typical depth of 600 mm at other channel sections, given the presence of two isolated steps in the channel invert. As revealed from post-landslide inspections, the shotcrete slope cover in the proximity of the eroded area and the 900 mm U-channel were both in a poor state of maintenance as evidenced by the cracking and spalling. Discharge at high velocity was observed from the cross-road drain outlet. With the sharp change in flow gradient and the reduced channel depth, the section of 900 mm U-channel concerned was susceptible to overshooting and overflow under heavy and high-velocity flow. Despite the said deficiency in drainage detailing, no instability was recorded in the past probably due to the presence of sloping aprons which might have returned any spillage back to the channel. Although the failure location was covered with hard surface, lack of maintenance and deterioration rendered it vulnerable to the washout failure.

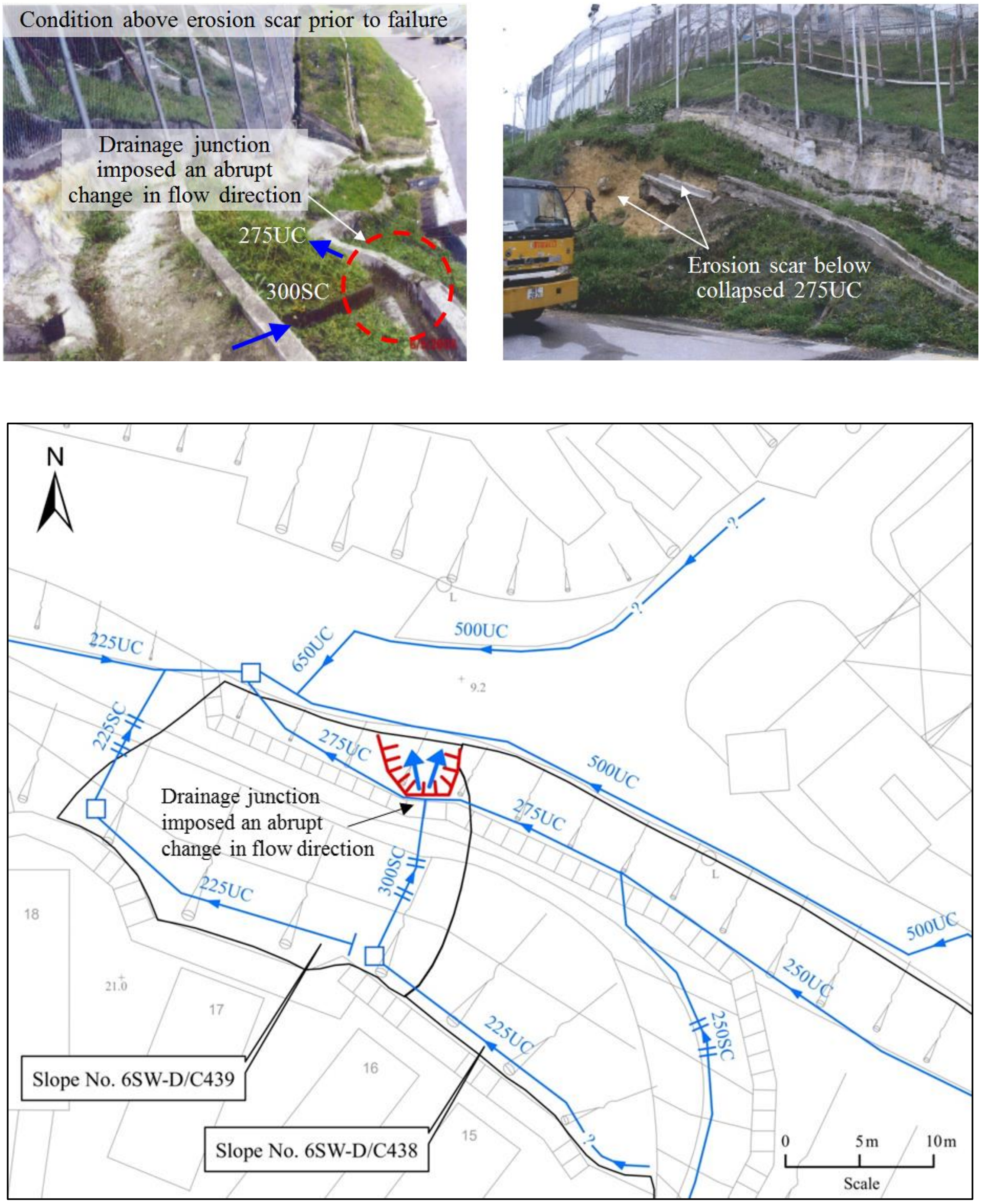
The incident highlights the importance of proper detailing at channel sections or junctions involving a sharp change in flow gradient where provision of proper containment measures, e.g. channel covers, may be warranted. Where a step is provided within a channel, it could form a spot vulnerable to overflow if the freeboard is insufficient. The case also reiterates the importance of regular slope maintenance to upkeep the condition of drainage measures as well as slope surface cover against erosion and water ingress.



Flooding Arising from Overflow at a Blocked Culvert Inlet

Post-incident Drainage Improvement Measures

Figure 3.3 Flooding at Haven of Hope Hospital in July 2010



Legend:

Landslide scar	275 mm U-channel	300 mm stepped channel
Catchpit	Probable surface water flow path	

Figure 3.4 Washout at Tai Lam Correctional Institution in April 2009

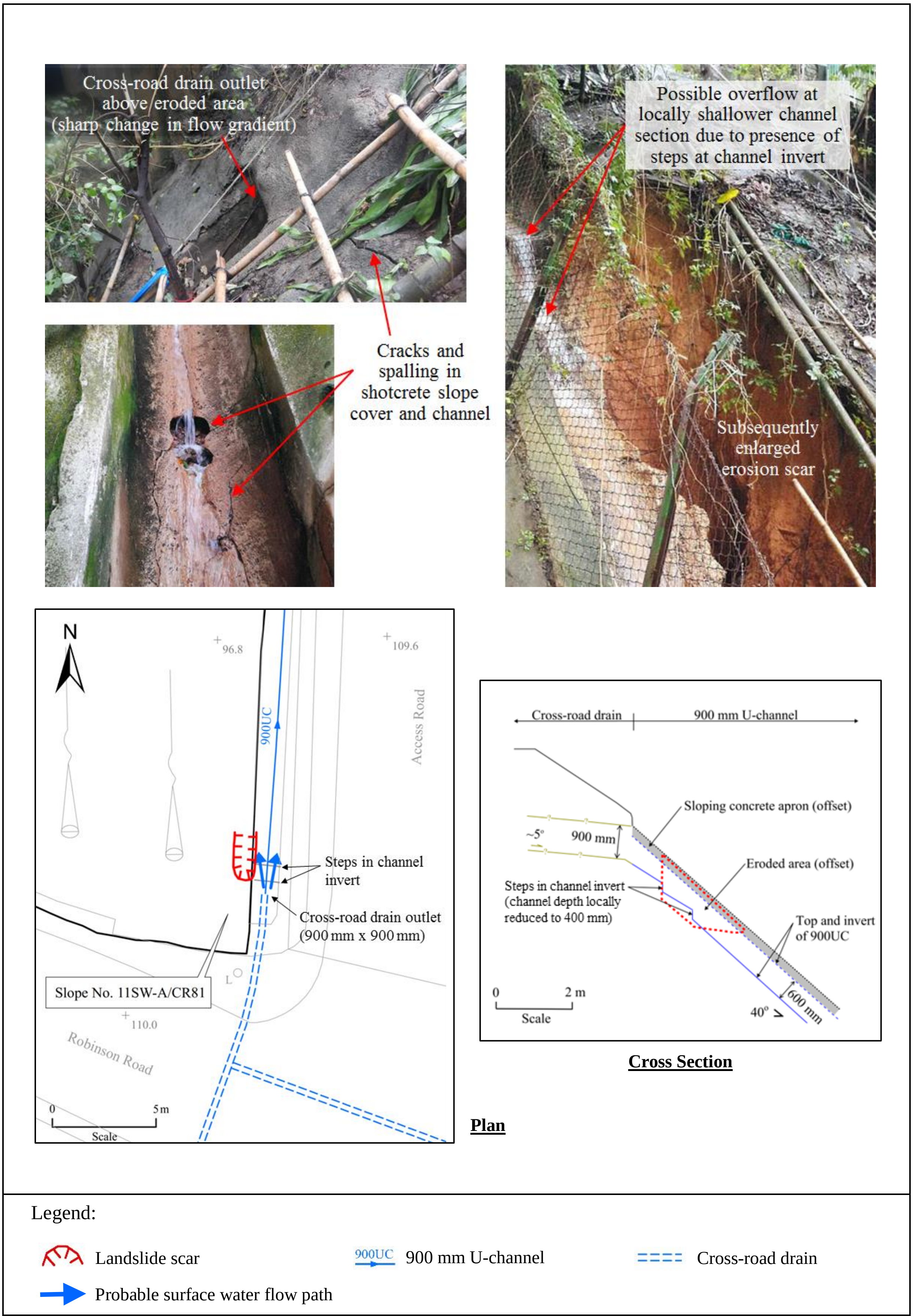


Figure 3.5 Washout below Robinson Road in June 2017

3.3 Key Lessons Learnt and Technical Considerations

The incidents presented have revealed some typical deficiencies in surface drainage management and emphasised its importance to slope performance. A brief summary of the key lessons learnt from each case is given in Appendix A. With due regard to the lessons learnt and other general observations in the slope surface drainage management practice, some technical considerations are highlighted in this Section.

Inadequate surface drainage management can render a slope more vulnerable to landsliding. Some of the incidents presented did not occur under very intense rainfall. An inadequately managed surface drainage system could be overwhelmed under even a mild rainstorm giving rise to uncontrolled surface flow which increases the chance of slope instability. Systematic study of landslides reveals that inadequate surface drainage management has also resulted in landslides on some slopes of fairly gentle gradient. Such impact could be more prominent and damaging where the site settings favour the development of velocity and momentum of the flow, e.g. overland flow channelised on a long sloping road, concentrated flow continued from hard surfaced slope batters at steep gradient or upslope depressions, etc.

Given the dense urban settings in Hong Kong, landslides could give rise to significant consequences and ‘near-miss’ cases are not uncommon. The increasing public expectation also calls for a high standard of slope safety. It is noteworthy that inadequate surface drainage management, when coupling with other adverse factors, could exacerbate and lead to sizeable landslides even on engineered slopes as illustrated in the ex-Turret Hill Quarry landslide (Section 3.2.1). Therefore, every endeavour should be made to achieve a properly managed slope drainage system through collaborative efforts by different parties at various stages of a project from design, construction to maintenance. The key elements in practice include:

(a) Proper identification and assessment of the potential sources of water, locations vulnerable to drainage problem (e.g. turbulence, overflow, spillage, etc.) and the associated impact,

(b) Allowance of sufficient redundancy and robustness in drainage design to cater for blockage and uncertainties,

(c) Adequate attention to drainage detailing,

(d) Provision to ensure the accessibility for maintenance,

(e) Adequate construction control by suitably experienced supervisory personnel, and

(f) Proper maintenance and review of drainage performance.

The drainage provisions on slopes should be tailored to suit the flow characteristics at individual sites with due regard to any adverse site settings as well as environmental conditions. Apart from broad principles, experience and judicious judgement are imperative in devising an effective drainage system. Proper detailing is crucial particularly for the purpose of flow containment. The incidents presented reveal some trivial yet critical drainage features that may not have received sufficient attention in design, e.g. locations with abrupt change in flow direction or gradient being prone to spillage. In this respect, designers should evaluate the suitability and effectiveness of relevant detailing to tackle a given drainage problem taking cognizance of the fact that slope surface drainage typically follows the slope geometry and topography which could vary considerably from one spot to another. A slope with highly irregular geometry may possess more spots vulnerable to drainage problem deserving further attention in the design.

Regular maintenance is another key aspect in surface drainage management. Slopes even with adequate prevailing drainage provisions are liable to failure without proper maintenance. Professional input is highly valued in maintenance particularly in identifying obvious deficiencies and areas for improvement. The adequacy of the drainage measures and maintenance access should be reviewed regularly, e.g. through Engineer Inspections. Environmental changes should be given due attention in the review as existing drainage measures could consequently be overwhelmed despite the apparently satisfactory performance in the past, e.g. substantially greater amount of surface runoff may be conveyed to channels due to increased paved area or modified topography at upslope. It should also be acknowledged that in some cases the surface flow regime may be too complex that could not be fully appreciated in the design. Post-construction drainage improvement measures may be implemented to enhance the flow efficiency where appropriate. Some typical examples include the construction of baffle walls or elevated channel sidewalls, enlargement of channels and modification of abrupt channel alignments.

4 Areas Deserving Attention in Slope Surface Drainage Management

4.1 General

Over the years, various technical documents have been promulgated which provides guidance pertaining to surface drainage management, e.g. GCO (1984), GEO (2004, 2006, 2009, 2014a, 2014b, 2017a, 2017b, 2018a & 2018b), DSD (2014 & 2018), Au & Suen (1991), Ho et al (2003), Hui et al (2007), Tang & Cheung (2007), etc. In this Section, the areas deserving particular attention in slope surface drainage management at various stages of a project cycle from design (Section 4.2), construction (Section 4.3) to maintenance (Section 4.4) are consolidated and highlighted based on a review of the published guidance documents and the observations and lessons learnt from landslide studies. Illustrative examples of good practice and inadequacy in particular aspects of surface drainage management are presented. These serve to provide a useful reference to practitioners with involvement in the subject and to promote further enhancement of the practice.

4.2 Design

4.2.1 Principles

The main purpose of surface drainage is to improve slope stability by reducing infiltration and erosion caused by heavy rainstorms. To facilitate the design, a surface water model should be formulated based on a comprehensive assessment of the drainage aspects of the site including the upslope catchment. With the likely flowpaths and volume of surface runoff assessed, the design should ensure adequate flow and downstream discharge capacity together with the containment of flow.

Apart from broad principles, designers should exercise judicious judgement in the design, in particular the detailing of drainage measures. In most cases, a satisfactory solution can be achieved notwithstanding the difficulties and uncertainties in the drainage aspects of the site.

4.2.2 Formulation of Surface Water Model

The formulation of a reliable surface water model essential for design is built on the proper delineation of catchment area together with a good understanding of the catchment characteristics. The site settings and related environmental factors including topographic features and pre-existing drainage measures should be mapped out. Exacerbated by the dense urban environment, any vulnerable locations which may render a slope particularly susceptible to surface water impact, see Table 4.1 for examples, should be identified and attended to. The potential adverse effect on slope stability, such as concentrated surface flow and enhanced infiltration, should be carefully considered in the design with due regard to the potential consequence.

Table 4.1 Examples of Vulnerable Locations Deserving Attention in Design

Examples of Vulnerable Locations with Possible Adverse Impact of Drainage on Slope Stability
• Slopes below local low points (e.g. the lowest point of a slope berm or platform) susceptible to concentrated flow and ponding-induced enhanced infiltration. • Slopes below or within topographic depressions with considerable flow concentration. • Slopes below platform discharge points susceptible to concentrated flow. • Slopes below a catchwater susceptible to overflow in the event of blockage (e.g. by landslide debris). • Roadside slopes subjected to the following vulnerable settings: - A long and sloping road traversing a sizeable upslope catchment susceptible to overland flow in the event of blockage of the nearby catchpits, drainage channels or road drainage components. - Road sections traversed by drainage culverts or pipes draining large catchment areas uphill, the blockage of which or the blockage of the nearby stormwater inlets could lead to severe flooding and adversely affect the stability of slopes in the adjacent area. - Sag points of roads susceptible to large runoff from adjacent road surfaces and slopes which could be discharged onto downhill slopes. - Road bends where downhill slopes could be susceptible to spillage. - Road sections with significant superelevation and large cambering (e.g. greater than 5%), which may lead to overflowing across the carriageway and onto the downhill slopes.

In determining the catchment for drainage design, attention should be paid to features or water sources even at some distance away from the site that may lead to substantial increase in the size of the catchment, e.g. roads, stream courses and catchwater discharges. With the identified water sources, all conceivable water flow pathways and the potential for concentration of surface water flow that may affect the slope should be considered in the design. A review of the past flooding/landslide reports and maintenance records, and field inspections conducted during or shortly after heavy rainstorms often reveal invaluable information on the surface flow conditions and characteristics. Local residents may be consulted for further surface flow information such as the locations of water concentration.

4.2.3 Selection of Types of Drainage Measures

The suitability of drainage measures is dependent on the hydraulic requirements, maintenance needs and in some cases the aesthetics. The areas deserving attention on these aspects are discussed in the subsequent sections. Table 4.2 presents some common types of surface drainage measures and the relevant considerations on their application.

Table 4.2 Considerations in the Selection of Surface Drainage Measures

Functions	Some Common Types of Drainage Measures and Considerations
Measures to convey water flow	• Channels for slope drainage are typically open concrete-lined U-channels whilst pipes should generally not be incorporated. • Stepped channels are commonly used to convey flow along sloping profile for energy dissipation and flow velocity reduction. Cascades are much more effective at controlling the velocity of water flow than stepped channels, and are preferred especially for channels larger than 400 mm wide. • If the gradient is very steep (say inclined at an angle greater than 65^{o}), surface channel may be replaced by a downpipe or covered up on top to avoid splashing. • For rock slopes, the excavation of rock for channel construction can be tedious. Half-round or alternative flat channels (details given in GEO (2009)) may be adopted to minimise rock excavation. Berm channels may be omitted for steep rock slopes with small catchment of the slope face.
Measures for solid retention	• If the drainage system is liable to carry considerable amount of eroded materials, it is prudent to construct a sand trap, or alternatively a sumped catchpit if space is restricted, at the slope toe or other locations convenient for inspection and maintenance. • For channels receiving flow from a stream course strewn with rocks and boulders, rock traps may be provided to prevent blockage and damage to the channels. • Trash grilles may be provided at locations convenient for maintenance, e.g. in the vicinity of drainage inlets (refer to Section 4.2.5 for judicious arrangement of trash grilles).

4.2.4 Drainage Capacity

Undersized surface channels can lead to uncontrolled overflow and splashing, hence causing water ingress and surface erosion, and posing detrimental effect on slope stability. In addition to satisfying the hydraulic requirements, designers should exercise engineering judgement to allow sufficient redundancy in the capacity of drainage services to cater for possible blockage and uncertainties. In this regard, the overall site settings, site-specific environmental factors, past performance in surface drainage, consequence of uncontrolled discharge/overflow in the event of blockage (e.g. presence of vulnerable downhill slopes) and the uncertainties involved should be considered in a holistic manner. As far as reasonably practical, crest channels where provided should be not less than 300 mm in size even if theoretical calculations suggest smaller drains may be adequate. Projected rainfall increase under the effect of climate change has been incorporated in slope drainage design (GEO, 2018b). Apart from channels, catchpits are also prone to blockage and 'oversized' catchpits may be provided to enhance the redundancy.

Water flow in stepped channels is turbulent and the freeboard should be sufficient to contain the aerated flow to avoid splashing. GEO (2006) promulgated the improved guidance on the design of stepped channels taking into account the supercritical and turbulent hydraulic flow conditions. Where a stepped channel crosses a berm, a hydraulic jump may form and proper provision against splashing should be allowed for.

Similar to channel sizing, the stipulation of channel fall should also be fairly generous where practicable to minimise the risk of blockage. The flow velocity in channels should be within an appropriate range and fulfill the minimum requirement to promote the capability of self-cleansing.

For the discharge of slope drainage (e.g. into existing drainage systems or watercourses), the implication should be considered and accounted for as part of the design. The design should aim to avoid slope or ground instability and overwhelming of the existing drainage facilities causing problems such as flooding at the downstream area. The relevant government departments should be consulted as appropriate.

4.2.5 Drainage Layout and Detailing

Proper drainage layout and detailing are both important for ensuring the intended functioning of a drainage system. As a general rule, the drainage layout over a slope particularly for a large slope should be suitably planned such that the catchment area would be partitioned into smaller portions and that surface runoff is diverted to several discharge points as far as practicable. These in effect avoid the need of overly large and deep surface channels. In respect of drainage detailing, the prime objective is to contain the flow within the drainage measures. Cautious design is warranted at locations vulnerable to turbulence, spillage, overflow, overshooting and backwater effect.

The areas deserving particular attention in the design layout and detailing of a drainage system are summarised in Tables 4.3 and 4.4 respectively. Sample photographs to illustrate the good practice and inadequacy in some of these aspects are presented in Figures 4.1 and 4.2 respectively.

Table 4.3 Areas Deserving Attention in Drainage Layout

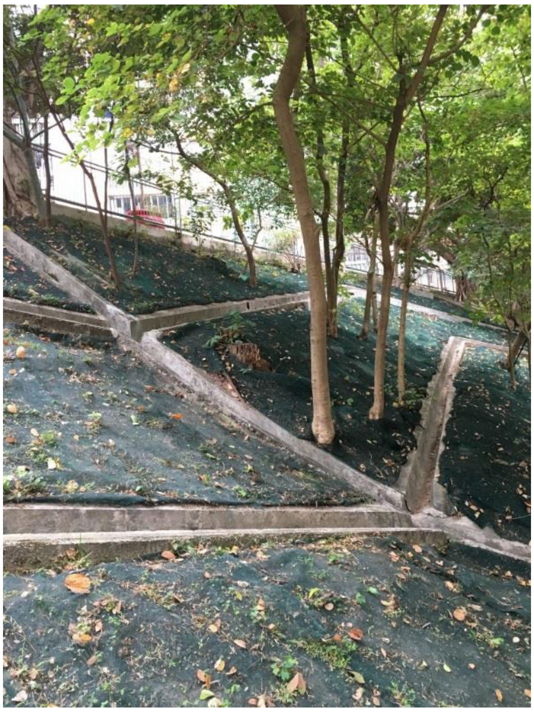
Locations	Considerations
Horizontal drainage	● Crest channels should normally be provided. However, these may not be critical for the special case of small slopes being well protected against infiltration and erosion by impermeable surface cover with minimal direct catchment uphill and no obvious depressions or low points to concentrate surface flow towards the slopes. ● Provision of intermediate channels (e.g. chevron drains; Figure 4.1(a)) may be considered on slopes susceptible to erosion or to intercept surface runoff from large catchments. ● Channels should be provided at the junction of an upper batter with an impermeable surface cover and a lower batter without such cover (Figure 4.1(b)), or where there is a significant change in slope gradient between batters (e.g. along break-in-slope at soil/rock interface) (Figure 4.1(c)), in order to minimise scouring/overshooting and water ingress into the lower batter. ● Runoff should be conveyed by the most direct route away from vulnerable areas of the slope. ● Surface overflow/runoff from road should not be diverted to slope.
Down-the-slope drainage	● For a sizeable slope, runoff should be led down the slope in several stepped channels. Where practicable, the stepped channels should be spaced at about 15 m to 20 m horizontally to facilitate rapid discharge of runoff from crest or berm channels. ● Concentrated flow or heavy discharge (e.g. stream course) should be diverted away from the slope where possible. Otherwise, it should preferably be conveyed directly down the slope (i.e. no change in the flow direction) instead of directing to peripheral channels with the attendant risk of overshooting or spillage. Any change in flow direction needed to join the discharge points should be positioned at the slope toe where practicable.
Low points	● The implication of low points over the slope crest and berms on slope stability, viz. ponding and flow concentration, should be assessed (Figure 4.2(a)). ● Adequate drainage measures (e.g. intersecting drains; Figure 4.1(d)) should be provided at low points as appropriate.
Discharge points	● Surface flow from a slope should be discharged to a proper drainage system where practicable. ● It is prudent to provide multiple discharge points to mitigate flooding and the associated ground stability impact at vulnerable areas, particularly for sizeable slopes. ● Discharge of surface runoff from a slope directly onto road surface (Figure 4.2(b)) should be avoided.

Table 4.4 Areas Deserving Attention in Drainage Detailing (Sheet 1 of 2)

Locations	Considerations
Channel sections with change in flow direction (e.g. junction /bend) or gradient (e.g. break-in-slope)	● A smooth transition of both horizontal and vertical alignment (e.g. curved profile) should be provided along channels and at channel junctions where practicable in order to improve the hydraulics of flow (Figure 4.1(e)). ● Channel bends should be of sufficient radius in consideration of the flow velocity. Alternatively, sufficient freeboard or containment measures (e.g. catchpits, baffle walls, concrete surrounds/covers or elevated channel sidewalls; Figures 4.1(f) to (i)) should be provided to contain the superelevation of the water surface and at locations where splashing/turbulence is anticipated. ● Channel sections, particularly for conveying high-velocity flow, with abrupt change in flow direction/gradient or channel junctions without suitable provisions against spillage should be avoided (Figure 4.2(c)).
Crest and toe areas of slope	● At slope crest, adequate precautionary measures against overtopping of surface runoff to the slope below (e.g. upstand wall or crest channel with upstand; Figure 4.1(j)) should be provided particularly at low points or where there is a sizeable upslope catchment. ● The potential problem of local ponding behind an upstand should be addressed. Where an upstand is provided, the gradient along the alignment of the channel should exceed 1 in 10. ● Deep catchpits may be provided at slope toe to act as a temporary buffer zone to cater for excessive flow during intense rainfall, with due regard to buildability issues and adequate access for maintenance. ● Surface outflow from discharge points at slope toe should be sufficiently slow to prevent erosion of the downslope areas. Robust surface protection (e.g. local impermeable surface cover such as stone-pitching) should be provided at the immediate downslope areas receiving the discharge to enhance the resistance to erosion (Figure 4.1(k)).
Channel connections with adjoining ground	● Adequate surface protection should be provided to the ground adjoining channels to minimise undue erosion caused by splashing. ● Aprons provided to the sides of channels should be of sufficient size (Figures 4.1(l) & 4.2(d)). ● Sloping aprons are preferred particularly for stepped channels to return any splashing to the channels (Figure 4.1(m)). ● Channel sidewalls protruding above the adjoining ground could render erosion along the sides of the channel (Figure 4.2(e)). Tops of the channel sidewalls should flush with the slope surface. ● Presence of a concrete stairway adjoining channel is liable to act as an interceptor preventing surface runoff from getting into the channel (Figure 4.2(f)).
Drainage inlets	● Suitable precautionary measures at drainage inlets are warranted (e.g. trash grilles or debris screens at inlets of major drains/culverts) if materials carried by the flow are likely to result in blockage of the downstream drainage system particularly if it is difficult to access for inspection and maintenance. ● Trash grilles or debris screens, where provided, should maintain adequate flow capacity without water backing up the channel. Proper hydraulic input in detailing should be provided in design to avoid turbulent flow and splashing.

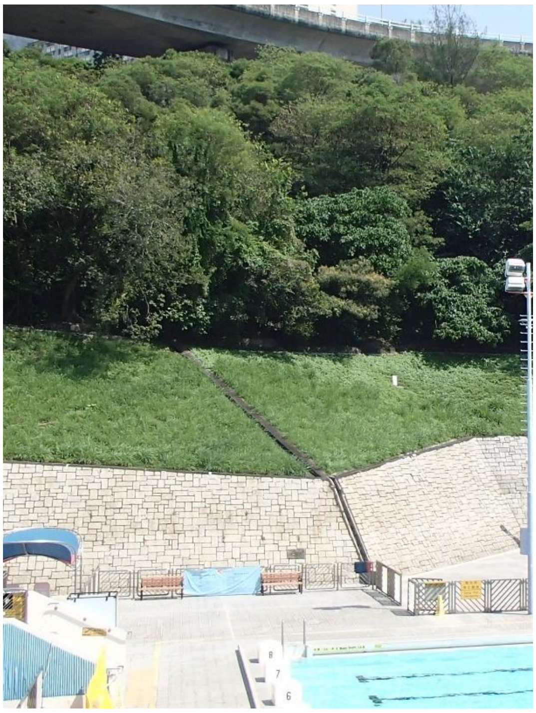
Table 4.4 Areas Deserving Attention in Drainage Detailing (Sheet 2 of 2)

Locations	Considerations
Drainage inlets (Con't)	● The flow regimes in the event of blockage of trash grilles or debris screens (e.g. overtopping) should be catered for as appropriate. Examples include setting back trash grilles or debris screens from inlet points, adopting trash grilles or debris screens with top level below channel sidewall to confine the flow to overtop within the channel (Figure 4.1(n)) and providing a series of trash grilles or debris screens at upstream to increase the solid retention capacity (Figure 4.1(o)). ● Trash grilles or debris screens in the form of a rack may be provided and suitably configured to reduce the chance of blockage (Figure 4.1(p)). These should be tailored to suit the specific drainage requirements. ● Headwalls may be built at drainage inlets providing additional freeboard to attenuate peak flow (Figure 4.1(q)).
Connections between slope and road drainage	● For roadside slopes, the detailing of slope drainage should consider the associated road drainage measures in a holistic manner. ● Particular attention should be paid to the proper detailing of the connections between cross-road drains/culverts and slope drainage, which often involve abrupt change in flow gradient/direction vulnerable to spillage (Figure 4.1(r)).
Others	● Channels should not be constructed in close proximity to trees, given the potential of damage, blockage or heave by tree root growth (Figures 4.2(g) & (h)). Any removal of tree roots could also have an attendant risk of causing an adverse effect on the tree health condition (Figure 4.2(i)). ● Large channels discharging into smaller-sized channels should be avoided. ● Drainage services discharging into channels should not form obstructions impeding the channel flow (Figure 4.2(j)). ● Adequate movement joints should be provided for channels that are liable to be subjected to post-construction differential movement, e.g. across a site with recompacted fill overlying untreated old fill in a valley setting. ● Specification of invert levels to facilitate proper construction of drainage channels should be considered. ● For a catchpit, offset between the alignments of inlet and outlet channels should be avoided and the downstream sidewall of the catchpit should be orientated normal to the direction of the outlet channel where practicable to minimise turbulence and splashing (Figure 4.2(k)). Where appropriate, containment measures may be provided to outlet channels below catchpits to minimise splashing. ● Channels into which subsurface drains discharge should be designed to prevent the subsurface drainage outlets from becoming drowned (Figure 4.2(l)). Otherwise, the system could facilitate concentrated water ingress into the groundmass through the subsurface drainage outlets. Where necessary, a separate system should be provided for the subsurface drainage outfall (Figure 4.1(s)). ● Short relief pipes may be provided below the treads of stepped channels to intercept shallow subsurface flow (Figure 4.1(t)).

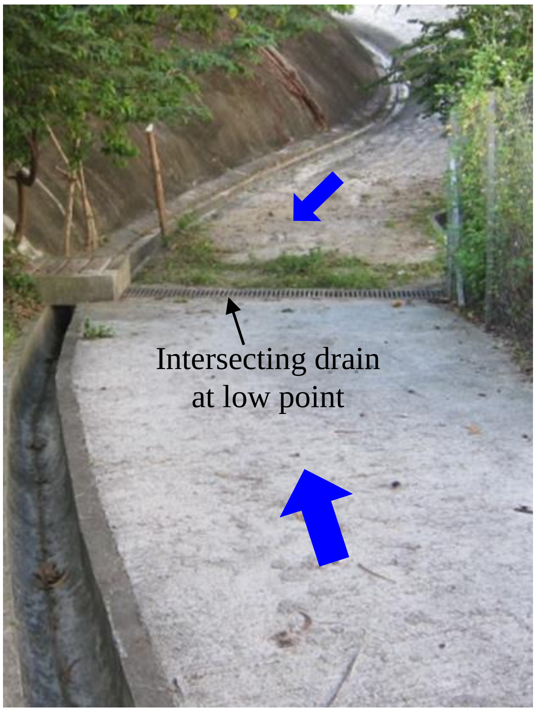


(a) Chevron Drains as Intermediate Channels on Slope Susceptible to Erosion

(b) Channel along Interface of Batters below Impermeable Surface Cover



(c) Channel along Interface of Batters with Significant Change in Gradient



(d) Intersecting Drain at Low Point

Figure 4.1 Examples of Good Practice in Drainage Layout and Detailing (Sheet 1 of 5)

(e) Smooth Curved Profile along Channel and at Channel Junction

(f) Catchpit at Channel Junction for Flow Containment

(g) Baffle Wall at Channel Junction as Additional Freeboard

(h) Concrete Surround for Channel Section below Catchpit for Flow Containment

Figure 4.1 Examples of Good Practice in Drainage Layout and Detailing (Sheet 2 of 5)

(i) Elevated Sidewalls for Channel Section below Catchpit as Additional Freeboard

(j) Crest Channel with Upstand

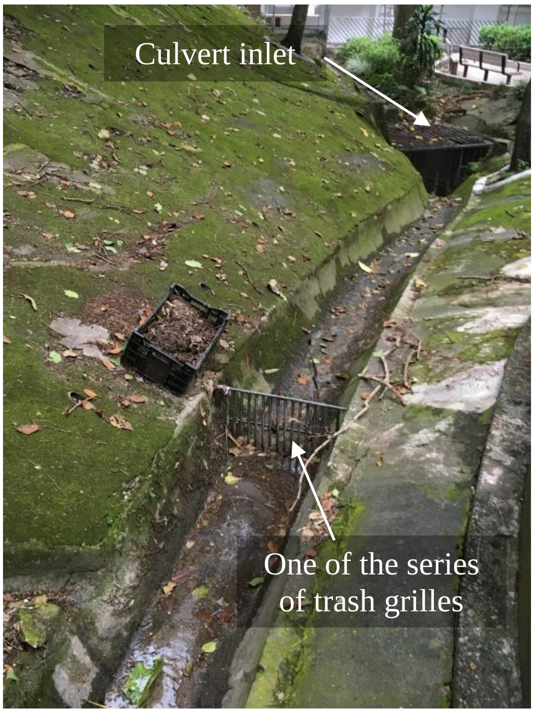
(k) Stone-Pitching below Discharge Point Enhancing the Resistance to Erosion

(l) Adequately Sized Channel Apron

Figure 4.1 Examples of Good Practice in Drainage Layout and Detailing (Sheet 3 of 5)

(m) Sloping Aprons Promoting the Return of Splashing to the Channel

(n) Judiciously Located and Sized Trash Grille to Avoid Overflow in the Event of Blockage



(o) Series of Trash Grilles at Upstream to Increase Solid Retention Capacity

(p) Trash Rack on Slope Surface Reducing the Chance of Blockage

Figure 4.1 Examples of Good Practice in Drainage Layout and Detailing (Sheet 4 of 5)

(q) Headwall at Drainage Inlet to Attenuate Peak Flow

(r) Flow Containment Measure at Connection between Road and Slope Drainage

(s) Connection of Subsurface Drainage Outfall to U-channel

(t) Stepped Channel with Short Relief Pipes to Intercept Shallow Subsurface Flow

Figure 4.1 Examples of Good Practice in Drainage Layout and Detailing (Sheet 5 of 5)

(a) Low Point with Insufficient Measure to Guard against Overflow

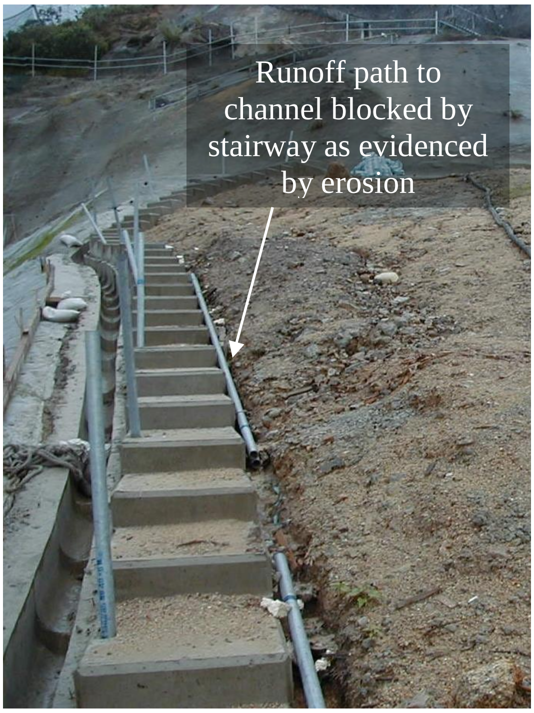
(b) Discharge of Runoff from Slope Directly onto Road Surface

(c) Channel Section with Abrupt Change in Flow Direction being Prone to Spillage

(d) Erosion Adjoining Channel with Apron of Limited Width

Figure 4.2 Examples of Inadequate Drainage Layout and Detailing (Sheet 1 of 3)

(e) Channel Sidewalls above Adjoining Ground with Erosion along the Side of Channel



(f) Concrete Stairway Preventing Surface Runoff from Getting into Channel

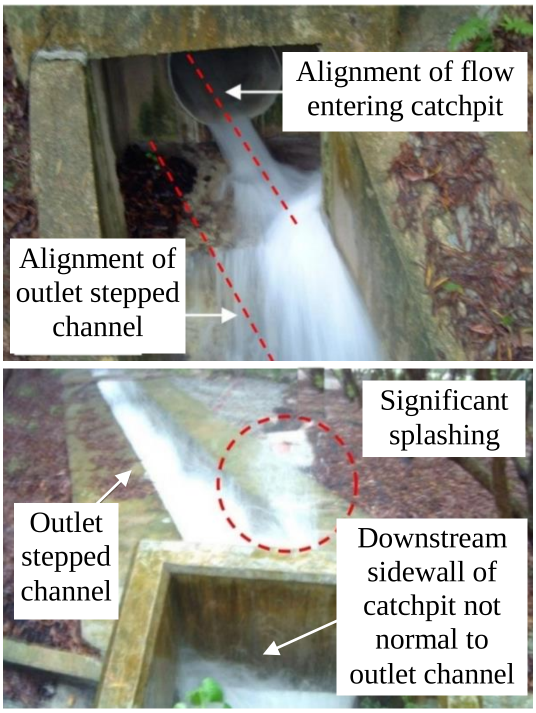
(g) Channel Damaged by the Root Growth of a Tree in Close Proximity

(h) Channel Blocked by the Root Growth of a Tree in Close Proximity

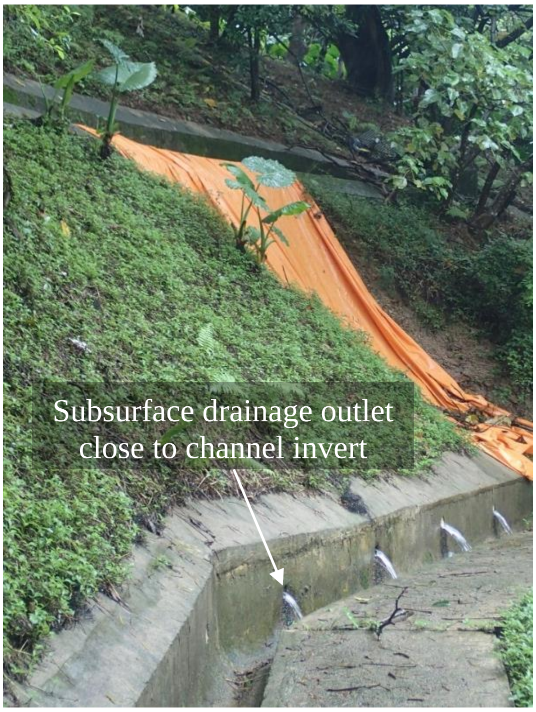
Figure 4.2 Examples of Inadequate Drainage Layout and Detailing (Sheet 2 of 3)

(i) Tree Health Condition may be Adversely Affected by the Cutting of Tree Roots for Channel Construction

(j) Drainage Service Forming Obstruction to Channel



(k) Offset between the Alignment of Flow at the Inlet and Outlet of a Catchpit Rendering Significant Splashing



(l) Subsurface Drainage Outlet Possibly Drowned Causing Concentrated Water Ingress into Groundmass

Figure 4.2 Examples of Inadequate Drainage Layout and Detailing (Sheet 3 of 3)

4.2.6 Maintenance and Aesthetics Considerations

Designers should adopt drainage measures with minimal maintenance requirements and facilitating inspection and clearance as necessary. Some examples are given below:

(a) Drainage measures that are less prone to blockage are preferred, e.g. open channels and baffle walls generally require less maintenance than covered channels and catchpits respectively. Open drainage measures are also more likely to be cleared in routine maintenance.

(b) Half-round channels may be graded to U-channels along berms in existing slopes to achieve steeper gradient and hence promote self-cleansing.

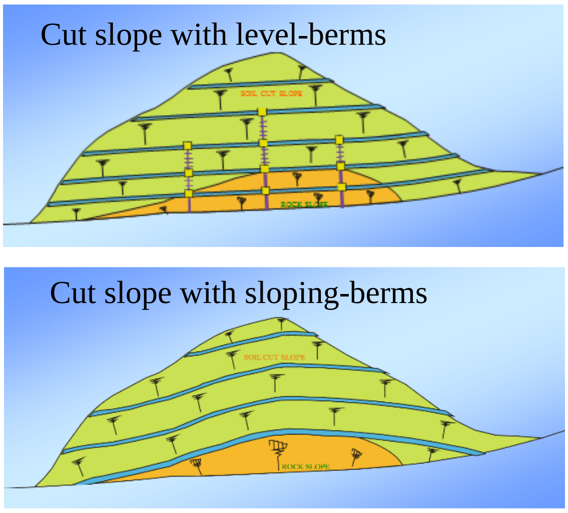
(c) Trash grilles or debris screens may be judiciously located and sized to relieve the burden on the need of frequent maintenance or otherwise their blockage could back up the water within the channel resulting in concentrated overflow (also refer to Sections 3.2.3 and 4.2.5).

The provision of proper access for inspection and maintenance should form part of the design. Some drainage measures provided may also have to be accessible for mechanical desilting, e.g. sumped catchpits and sand traps, and these should be catered for in the design.

Attention should also be paid to the design of drainage measures to minimise their visual impact yet without compromising the hydraulic efficiency. Stepped channels or downpipes on slope face are often visually intrusive. Runoff from berm channels may be directed onto peripheral down-the-slope channels thereby minimising stepped channels or downpipes on the slope face. Large stepped channels may be camouflaged using aesthetically adapted covers. Landscape architect may be consulted for advice on landscape treatment.

In the formation of new cut slopes, sloping-berms with channels (Figure 4.3) can be considered. Apart from giving a more natural slope appearance and a reduction in the volume of excavation, sloping-berms further reduce the visual impact by minimising the need to provide down-the-slope drainage on the slope face as compared with conventional level-berms design (Lam et al, 2002). Sloping-berms also provide an added benefit on surface drainage by promoting self-cleansing action and hence reducing the maintenance effort.

Schematic Diagram on Surface Drainage



In comparison, provision of down-the-slope drainage (e.g. stepped channels/downpipes and catchpits) is minimised and self-cleansing capability of berm channels is promoted by sloping-berms.

Figure 4.3 Benefits on Surface Drainage Provided by Sloping-berms

4.3 Construction

Slopes can be particularly vulnerable to failure during construction, e.g. upon the removal of vegetation or impermeable surface cover, the formation of steep temporary cuts, etc., especially in the wet season. In this respect, Sun & Tsui (2005) identified that temporary site drainage is one of the key areas that warranted attention based on a review of the notable landslides that occurred during slope works. This calls for adequate planning and supervision of the works (GEO, 2004).

The effect of surface flow during construction on slope stability and the existing drainage measures should be assessed. Sufficient and adequate temporary drainage provisions should be maintained on site at all times including during the period when the temporary drainage works are being re-routed or re-constructed. Inspections are to be undertaken particularly during and immediately after heavy rainfall to ensure the proper functioning. Temporary drainage plans should be updated in a timely manner to suit the site conditions, taking into account the change in topography and impact of adjacent works as appropriate, at various stages of the construction. Opportunities should be taken to construct part of the permanent drainage measures at an early stage of the works, e.g. crest drains and the associated discharge points, to enhance the drainage provision during construction.

Overwhelming of temporary drainage measures under severe rainfall can lead to landslides and serious consequences. In this connection, some practice enhancement has been enforced following the landslide investigation findings of two notable incidents that occurred during the course of site formation works at Sau Mau Ping in 2013 (FSWJV, 2013a & 2013b). For vulnerable site formation works, a risk assessment should be conducted and precautionary and mitigation measures should be put in place where necessary to discharge the surface water safely at different stages of construction (GEO, 2014a).

For permanent drainage provisions, design review is important throughout the construction. Observations made on the surface flow conditions during construction provide valuable information for the design review. It sometimes reveals assumptions or matters that may not have been attended to in sufficient detail during the design stage. The adequacy of the capacity, layout and detailing of the drainage provisions should be reviewed with amendments made as appropriate to suit the actual site conditions taking into account the weather conditions encountered. Attention should be given to the adequacy of the containment of flow to avoid spillage. Areas of ponding may indicate local low points which should be addressed in the drainage design to minimise the potential impact on slope stability. Early identification of any drainage problems would allow prompt rectification to be made at a lower cost and also avoid unnecessary maintenance effort.

Adequate site control by experienced supervisory personnel is of paramount importance to ensure the quality of works. Apart from the concerns on drainage and slope stability, poor construction could result in other types of problems, including breeding of mosquitoes and growth of unplanned vegetation. Examples given below highlight some issues on construction and workmanship with potential impact on the performance of a surface drainage system which deserve particular attention:

(a) Inadequate fall or uneven surface hampering the drainage performance and the self-cleansing capability of a channel,

(b) Abrupt change in flow direction or gradient susceptible to spillage, e.g. modification to suit actual site conditions (also refer to Section 4.2.5 and Figure 4.2(c)),

(c) Presence of gaps outside channel sidewalls promoting water ingress,

(d) Tops of the channel sidewalls being above the adjoining ground, possibly due to under-excavation of the channel depth, leading to erosion alongside the channel (also refer to Section 4.2.5 and Figure 4.2(e)),

(e) Channels aligned in close proximity to trees with the potential of damage, blockage or heave by tree root growth (also refer to Section 4.2.5 and Figures 4.2(g) & (h)), and

(f) Stockpiled materials or unremoved spoil from excavation altering the surface flow regime and becoming the source of materials that may be washed down rendering blockage of the drainage system.

4.4 Maintenance

The earlier Sections emphasise the importance of maintenance to slope performance. From the drainage perspective, maintenance serves to ensure the proper functioning of drainage measures by upkeeping their conditions. The standards of good practice on slope maintenance are given in GEO (2018a).

Regular maintenance inspections and works at appropriate frequency should be conducted by suitably-qualified personnel and agents/contractors respectively. Figure 4.4 shows some examples of poorly maintained drainage measures. Routine maintenance works on drainage measures typically involve clearance of blocked channels, removal of materials trapped by trash grilles/debris screens/sand traps/catchpits, repairing of cracked/damaged channels and trimming of overgrown vegetation near channels. Any removed materials should be disposed of where they cannot be washed back into the drainage systems in subsequent rainstorms. Additional maintenance effort may warrant for drainage measures that are more susceptible to blockage, e.g. trash grilles or debris screens, and those situated below hillside with ample supply of withered leaves and eroded materials during rainfall.

It is crucial to regularly appraise the drainage performance and the adequacy of the maintenance access provided (also refer to Section 3.3). Apart from blockage and deterioration, maintenance inspections should take note of any probable drainage deficiency particularly during the periodic inspections conducted by professionally-qualified engineers. Signs of drainage deficiency are often noticeable, e.g. water ponding or erosion alongside channels especially if they are clear from blockage (Figure 4.5) may reveal inadequate drainage layout/detailing or undersized channels. If the adequacy of a drainage system is in doubt, inspections may be arranged during rainstorms to ease identification of drainage problems. Maintenance inspections may also be extended to the area beyond the boundary of a slope, e.g. where sign of concentrated flow is observed diverting towards the slope. For sites involving change in surface cover, due attention should be paid to the change in surface runoff characteristics as these may be significantly altered. Apart from field observations, engineers should take opportunity to review the records of maintenance inspections and works, and any reports of recent landslides to examine if these reveal any concern on drainage. Where maintenance works are repeatedly required at a particular location such as the reinstatement of areas of serious erosion, the problems should be investigated. Drainage improvement measures may be implemented to enhance the flow efficiency where necessary.

(a) Heavily Cracked Channel

(b) Dislodged Channel Sidewall

(c) Channel Blocked by Vegetation and Withered Leaves

(d) Backing Up of Water within Blocked Channel and Catchpit

Figure 4.4 Examples of Poorly Maintained Drainage Measures

Figure 4.5   Example of Sign of Drainage Deficiency

5   Conclusions

Exacerbated by the dense urban settings in Hong Kong, inadequate surface drainage management often results in uncontrolled surface water flow contributory to landsliding. Selected incidents that occurred in recent years are presented in this report providing insight into the lessons learnt pertaining to the aspects of surface drainage management that are important to slope performance. The failure rates of slopes have been contained suggesting a satisfactory overall state of slope maintenance with continuous general improvement over time. Both routine and preventive maintenance have played an important role in containing and to certain extent combating the risk of landslides. Notwithstanding that, some isolated landslides remind us that inadequate drainage maintenance could exacerbate and lead to sizeable landslides even on engineered slopes. Some landslides might have been averted had there been proper drainage maintenance.

Adequate inputs during different stages of a project cycle, from design, construction to maintenance, are in essence important to ensure drainage measures serving the intended function. This calls for concerted efforts by the various parties responsible for slope surface drainage management. With reference to the various published guidelines and lessons learnt from landslide studies, the areas deserving particular attention in slope surface drainage management at each project stage are highlighted. Examples of good practice and inadequacy are presented for the ease of reference of the practitioners with a view to promoting further enhancement of the practice.

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Appendix A

Summary of Lessons Learnt from the Notable Incidents Involving Inadequate Surface Drainage Management

Table A1 Summary of Lessons Learnt from the Notable Incidents Involving Inadequate Surface Drainage Management (Sheet 1 of 2)

Incident Location (Year)	Type and Scale of Incident	Summary of Lessons Learnt Pertaining to Surface Drainage Management
Ex-Turret Hill Quarry (2015) [Section 3.2.1]	Rockslide (150 m^3)	● Highlight that inadequate surface drainage management in combination with other unfavourable factors, e.g. adverse geological conditions and site settings, can lead to sizeable landslides. ● Emphasise the importance of providing proper maintenance access and drainage measures over the slope as well as regular maintenance. ● Reiterate the potential need to address insufficient drainage capacity of stepped channels designed in early days when aerated flow was not considered.
Pak Wan Street (2010) [Section 3.2.2]	Washout (150 m^3)	● Highlight the importance of appreciating adverse topographical settings and their implications, e.g. sloping roads can act as conduits channelising high-velocity flow and possible spillage at road bends, which may warrant particular attention in slope drainage design. ● Shed light on possible precautionary measures such as the provision of an upstand or a baffle wall at the slope crest if a slope could be subjected to the impact of overland flow fed by surface catchment well beyond the immediate upslope area. ● Remind that the catchment area for surface channel design should be cautiously assessed.
Haven of Hope Hospital (2010) [Section 3.2.3]	Flooding	● Highlight that a trash grille may inadvertently become a spot susceptible to overflow in the event of blockage and hence warrant judicious arrangement in the provision, e.g. setting back trash grilles from inlet/outlet points, setting the top of trash grilles to be below channel sidewalls to confine the flow to overtop within the channel, and providing a series of trash grilles at upstream to increase the solid retention capacity. ● Shed light on other possible drainage improvement measures such as enlargement of drainage inlet to increase flow capacity and extension of headwall at drainage inlet to provide additional freeboard to attenuate peak flow.
Tai Lam Correctional Institution (2009) [Section 3.2.4]	Washout (10 m^3)	● Highlight the importance of proper detailing at the junction of surface channels to avoid spillage due to an abrupt change in flow direction, e.g. by provision of proper containment measures such as a catchpit or a baffle wall. ● Reiterate the importance of properly assessing the size of catchment for surface channel design giving due regard to any possible sources of water diverted from outside the slope.

Table A1 Summary of Lessons Learnt from the Notable Incidents Involving Inadequate Surface Drainage Management (Sheet 2 of 2)

Incident Location (Year)	Type and Scale of Incident	Summary of Lessons Learnt Pertaining to Surface Drainage Management
Robinson Road (2017) [Section 3.2.5]	Washout (1 m^3)	● Highlight the importance of proper detailing at channel sections or junctions involving a sharp change in flow gradient where provision of proper containment measures, e.g. channel covers, may be warranted. Where steps are provided within a channel, sufficient freeboard should be provided against overflow. ● Reiterate the importance of regular slope maintenance to upkeep the condition of drainage measures as well as slope surface cover against erosion and water ingress.

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