Detailed Study of the 3 August 2021 Landslide on the Natural Hillside above Block 3, Middleton Towers, 140 Pok Fu Lam Road

GEO Report No. 369

Fugro (Hong Kong) Limited

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

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This report was originally produced in March 2023
as GEO Landslide Study Report No. LSR 3/2022

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
Head, Geotechnical Engineering Office
February 2024

Foreward

This report presents the findings of a study of a landslide (Incident No. 2021/08/3020) which occurred on 3 August 2021 on the natural hillside located above Block 3, Middleton Towers, 140 Pok Fu Lam Road. The incident involved an open hillslope failure with a failure volume of about 110 m^3. The landslide had ruptured an 8" diameter fresh water pipe. Landslide debris had deposited over the lower portion of the hillside and within a rigid debris-resisting barrier located downslope (Feature No. 11SW-C/ND14). Middleton Towers was unaffected and no casualties were reported as a result of the landslide.

The key objectives of this study were to document the facts about the landslide, present relevant background information and establish the probable causes of the landslide. The discussion and views expressed in this report are not intended to establish the existence of any duty of law on the part of the Government of the Hong Kong Special Administrative Region (HKSARG), its employees or agents, contractors, their employees or agents, or subcontractors, or any other party. This report neither determines nor implies liability towards any particular organisation or individual except so far as necessary to achieve the said objectives.

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Y C Koo
Project Director
Fugro (Hong Kong) Limited

Agreement No. CE 28/2018 (GE)
Study of Landslides Occurring on Hong Kong Island and Outlying Islands between 2019 and 2021 - Feasibility Study

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1 Introduction

At about 6:30 a.m. on 3 August 2021, a landslide (Incident No. 2021/08/3020) occurred on the natural hillside located above Block 3, Middleton Towers, 140 Pok Fu Lam Road (Figure 1.1). The incident originated from about 50 m southwest of the Pok Fu Lam No. 1 Fresh Water Service Reservoir and about 70 m northeast of Block 3, Middleton Towers (Figures 1.1 and 1.2), with a failure volume of about 110 m^3. The incident resulted in the rupture of an 8" diameter fresh water pipe located below the landslide source area. The landslide debris had deposited over the lower portion of the natural hillside and within a rigid debris-resisting barrier (Feature No. 11SW-C/ND14) located downslope. Middleton Towers was unaffected and no casualties were reported as a result of the landslide.

Following the landslide, Fugro (Hong Kong) Limited (FHK) carried out a detailed study of the landslide for the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) under Agreement No. CE 28/2018 (GE).

The key objectives of the study were to document the facts about the landslide, present relevant background information and establish the probable causes of the landslide. This report presents the findings of the study, which comprises the following key tasks:

(a) Review of all known relevant documents relating to the site,

(b) Site inspections and field measurements at the landslide location,

(c) Aerial photograph interpretation (API),

(d) Analysis of rainfall records, and

(e) Diagnosis of the probable causes of the landslide.

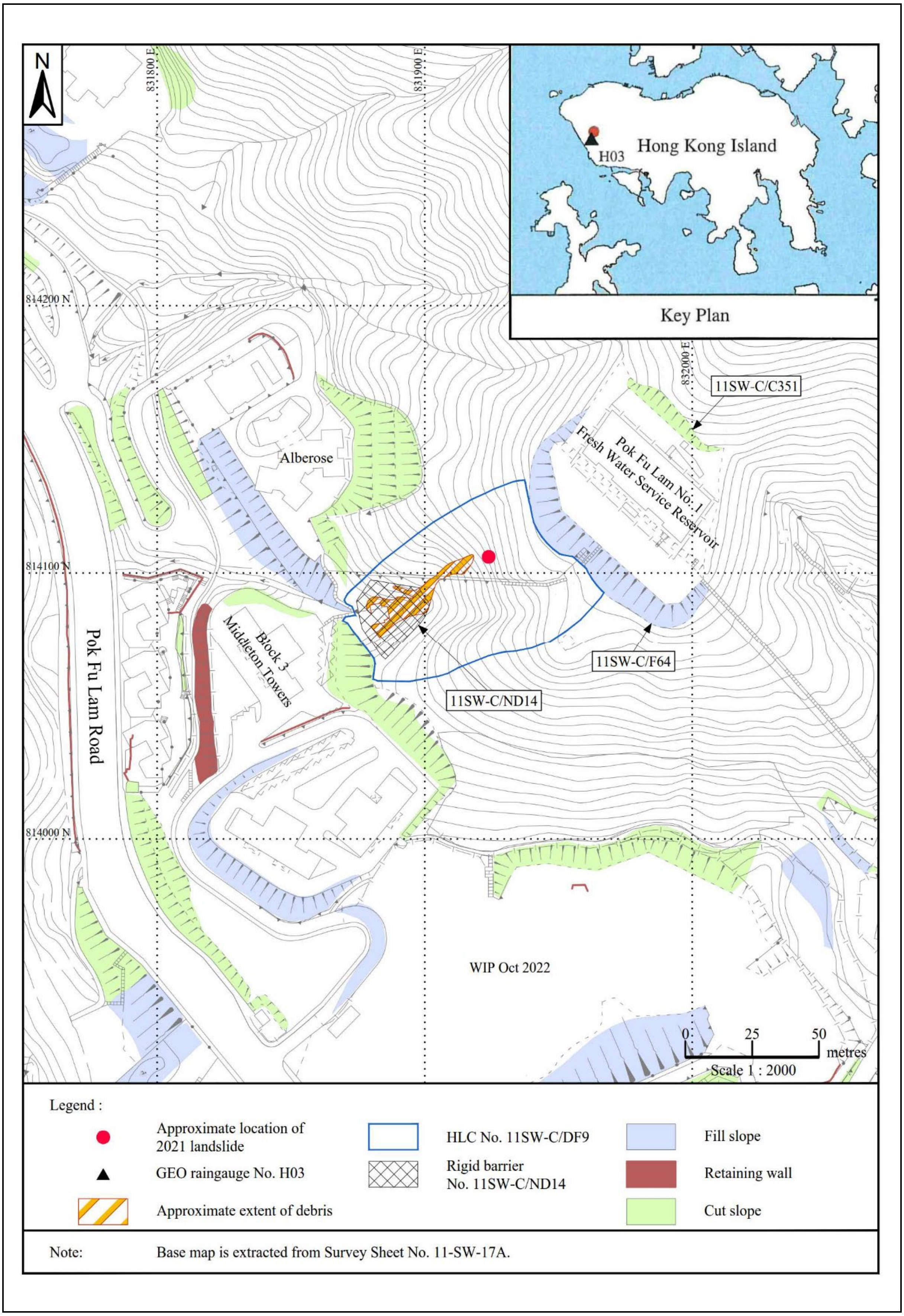
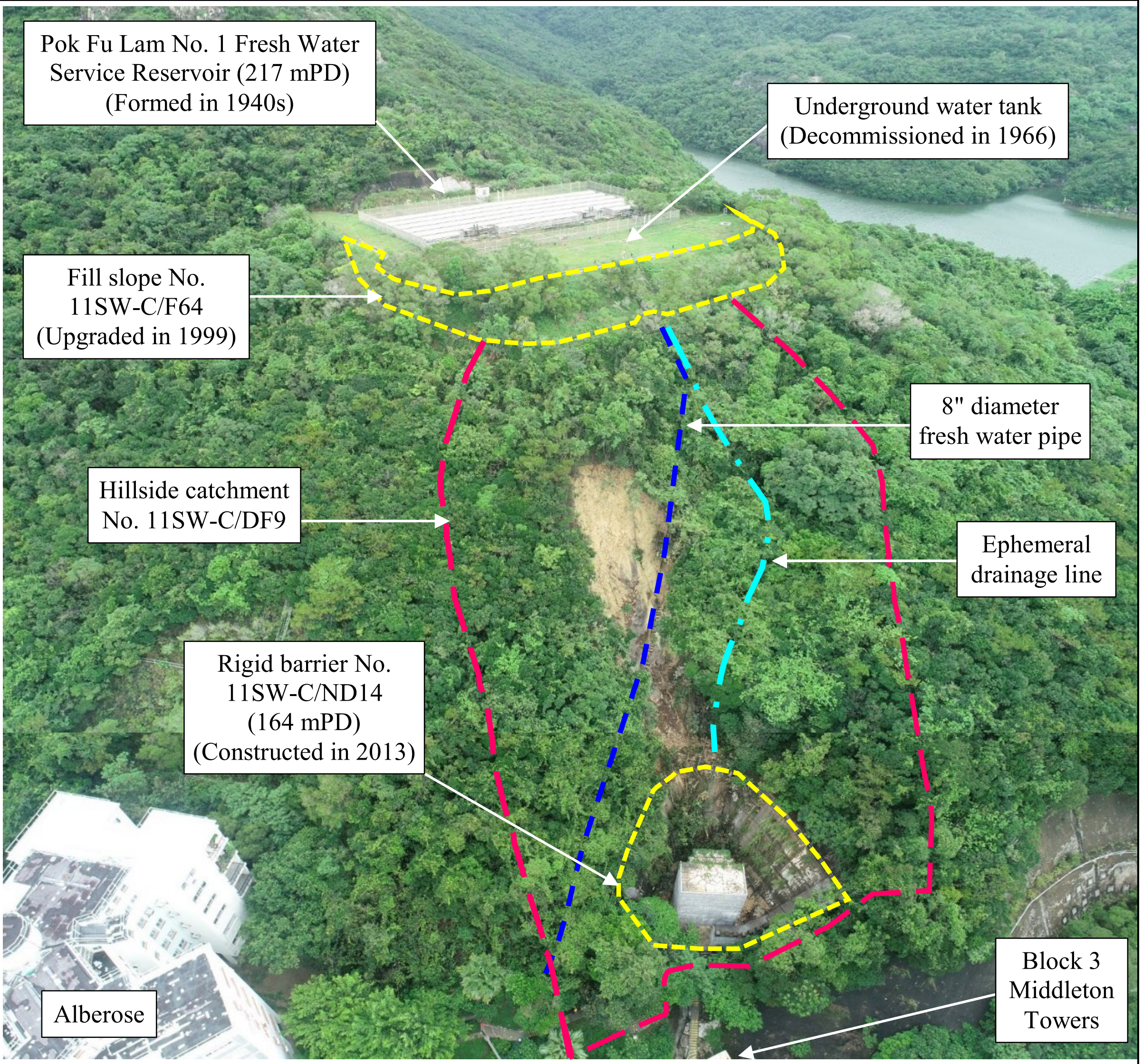


Figure 1.1 Location Plan



Note: Oblique aerial view captured by GEO.

Figure 1.2 General View of the Landslide Site (Photograph Taken on 4 August 2021)

2 The Site

2.1 Site Description

The 3 August 2021 landslide occurred on a southwest-facing natural hillside in Pok Fu Lam, Southern District of Hong Kong Island (Figure 1.1). The landslide is located on Historical Landslide Catchment (HLC) No. 11SW-C/DF9 between Pok Fu Lam No. 1 Fresh Water Service Reservoir at the crest and Block 3 of Middleton Towers, No. 140 Pok Fu Lam Road at the toe (Figure 2.1). The catchment is about 47 m high (from 164 mPD to 211 mPD) and comprises a heavily vegetated terrain sloping at 35° to 40°. The catchment is characterised by a small valley with a westerly trending ephemeral drainage line (Figures 1.2 and 2.1).

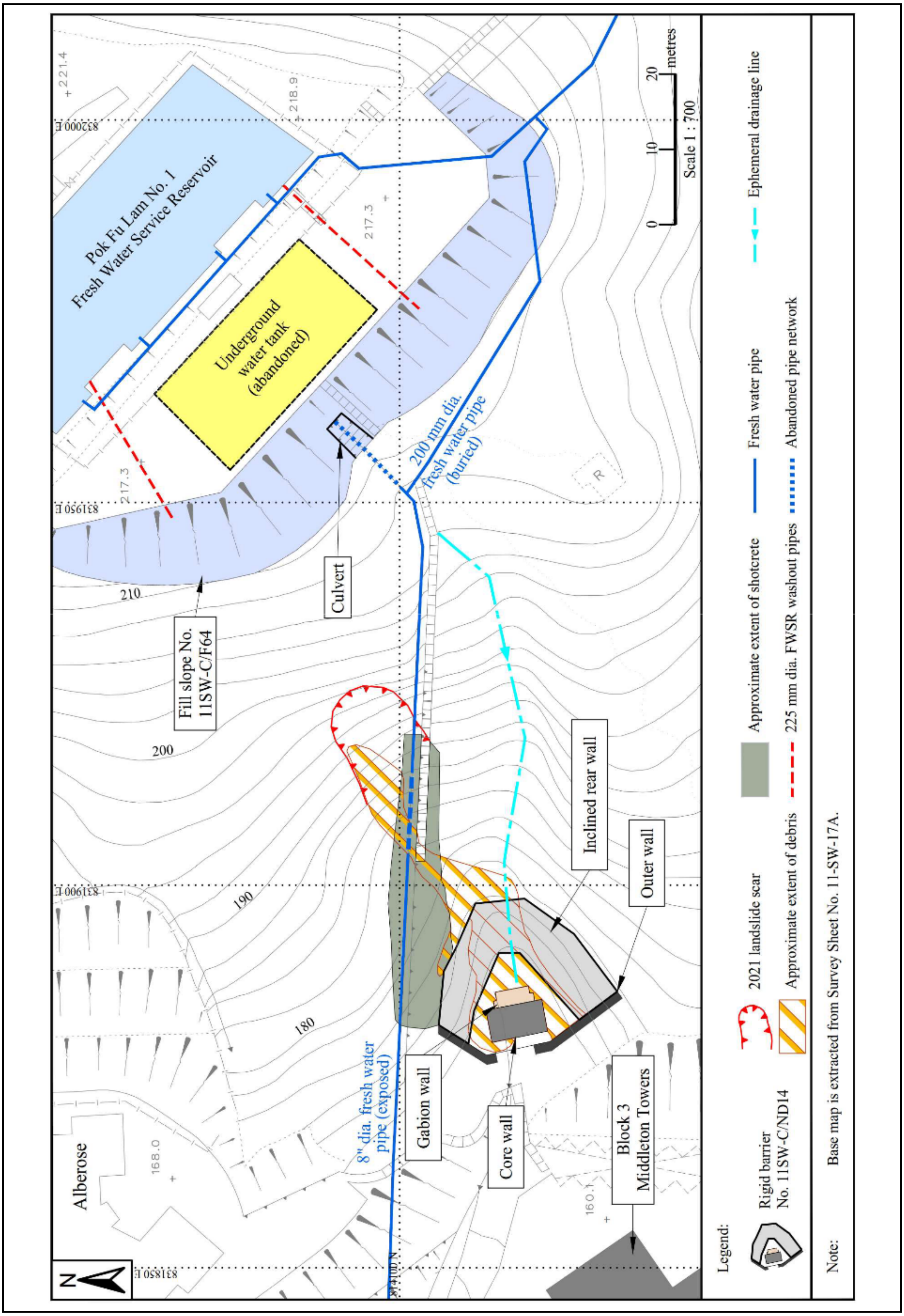


Figure 2.1 Site Plan

Rigid barrier No. 11SW-C/ND14 is located near the toe of the catchment, above the car park to the rear of Middleton Towers (see Section 2.2). At the crest of the catchment, fill slope No. 11SW-C/F64 (see Section 2.3) is located between the natural slope and the service reservoir (see Section 2.4).

An exposed 8" diameter fresh water pipe traverses the natural slope, connecting the reservoir upslope to a network of water pipes along Pok Fu Lam Road and the properties adjacent to the road. An access staircase is aligned alongside the upper section of the fresh water pipe and an area of shotcrete over the hillside is present around the lower section of the fresh water pipe.

At the toe of HLC No. 11SW-C/DF9, an access staircase provides pedestrian linkage between Middleton Towers and Alberose (No. 132 Pok Fu Lam Road) to the north.

2.2 Feature No. 11SW-C/ND14

Feature No. 11SW-C/ND14 is a reinforced concrete rigid barrier (Figure 2.2) constructed at the toe of the ephemeral drainage line within HLC No. 11SW-C/DF9 (see Section 3.4.1). The barrier comprises a central core wall, an outer wall and an inclined rear wall. The central core wall is 4 m thick and 9.5 m high with a 2 m thick and 8 m high cushioning gabion wall at the rear. The outer wall is 4 m high and 40 m long. The inclined rear wall is sloping at 50° to 60°, 45 m long and 9.5 m high and was installed with 4 rows of 7 m to 8 m long tie-back nails. A 1 m high planter is located in the containment basin, at the rear of the central core wall and the gabion wall.

The maintenance responsibility of the barrier rests with the Lands Department.

Note: Extracted from Maintenance Manual MM (H) 026/2014.

Figure 2.2 Rigid Barrier No. 11SW-C/ND14 (Photograph Taken on 20 January 2014)

2.3 Feature No. 11SW-C/F64

Feature No. 11SW-C/F64 is a 6 m high and 110 m long fill slope with an average gradient of about 30°. The slope comprises a single batter and is fully vegetated with trees, shrubs and grass (Figure 2.3). The slope has a surface drainage system which ultimately discharges into the ephemeral drainage line below the fill slope.

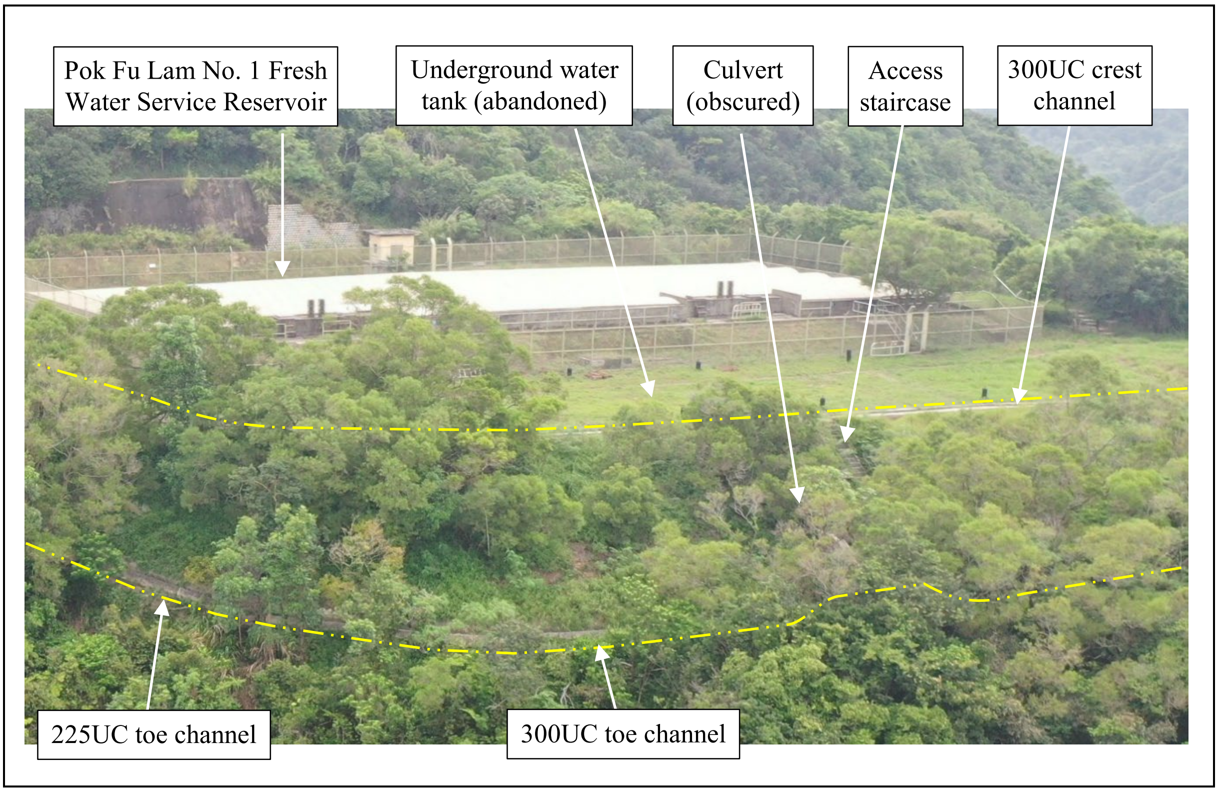


Figure 2.3 Fill Slope No. 11SW-C/F64 (Photograph Taken on 4 August 2021)

At the central area of the fill slope, two abandoned 8" diameter water pipes emerge from a culvert. An access staircase connecting the slope crest to the slope toe is located alongside the culvert.

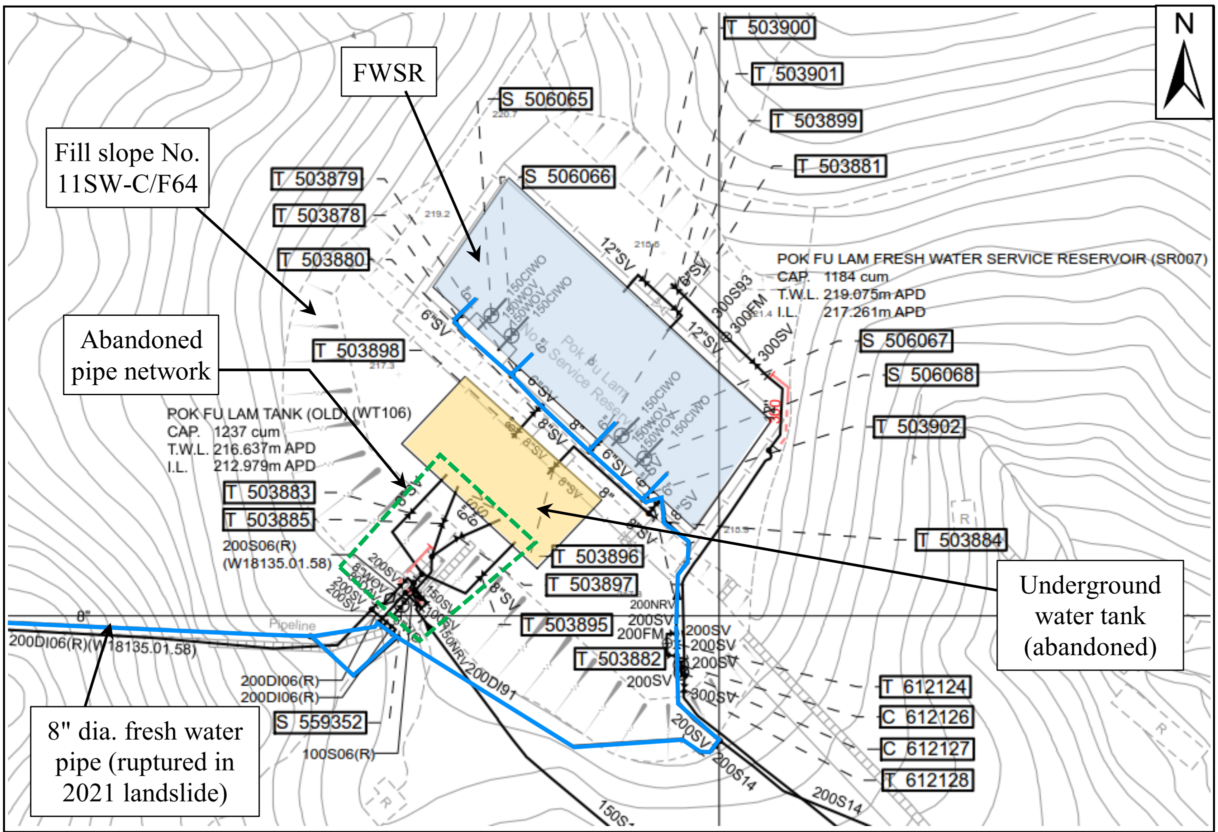
The consequence-to-life (CTL) category of the fill slope is 2 and its maintenance responsibility rests with the Water Supplies Department (WSD).

2.4 Pok Fu Lam No. 1 Fresh Water Service Reservoir

Pok Fu Lam No. 1 Fresh Water Service Reservoir (FWSR) is located about 21 m from the crest of fill slope No. 11SW-C/F64. Record drawings of the service reservoir are given in Appendix A.

Based on the available information, the reservoir facilities include an abandoned underground water tank located at about 3.5 m behind the crest of the fill slope and the FWSR (converted from the original filter beds) located at about 7 m behind the abandoned tank (Figure 1.2 and 2.4). The underground water tank and the connecting pipe network were decommissioned in 1966 following the conversion of the filter beds structure into the FWSR.

The fresh water outflow from the FWSR is discharged via a buried 200 mm diameter fresh water pipe aligned along the toe of the southern portion of fill slope No. 11SW-C/F64 (Figure 2.4). Below the culvert at the central area of the fill slope, the 200 mm diameter pipe connects to the exposed 8" diameter fresh water pipe aligned across HLC No. 11SW-C/DF9 which ruptured during the 3 August 2021 landslide (Figure 1.1).

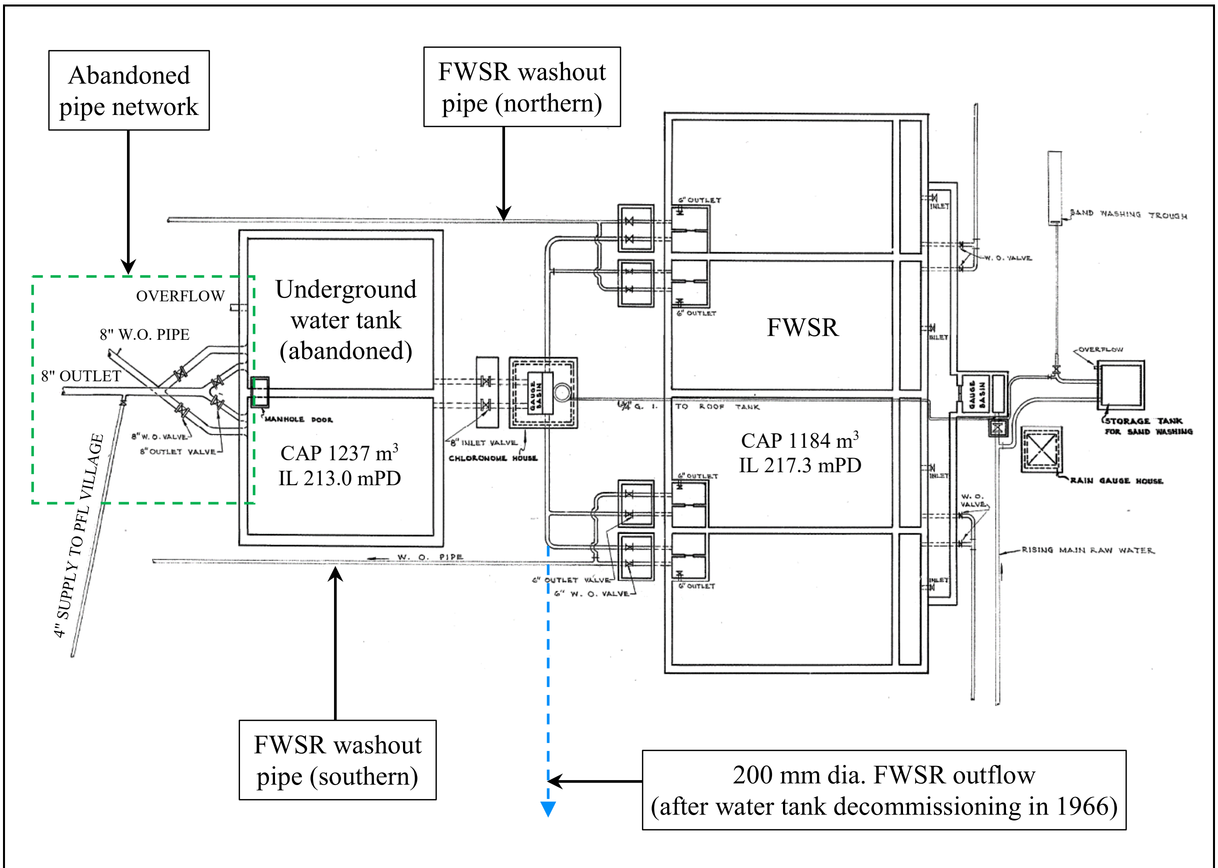


Notes: (1) Extracted from WSD Drawing No. W67880/11-SW-17A, 1998.
(2) Supply routing to the ruptured 8" diameter fresh water pipe is shown in blue.
(3) Underground water tank (yellow) and connecting pipe network (enclosed with green dashed line) were decommissioned in 1966.

Figure 2.4 Fresh Water Mains Record Plan

The FWSR is about 18 m wide by 49 m long with an invert level of 217.3 mPD (about 1.3 m below ground level). The abandoned underground water tank is about 14 m wide by 27 m long with an invert level of 213.0 mPD (about 4.3 m below ground level). The invert levels of the FWSR and abandoned tank are about 6 m and 2 m above the toe level of the fill slope (about 211 mPD) respectively.

The diagrammatic layout of the reservoir facilities is shown in Figure 2.5. The FWSR was installed with two 225 mm diameter washout pipes (size as measured during post-landslide inspections (see Section 5.3.4)). The washout pipes are mainly used for draining off water at the bottom level of the FWSR during cleaning operations. The discharge outlets of the two washout pipes are located below the crest of fill slope No. 11SW-C/F64 where they connect to the surface drainage system of the slope (Figure 2.1).



Note: Extracted from WSD Drawing No. W2134, 1954.

Figure 2.5 Diagrammatic Layout of Pok Fu Lam No. 1 Fresh Water Service Reservoir

3 Site History and Past Instabilities

3.1 General

The site history and past instabilities have been established from an interpretation of the available aerial photographs, together with a review of relevant documentary information. Detailed observations from the aerial photograph interpretation (API) covering the period between 1924 and 2019 are summarised in Appendix B, with the salient observations given in the following sections.

3.2 Site History

The hillside catchment on which the 2021 landslide occurred (HLC No. 11SW-C/DF9) is characterised by a small valley with an ephemeral drainage line. The catchment is identified as having a history of instabilities (see Section 3.3).

In 1924, Pok Fu Lam Road had already been formed while the catchment on which the 2021 landslide occurred was undeveloped. The catchment was bounded to the north and south by steep, southwest sloping rounded spurlines and a westerly trending ephemeral drainage line within the valley (Figure 3.1). The north and south facing valley sideslopes were steep, concave-planar and incised. To the east, the upper part of the catchment was characterised by a steep, west-facing planar slope. On the west-facing planar slope above the landslide location, there was a change-in-slope morphology (at about 205 mPD) from gently sloping planar-convex morphology above to steeply sloping planar-concave morphology below.

The filter beds at the current FWSR location, underground water tank and the associated cut and fill slopes (including fill slope No. 11SW-C/F64) had been formed between 1924 and 1945. Middleton Towers had been constructed at the toe of the catchment between 1963 and 1972. The exposed 8" fresh water pipe was first observed in the 1945 aerial photographs. The shotcrete area around the lower section of the pipe could not be identified in the aerial photographs, probably obscured by the dense vegetation cover.

In 1963, slope surface drainage was observed on fill slope No. 11SW-C/F64 at the locations of the northern and southern FWSR washout pipes. In 1976, a drainage pipe corresponding to the location of the discharge outlet for the northern FWSR washout pipe was observed (see Section 2.4 and Figure 2.5). In 1997, ground investigation was evident on the fill slope and this was followed by slope upgrading works between 1998 and 1999.

Construction of rigid barrier No. 11SW-C/ND14 at the toe of the catchment started in 2012 and was completed by 2013. Since then, no significant changes of the site were apparent until the occurrence of the 2021 landslide.

From 1963 onwards, much of the catchment, including the landslide location, has been masked by dense vegetation. Several phases of vegetation clearance were apparent on the fill slope between 1967 and 2018.

3.3 Past Instabilities

3.3.1 Incidents from Landslide Inventories

Past landslides recorded within HLC No. 11SW-C/DF9 on which the 2021 landslide occurred are shown in Figure 3.1. Two past landslides are identified on the catchment of which one occurred in 1976 and one in 2005 (L1 and L2 in Figure 3.1 respectively).

The 1976 landslide was registered in the Enhanced Natural Terrain Landslide Inventory (ENTLI) as recent landslide ENTLI No. 11SW-C0587E identified from the 1977 aerial photographs south of the 2021 incident. The 1976 incident was a debris flow landslide with a 15 m wide and 16 m long source area. The failure volume was estimated to be about 120 m^3 (assuming a 1.5 m depth of failure).

The 2005 landslide (Incident No. 2005/08/0369) occurred on the steeply inclined (about 40° to 45°) southern flank of the catchment. The landslide was studied by Fugro Scott Wilson Joint Venture under Agreement No. CE 29/2003 (GE) (FSWJV, 2006). The landslide study has indicated that it was an open hillslope failure measuring 13 m wide by 20 m long by 2.5 m deep with an estimated volume of about 200 m^3 (Figure 3.2). The landslide appeared to have occurred within completely decomposed tuff (CDT) overlain by a thin layer of residual soil and/or colluvium. The debris had deposited into the ephemeral drainage line and over-spilled onto the platform area of Middleton Towers together with outwash from the uncontrolled overflow of storm water. No casualties or notable damage were reported as a result of the landslide. The trigger of the landslide was attributed to heavy rainfall. The presence of a relict concave depression in the locality might have previously affected the area of the 2005 landslide.

3.3.2 Evidence of Other Past Instabilities and Erosion

The detailed API carried out as part of the current study has also revealed signs of other possible past instabilities on HLC No. 11SW-C/DF9 apart from those mentioned in Section 3.3.1. Observations of other possible past instabilities are annotated in Figure 3.1 (E1 to E12).

In 1945, two small areas of reflectance (E1) were visible upslope of the fresh water pipe and these might be associated with anthropogenic disturbance, shallow erosion and/or instability.

In 1963, a change-in-slope (E2) identified above the location of the 2021 landslide might be indicative of possible past movement and the presence of ground conditions susceptible to instability. Two concave depressions (E3) on the southern flank of the drainage line represent possible relict instabilities. The depressions are generally at the locations of the subsequent 1976 and 2005 landslides. Relict instability might have resulted in a local break-in-slope and an oversteepening predisposed to further failure.

Various observations of possible erosion, anthropogenic or faunal disturbance were evident on the catchment throughout the review period. In 1977, some areas of erosion between fill slope No. 11SW-C/F64 and the 2021 landslide location were evident (E4). Three small areas of possible disturbance/erosion were observed along the toe of the northern portion of the fill slope in 1987 (E5 to E7), with the central one (E6) located above the 2021 landslide location. In 1990, disturbance at similar locations was again evident with the areas enlarged (E5, E6 & E8) and again in 1992 (E7 & E8). Disturbance at the central one of these areas (E6) was also observed in 2000 together with a break-in-slope (E9), possibly indicative of instability above the 2021 landslide location.

In 2008, some bare area was observed on the fill slope (E10), possibly associated with erosion or minor instability. In 2011, an area of vegetation loss (E11) was apparent to the southeast of the 2021 landslide location, just above the ephemeral drainage line, possibly associated with erosion or instability. Some bare area was also evident on the fill slope (E12) in 2013, possibly associated with minor erosion. In 2017, a small area of vegetation loss (E13) was present on the natural slope within the 2021 landslide location and such area expanded upslope in 2018, possibly associated with erosion or minor instability.

3.4 Relevant Previous Studies

3.4.1 Stage 3(H) Study

The hillside catchment on which the 2021 landslide occurred, HLC No. 11SW-C/DF9, was assessed by AECOM Asia Co. Ltd. as part of Study Area No. 11SW-C/SA3 in Agreement No. CE 15/2009 (GE) under the Landslip Prevention and Mitigation Programme (LPMitP). A Stage 3(H) Study Report (AECOM, 2011) was completed in July 2011 under this Agreement.

The Stage 3(H) Study has concluded that the catchment was prone to natural terrain hazards comprising open hillslope failure (OHF), channelised debris flow (CDF) and boulder fall. The study identified that the OHF could initiate from an oversteepened slope section predominantly comprising saprolite which could then become channelised within the drainage line further down the slope.

The design adopted a worst credible event (WCE) of 485 m^3 (400 m^3 source volume plus 85 m^3 entrainment volume). The source volume was based on the 16 m wide 19 m long topographical depression in the upper part of the catchment with an estimated depth of 2 m. The debris mobility under OHF was modelled using the frictional rheological model with an apparent friction angle of 20° and the debris mobility under CDF was modelled using the Voellmy rheological model with an apparent friction angle of 11.3° and turbulence coefficient of 500 m/s^2. The 2D debris mobility analysis showed that the debris could reach the downslope facilities. In light of the study findings, a rigid barrier (Feature No. 11SW-C/ND14) with retention capacity of 535 m^3 was constructed at the toe of the catchment to mitigate the hazards. Construction of the rigid barrier was completed in January 2013. A general description of the barrier is given in Section 2.2 and further details are recorded in the Maintenance Manual (AECOM, 2014).

3.4.2 Stage 3 Study

Fill slope No. 11SW-C/F64 was previously studied by FMA Consultants (a joint venture of Fugro (HK) Ltd., Mouchel Asia Ltd. and Atkins China Ltd.) in Agreement No. CE 13/96 under the Landslip Preventive Measures (LPM) Programme. A Stage 3 Study Report was completed in February 1998 (FMA, 1998).

The Stage 3 Study has concluded that the subject feature did not have an adequate factor of safety and that the loosely compacted fill was susceptible to flowslide. Recompaction and replacement of the loose surface fill (to a minimum of 3 m thick) was proposed to upgrade the slope to a minimum factor of safety of 1.2. Upgrading works comprising provision of compacted cement-stabilised fill, recompacted soil fill, surface drainage measures and vegetation surface cover were completed in July 1999. Details of the slope upgrading works are recorded in the Maintenance Manual (FMA, 2000).

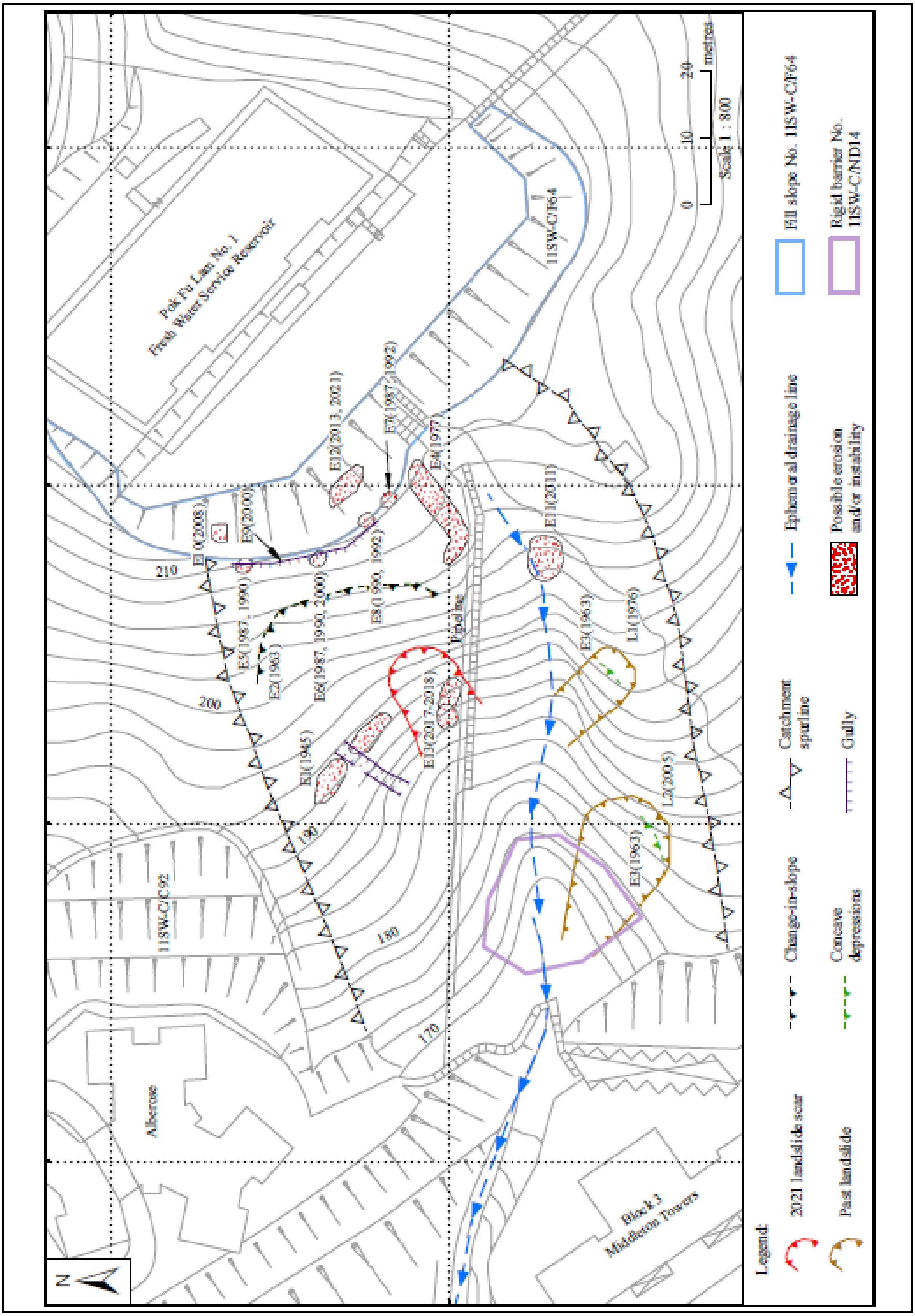


Figure 3.1 Site Morphology and Past Instabilities

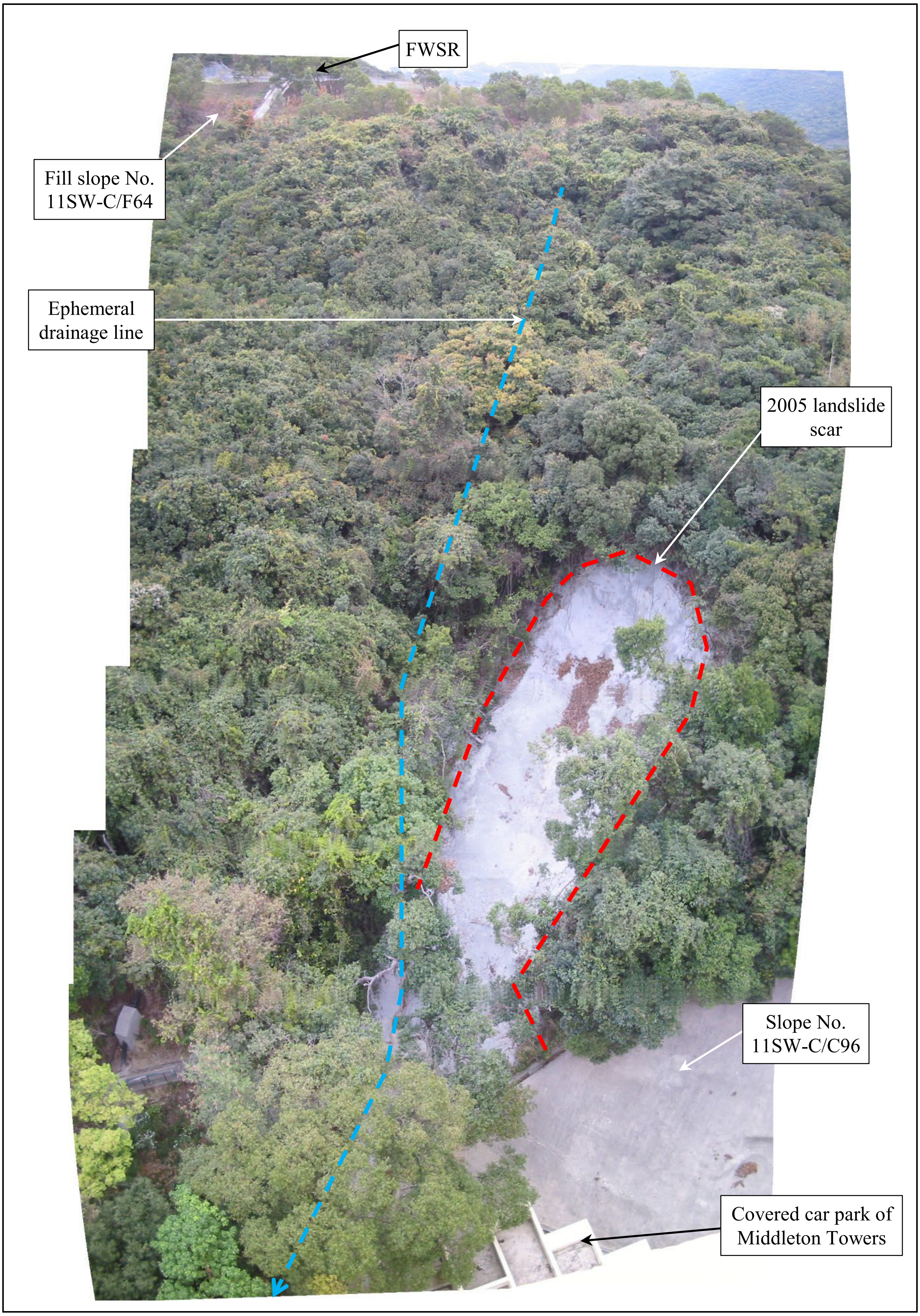
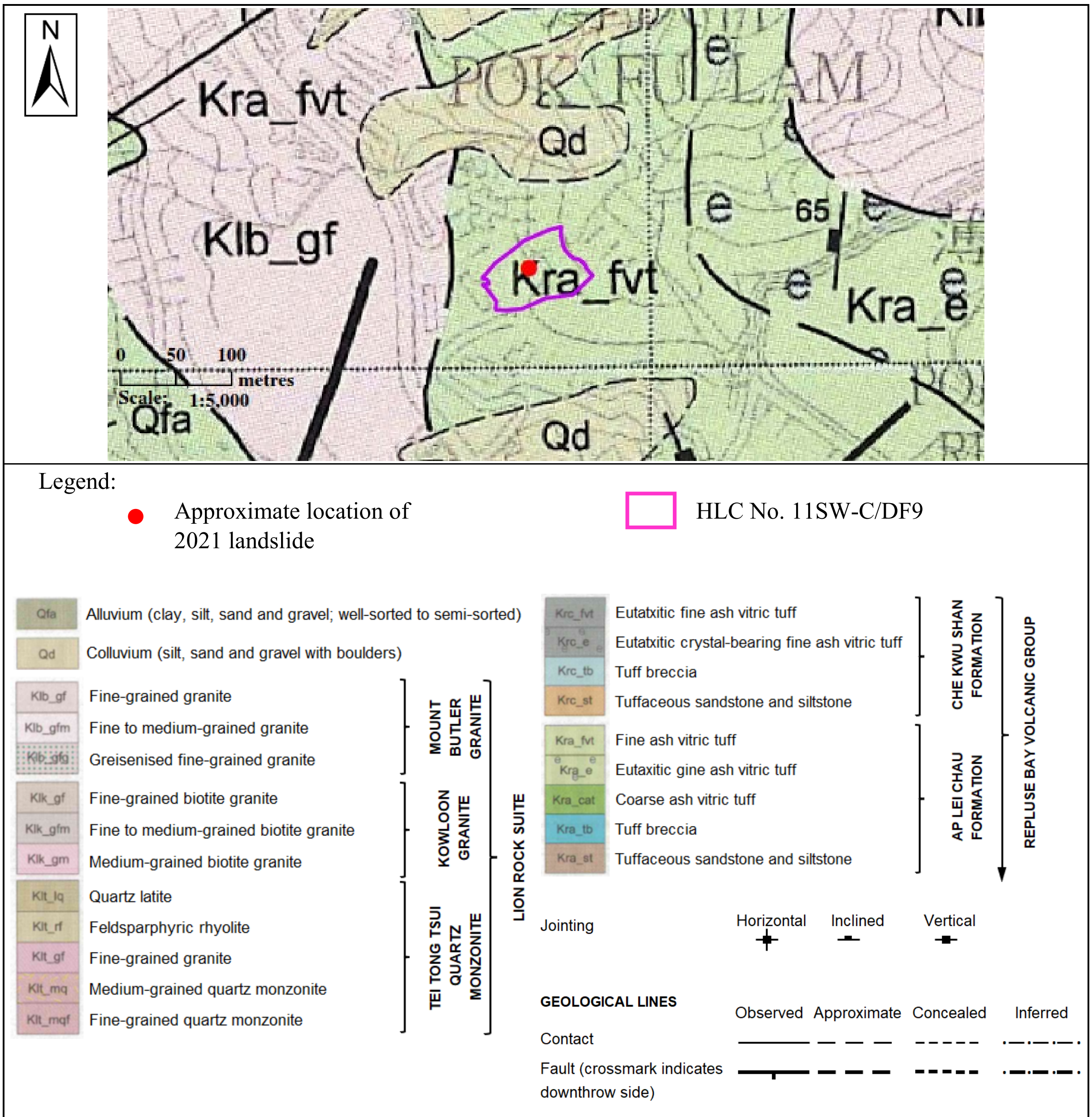


Figure 3.2 The 2005 Landslide (Photograph Taken on 13 March 2006)

4 Geology and Geomorphology

4.1 Regional Geology

The Hong Kong Geological Survey (HKGS) 1:20,000 scale Solid and Superficial Geology Map Sheet No. 11 - Hong Kong and Kowloon (GEO, 2012a) shows the solid geology of the 2021 landslide location consisting of Cretaceous undivided, mainly crystal-bearing fine ash vitric tuff of the Ap Lei Chau Formation (Figure 4.1). The HKGS 1:100,000 scale Pre-Quaternary Geology Map of Hong Kong also shows that the site is underlain by the Ap Lei Chau Formation, part of the Repulse Bay Volcanic Group (Sewell et al, 2000).



Note: Geological map is extracted and enlarged from the 1:20 000 scale Geology Map Series HGM 20, Sheet No. 11 (2012).

Figure 4.1 Regional Geological Map

4.2 Previous Ground Investigation

Previous ground investigation works were carried out in the vicinity of the 2021 landslide location associated with the Stage 3 Study of fill slope No. 11SW-C/F64 (Bachy, 1997) and the Stage 3(H) Study of HLC No. 11SW-C/DF9 (DrilTech, 2010a & 2010b). Locations of the previous ground investigation are shown in Figure 4.2.

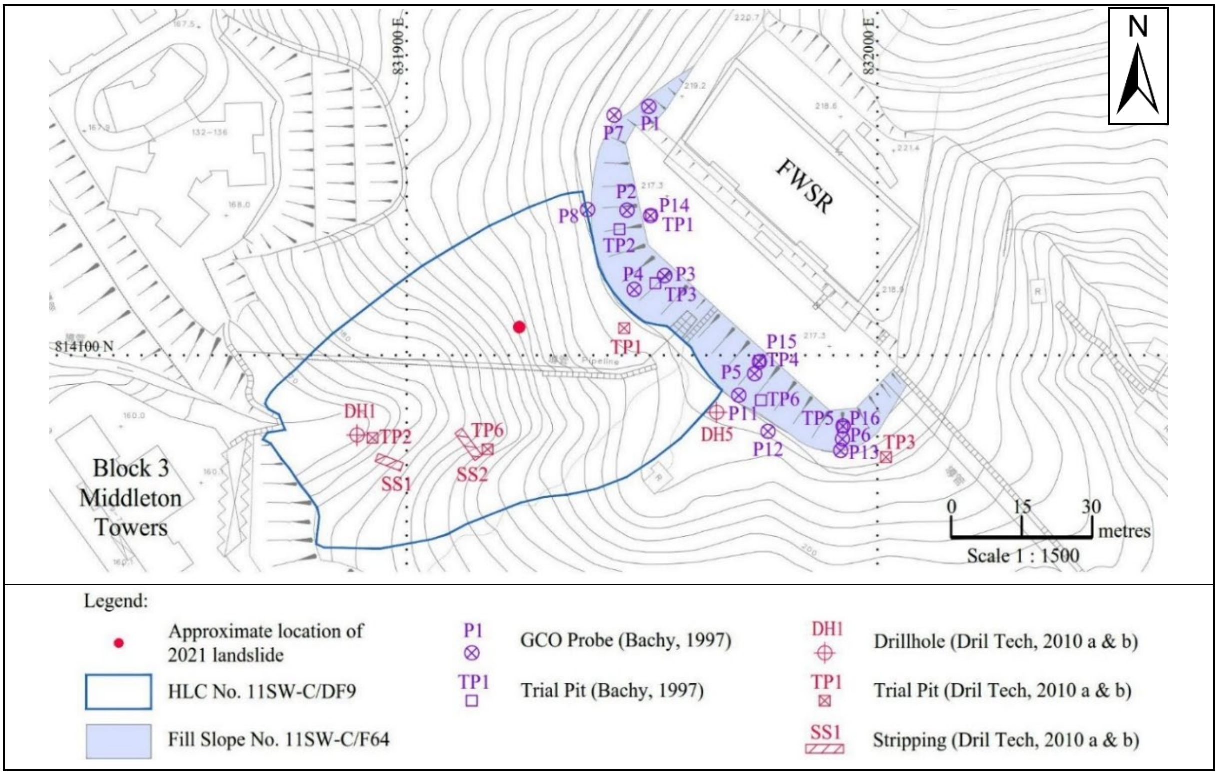


Figure 4.2 Locations of Previous Ground Investigation

Ground investigation works for the Stage 3(H) Study were undertaken in 2010 (Driltech, 2010a & 2010b). Two boreholes, three trial pits and two surface strippings were carried out on or near HLC No. 11SW-C/DF9. The trial pits were located about 20 m east (TP1), 40 m southwest (TP2) and 25 m to the south (TP6) of the 2021 incident location (Figure 4.2). The boreholes were located at the toe of the catchment (DH1) and on the spurline to the south of the catchment (DH5) around 40 m and 45 m from the incident location respectively. Trial pit TP1 exposed 0.6 m thick colluvium overlying Grade IV tuff to the termination depth of 2.6 m. Trial pit TP2 exposed 0.5 m thick landslide deposit (likely from the 2005 landslide) overlying 0.8 m thick colluvium underlain by Grade IV tuff to the termination depth of 3.0 m. Trial pit TP6 exposed 0.5 m thick landslide deposit (likely from the 1976 landslide) overlying 2 m of Grade V/IV tuff. TP6 terminated at a depth of 2 m in Grade IV rhyolite. The Grade V/IV tuff encountered in the trial pits generally had very closely to closely spaced, rough planar, tight to extremely narrow to occasionally narrow, iron and manganese oxide-stained, silty clay infilled (< 1 mm to < 4 mm) joints. In DH1, around 40 m directly below the landslide location, 3 m thick Grade V tuff and 3.3 m thick Grade IV tuff overlie the bedrock of Grade II/III tuff.

Six trial pits and 14 GCO probes were carried out in 1997 (Bachy, 1997) for the Stage 3 Study of fill slope No. 11SW-C/F64. The solid geology was identified as fine-grained granite contrary to the HKGS 1:20,000 scale Solid and Superficial Geology Map Sheet No. 11 and the findings from the ground investigation works for the Stage 3(H) Study. Upslope of the 2021 landslide location, the fill slope comprised 2.2 m thick fill overlying colluvium or Grade V to Grade V/IV granite. At the toe of the fill slope above the landslide location (at GCO probe P4), the inferred fill was 0.4 m thick and the depth to inferred Grade IV granite was 1.2 m.

In the groundwater monitoring results obtained from the ground investigation works in 2010 (DrilTech, 2010a & 2010b), the highest groundwater level was measured at 5.4 m below ground level (about 1.2 m above the bedrock level) in drillhole DH1 at the toe of the catchment between 24 April and 3 May 2010. No groundwater was detected in drillhole DH5 at the crest of the catchment. Seepage was not observed in any of the trial pits.

4.3 Site Geology and Geomorphology

The geology of the site has been determined based on the integrated findings from API, previous studies (Section 3.4), published geological information (Section 4.1), previous ground investigation (Section 4.2) and site observations (Section 5.3).

HLC No. 11SW-C/DF9 on which the 2021 landslide occurred is characterised by a small valley with an ephemeral drainage line, bounded to the north and south by steep southwest sloping, rounded spurlines. The upper part of the catchment comprises a west-facing sideslope changing from gently sloping (about 25°) planar-convex morphology at the crest to steeply sloping (about 40°) planar-concave morphology downslope.

The 2021 landslide initiated on the planar-concave, west-facing sideslope at the upper part of the catchment at an area of localised steepening (about 45°) approximately midway between the toe of fill slope No. 11SW-C/F64 and the crest of rigid barrier No. 11SW-C/ND14 (Figure 2.1).

The ground conditions over HLC No. 11SW-C/DF9 generally consist of a thin layer of colluvium (< 1 m) underlain by completely decomposed to highly decomposed tuff (C/HDT) with the inferred rockhead level at about 3 m to 4 m depth. At the area of localised steepening where the 2021 landslide initiated, the thin colluvium layer is underlain by highly to moderately decomposed tuff (H/MDT) at about 1.5 m depth. Rock outcrops can be observed in the small cut slope between the abandoned underground water tank and the FWSR beyond the crest of the catchment as well as over the toe of cut slope No. 11SW-C/C351 above the FWSR (Figure 1.1). Field observations were generally found to be consistent with the published geology and the ground investigation data obtained for the Stage 3(H) Study.

Localised deposits of landslide debris (< 0.5 m) are present on the valley sideslopes, indicative of past instabilities. On the upper part of the catchment, a thin layer of fill extends beyond the toe of fill slope No. 11SW-C/F64, presumably remaining from the original formation of the fill slope.

The groundwater table is generally interpreted as below the rockhead level at the upper catchment area and about 2 m above the rockhead level at the lower catchment area.

5 The August 2021 Landslide and Post-landslide Observations

5.1 General

The 3 August 2021 incident involved an OHF on HLC No. 11SW-C/DF9 above Middleton Towers resulting in the rupture of an exposed 8" diameter fresh water pipe aligned across the catchment (Figure 5.1). Landslide debris had deposited over the lower portion of the natural hillside and within the rigid barrier (Feature No. 11SW-C/ND14) located downslope (Figures 5.2 and 5.3). Middleton Towers was not affected and no casualties were reported as a result of the landslide.

The landslide was reported to the Government's 1823 Call Centre at 6:31 a.m. on 3 August 2021 by a resident of Middleton Towers with an estimated failure time of 6:30 a.m. At about 9:20 a.m., a report of no fresh water supply to Alberose (136 Pok Fu Lam Road) was received by WSD's Customer Telephone Enquiry Centre. WSD staff arrived on site at about 10:15 a.m. and the water supply to the ruptured pipe was isolated at about 11:30 a.m.

5.2 Witness Accounts

Following the landslide, interviews were conducted with the resident of Middleton Towers who reported the landslide and a security guard. Photographs and videos taken after the landslide by the resident between 6:30 a.m. and 7:00 a.m. and by the security guard at about 8:00 a.m. on 3 August 2021 were acquired.

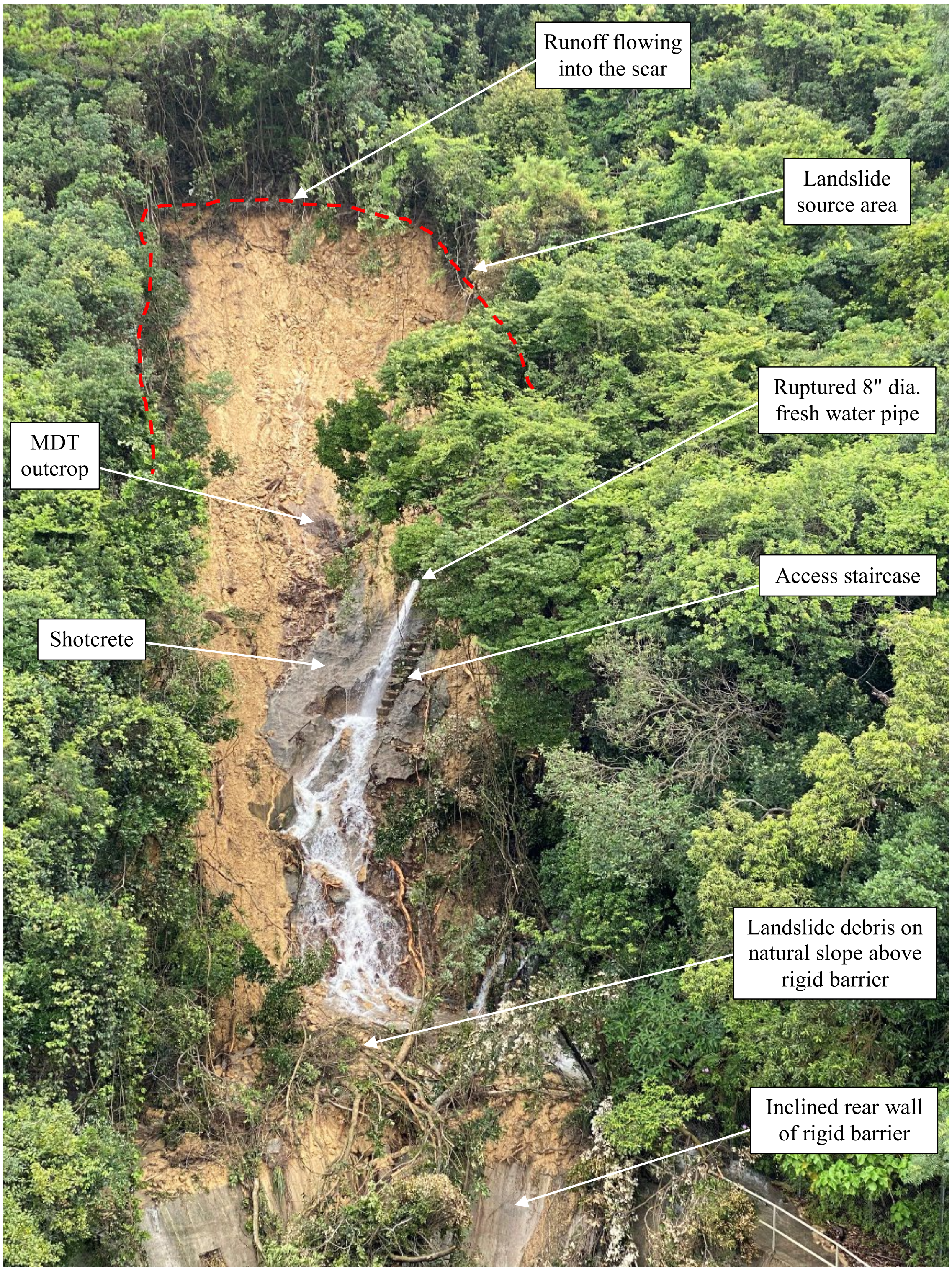
Based on the witness account provided by the resident, the landslide occurred at about 6:30 a.m. during which time light rainfall was noted. Following the landslide, a large amount of water was seen discharging from the ruptured 8" diameter fresh water pipe on the southern flank of the landslide scar. The photographs and videos also showed concentrated surface runoff flowing into the scar from above the landslide head scarp (Figure 5.4). The witnesses did not observe any premonitory signs of failure in the days preceding the landslide.

5.3 Post-landslide Observations

FHK carried out a landslide inspection in the afternoon of 3 August 2021 during intermittent rainy weather conditions. Follow-up inspections and mapping were also undertaken over August and September 2021. Salient post-landslide observations from the witness accounts and inspections by FHK and GEO District Division are discussed below.

Based on information from the eye-witnesses, water discharge from the ruptured 8" diameter fresh water pipe and concentrated surface flow over the crest of the landslide scar were observed around the time of the landslide at 6:30 a.m. on 3 August 2021 and such water flow conditions continued until at least 8:00 a.m. By 10:30 a.m. the concentrated surface flow was no longer apparent.

At the time of the initial field mapping, no works had been carried out on the failure scar and no debris had been removed. In addition to the field mapping, handheld laser scanning (HLS) of the landslide site and its vicinity, including the rigid barrier and the crest platform in front of the FWSR, was conducted on 4 and 6 August 2021 to better appreciate the post-landslide site conditions (Figure 5.5).



Note: Photograph taken by a security guard of Middleton Towers at about 8:00 a.m.

Figure 5.1 General View of the Landslide (Photograph Taken on 3 August 2021)

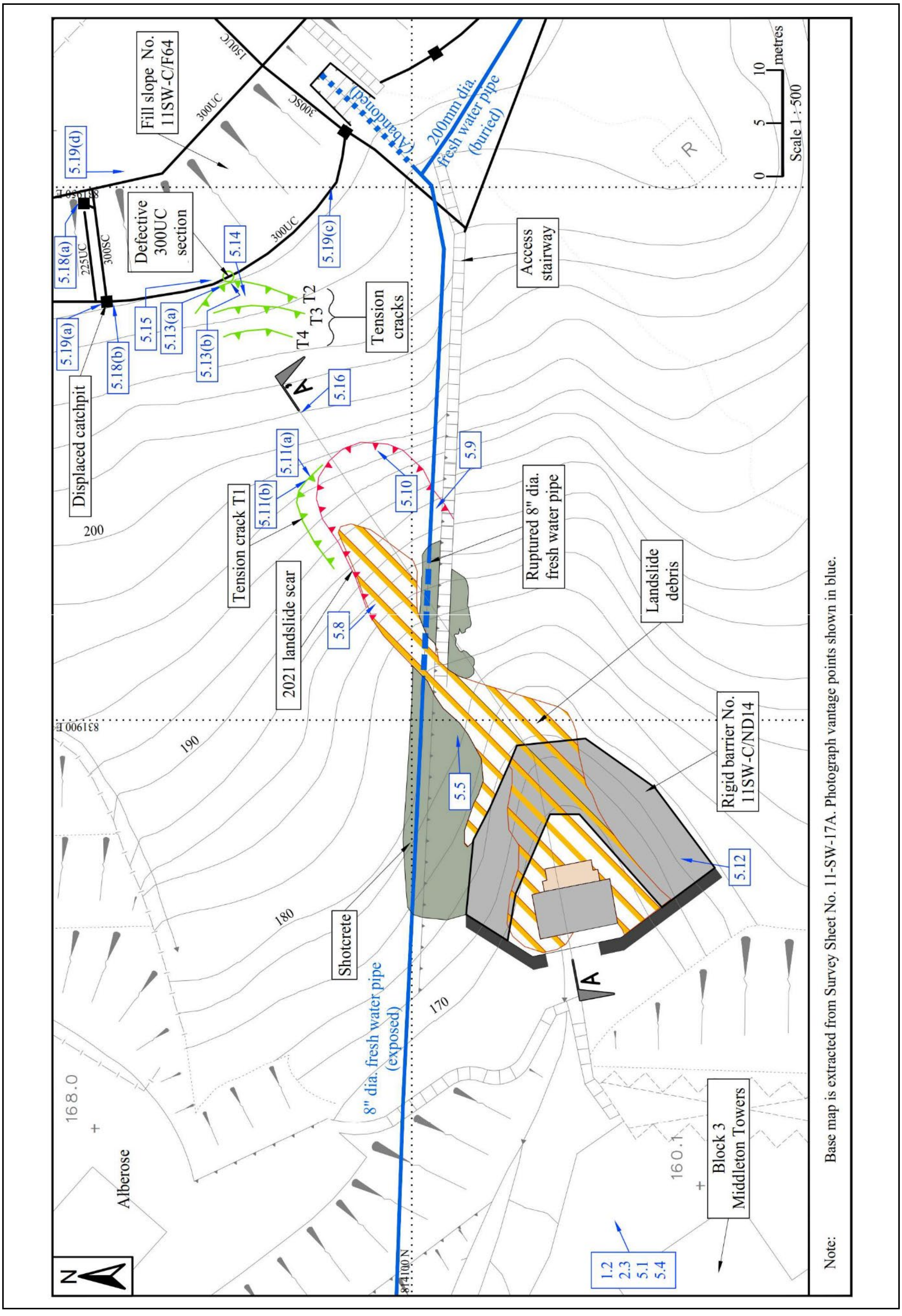


Figure 5.2 Post-Landslide Observations Plan

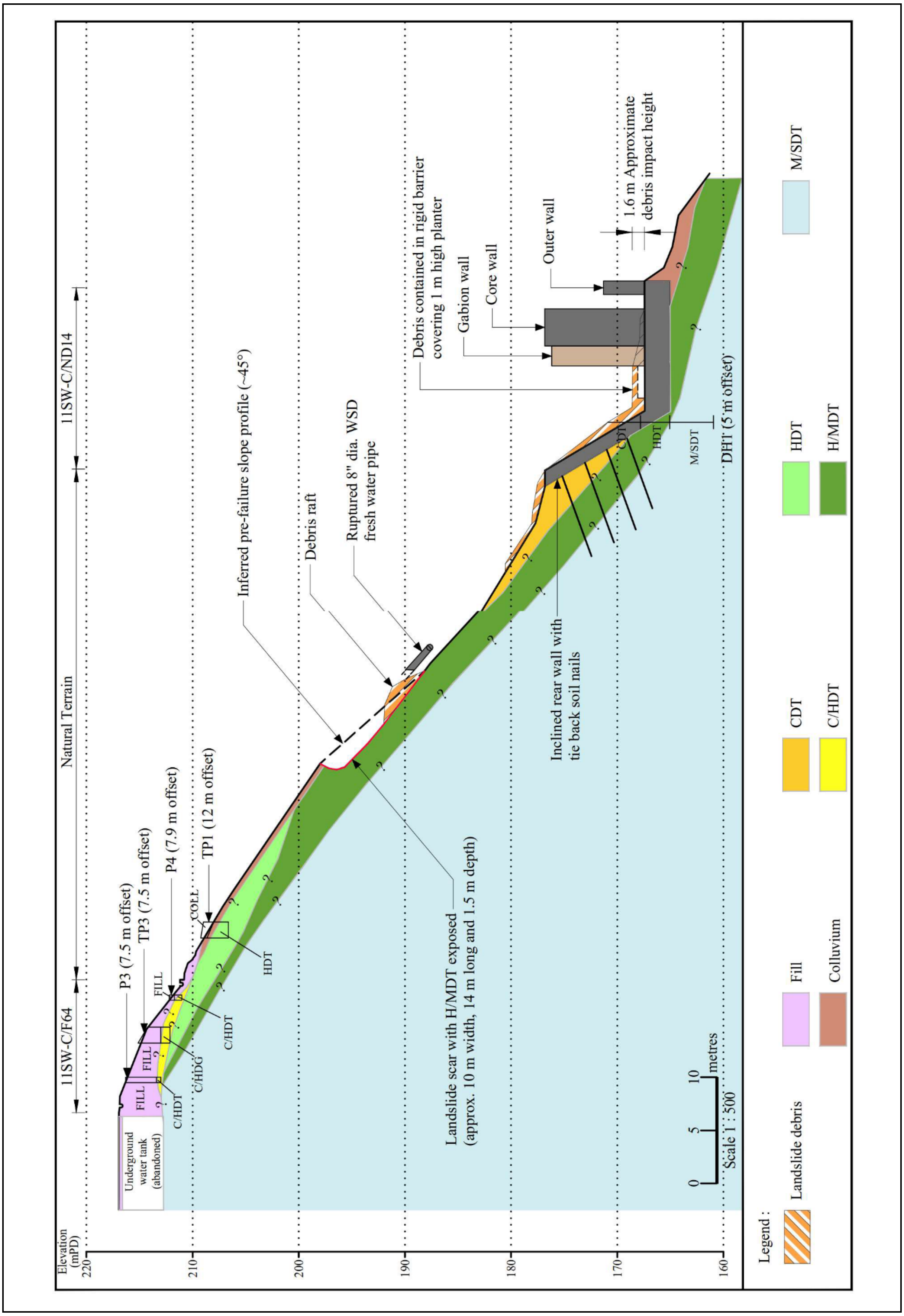


Figure 5.3 Cross-section A-A' through the 3 August 2021 Landslide

Note: Image captured from the video taken by a security guard of Middleton Towers at about 8:00 a.m.

Figure 5.4 Concentrated Surface Runoff from above the Landslide Head Scarp (Video Taken on 3 August 2021)

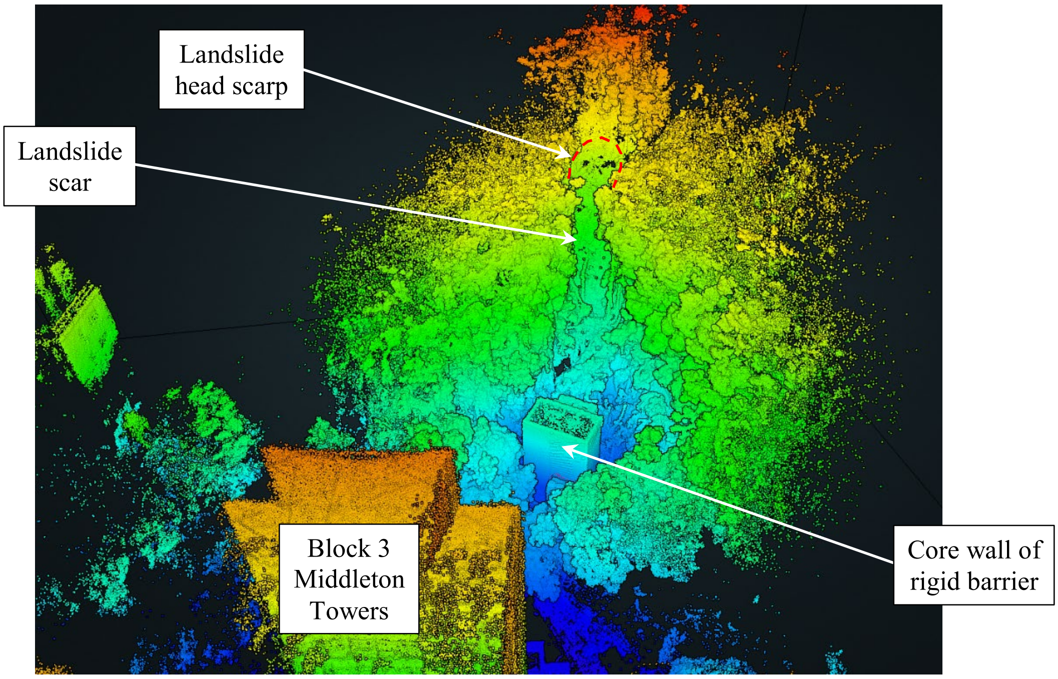
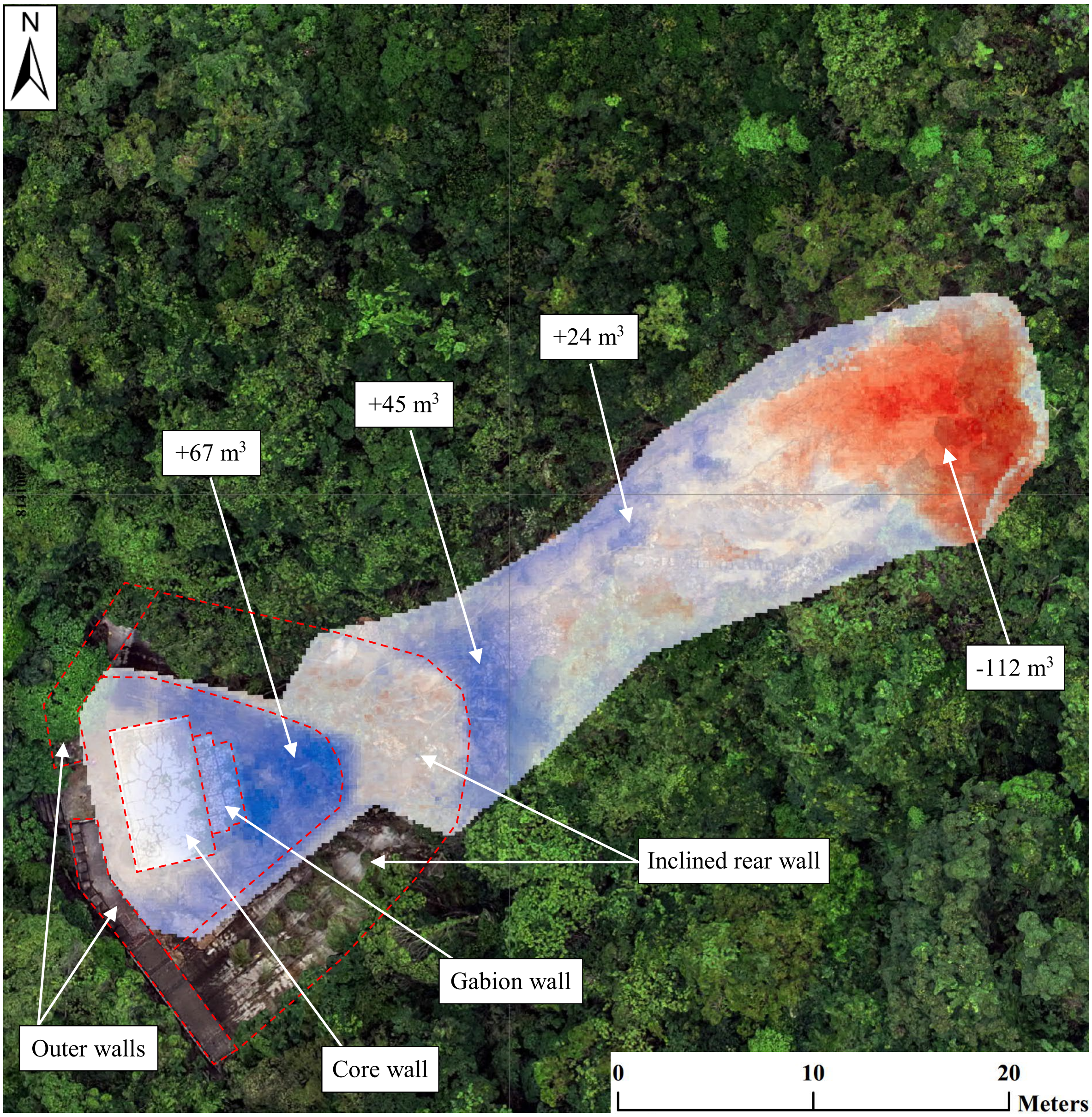


Figure 5.5 Point Cloud Model Generated from Handheld Laser Scanner

Change detection analysis was carried out by comparing the 3D point cloud model generated from the HLS with the pre-landslide 2020 Light Detection and Ranging (LiDAR) slope profile. The analysis results are presented in Figure 5.6. In general, a negative value from the analysis is considered indicative of failed ground while a positive value is considered indicative of landslide debris deposition. The landslide volume and debris distribution derived from the analysis were generally comparable with the field observations and mapping results (Sections 5.3.1 and 5.3.2).



Legend:

Rigid barrier   Negative change   Positive change

Note: Comparison between ground profiles derived from the ground points generated by the 2020 LiDAR and the post-landslide HLS.

Figure 5.6 Change Detection Analysis

5.3.1 Source Area

The landslide source area (from 188 mPD to 200 mPD) was located on a planar to slightly concave, open hillslope terrain with the lower extent situated immediately upslope of the ruptured 8" diameter fresh water pipe and a shotcreted area (Figure 5.7).

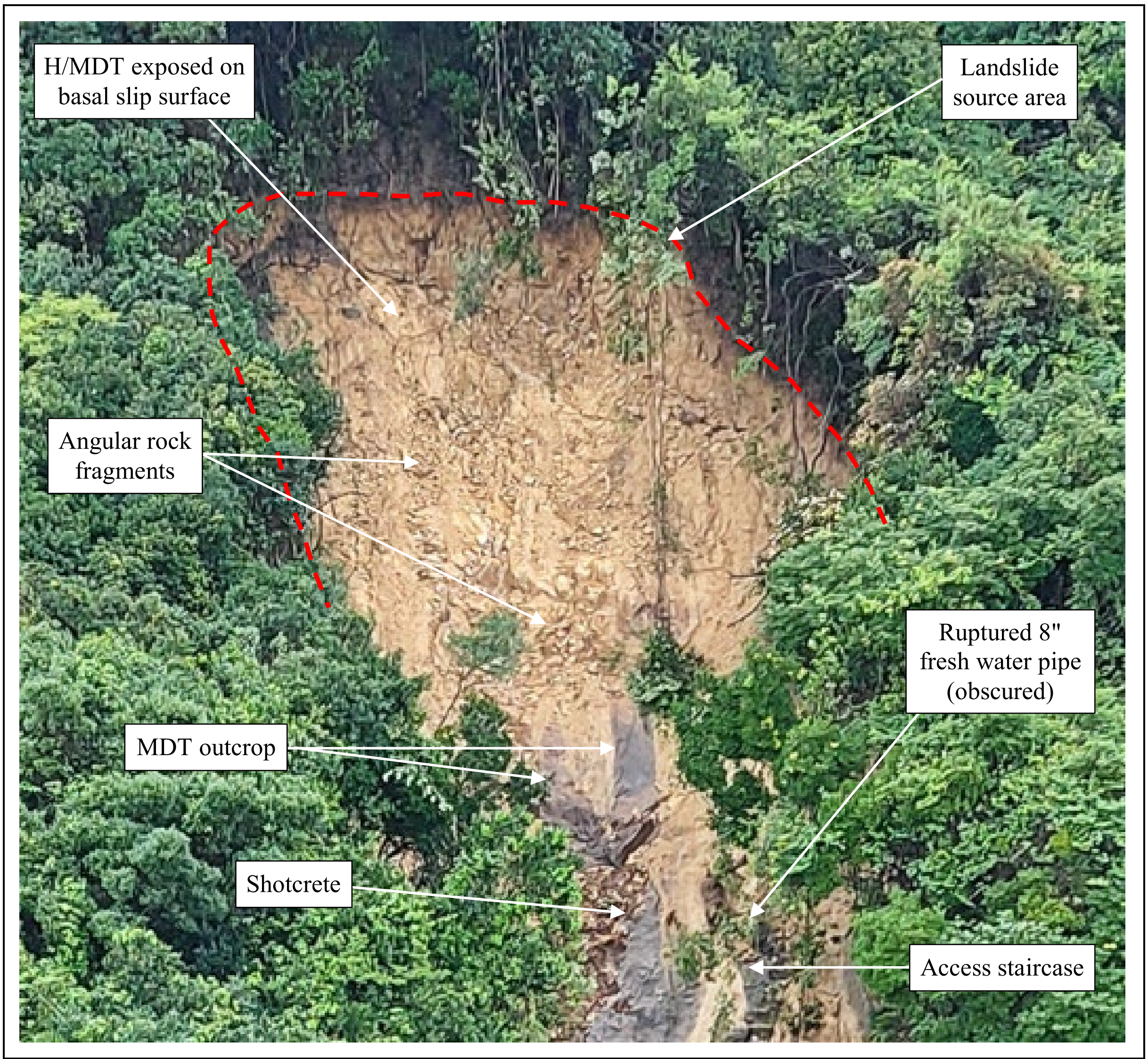


Figure 5.7 General View of the Landslide Source Area (Photograph Taken on 3 August 2021)

The dimensions of the source area were measured on site as about 14 m long, 10 m wide with a maximum depth of about 1.5 m. Based on the field mapping, the estimated failure volume is about 110 m^3 which is generally consistent with the results of the change detection analysis (Figure 5.6).

The pre-failure slope profile was steeply inclined at about 40° to 45° and vegetated with shrubs and trees, as inferred from the adjacent slope surface (Figures 5.8 and 5.9). The landslide scar revealed thin superficial layers of topsoil and colluvium up to about 1 m thick overlying sub-vertically and sub-horizontally jointed H/MDT (Figure 5.10). The failed materials predominantly comprised colluvium with some angular rock fragments of the highly fractured H/MDT surface. The observation of thin superficial layers over shallow rockhead is generally consistent with the findings of previous ground investigations. No seepage or soil pipes were observed on the scar at the time of the inspections.

On the northern flank of the landslide, a tension crack (T1) was observed as a continuation of the head scarp with some signs of displacement (Figure 5.2 and 5.11). Tension crack T1 was about 12 m in length and was displaced by about 0.3 m vertically and 0.2 m laterally.

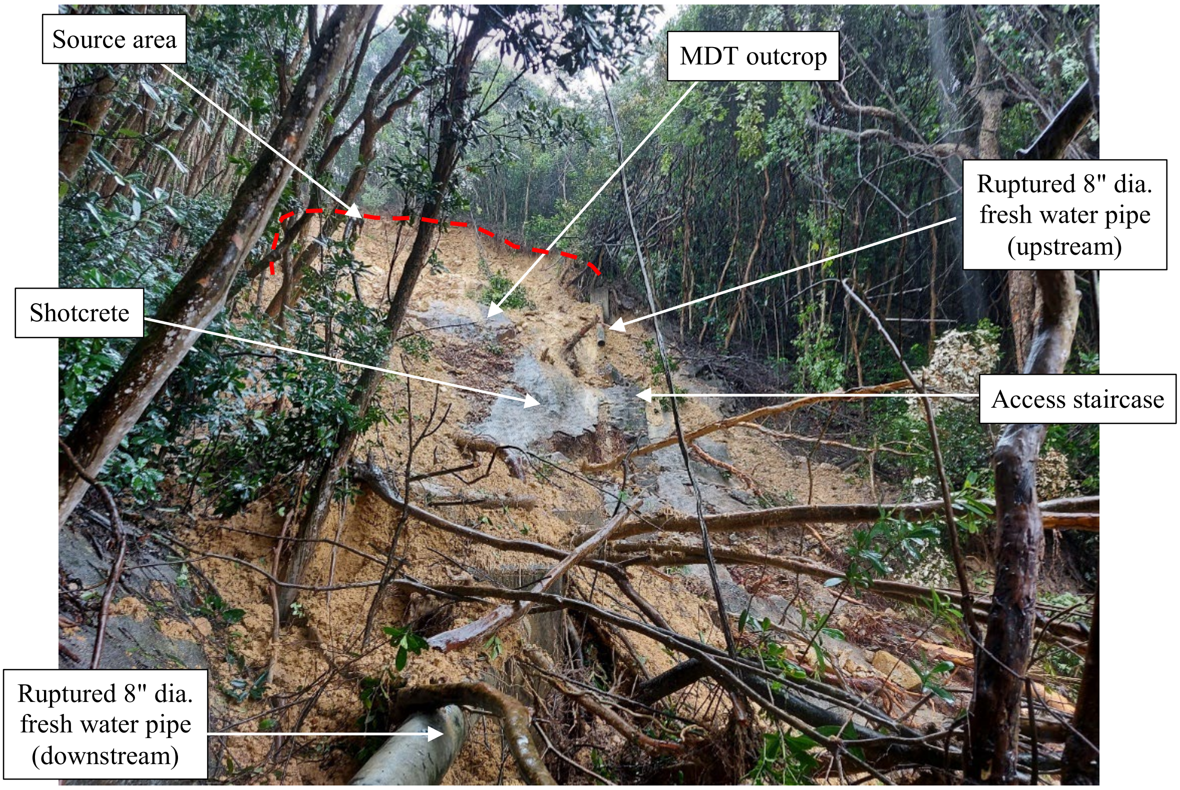


Figure 5.8 East-facing Lateral View of the Landslide (Photograph Taken on 3 August 2021)

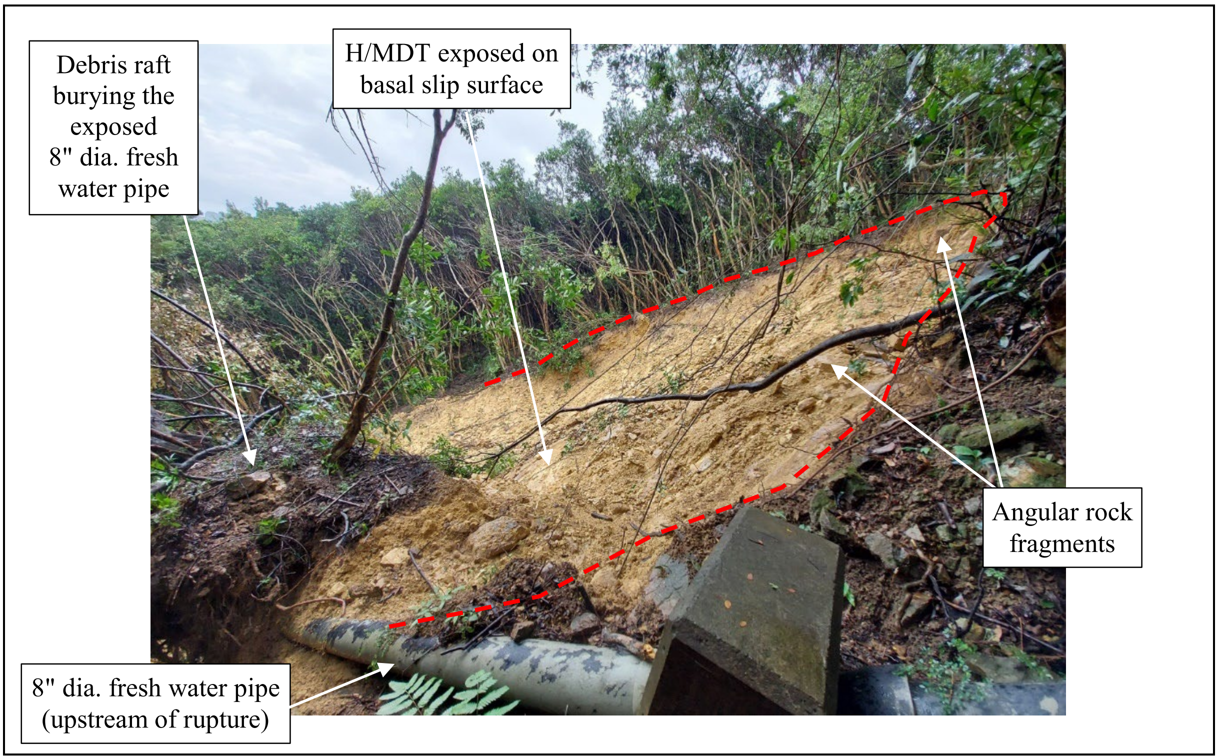


Figure 5.9 West-facing Lateral View of the Landslide Source Area (Photograph Taken on 3 August 2021)

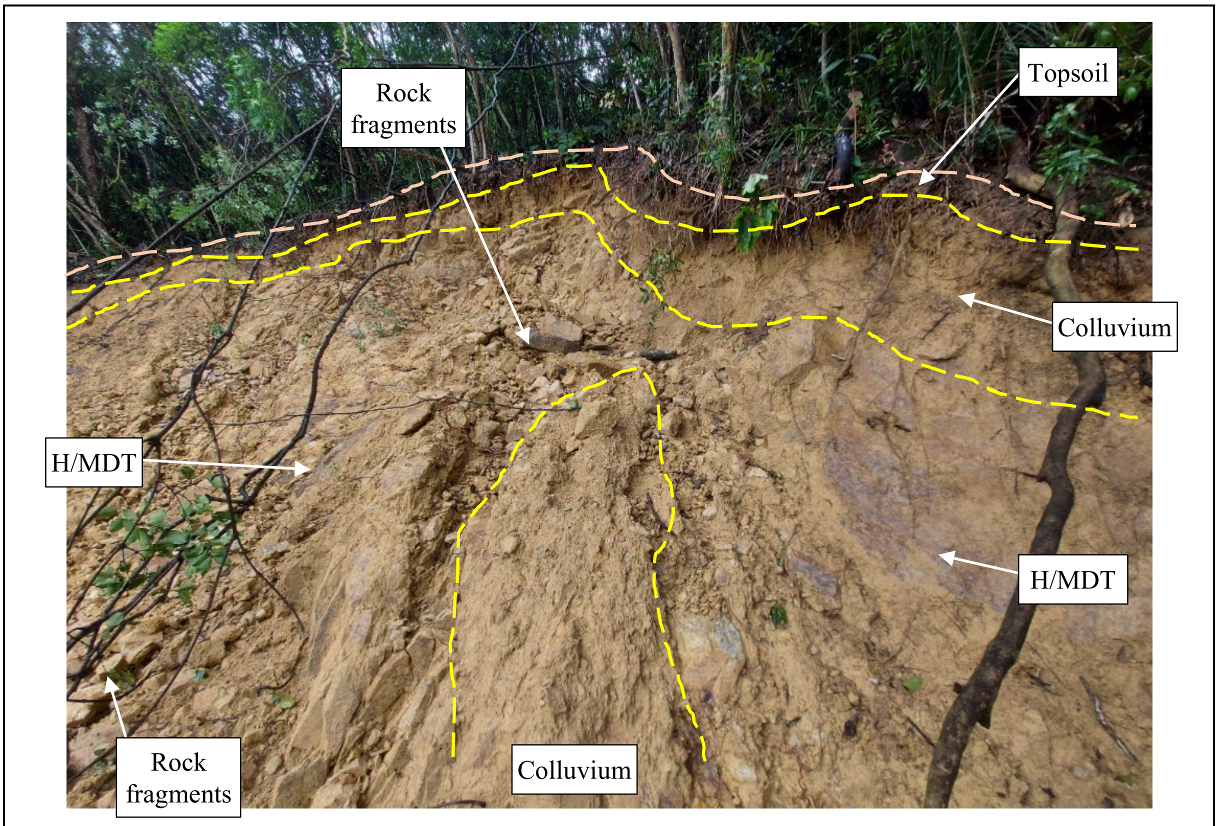
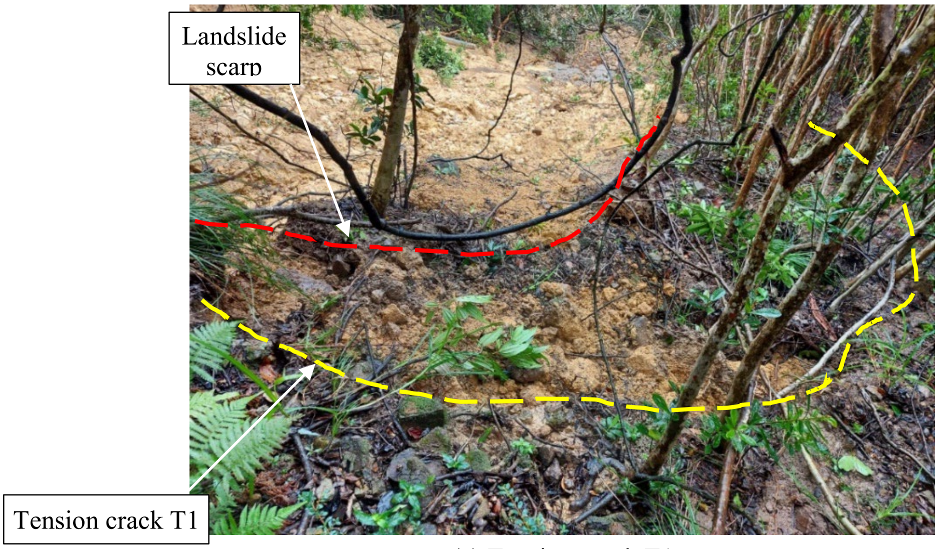


Figure 5.10 Landslide Head Scarp Exposure (Photograph Taken on 4 August 2021)

5.3.2 Debris Trail

The debris had deposited over the lower part of the natural slope and within the rigid barrier (Feature No. 11SW-C/ND14) at the toe of the catchment (Figures 5.3 and 5.12). The barrier had prevented further runout of the debris to Middleton Towers below.



(a) Tension crack T1

(b) Close up view of tension crack T1

Figure 5.11 Tension Crack T1 Extending from the Northern Side of the Landslide Head Scarp (Photographs Taken on 3 August 2021)

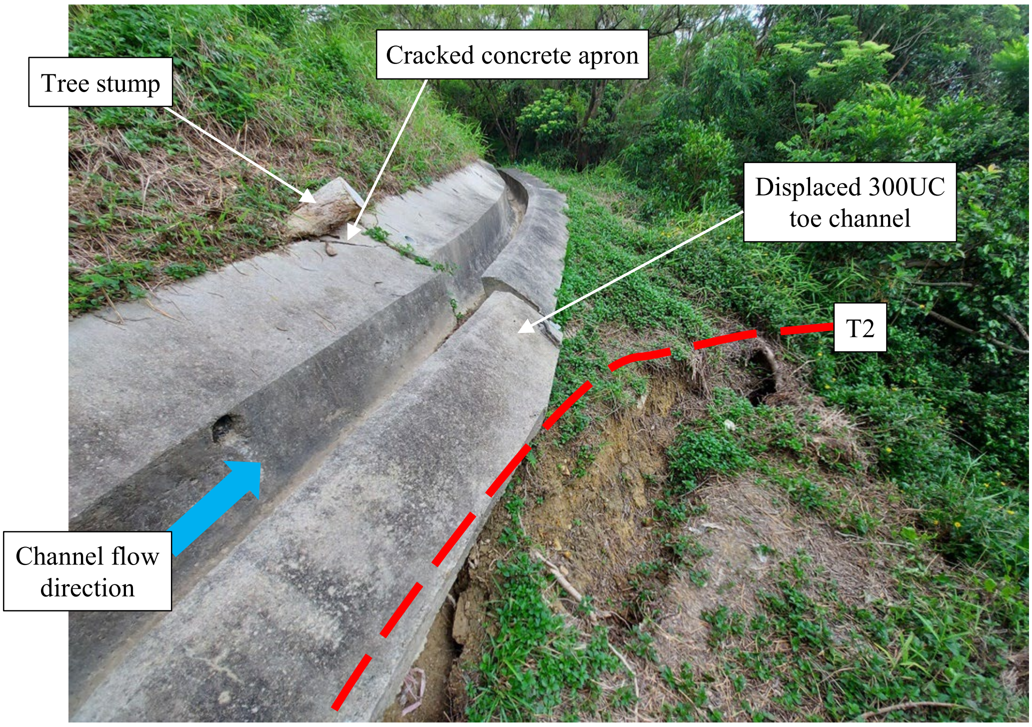
Figure 5.12 View of Landslide Debris Trail (Photograph Taken on 3 August 2021)

The debris volume was estimated as about 135 m^3, with approximately half accumulated in the containment basin of the rigid barrier (about 68 m^3) and half deposited on the natural hillside above the crest of the barrier (about 67 m^3) (Figure 5.6). The debris consisted of soil, rock, uprooted trees and a large section of the ruptured 8" diameter fresh water pipe.

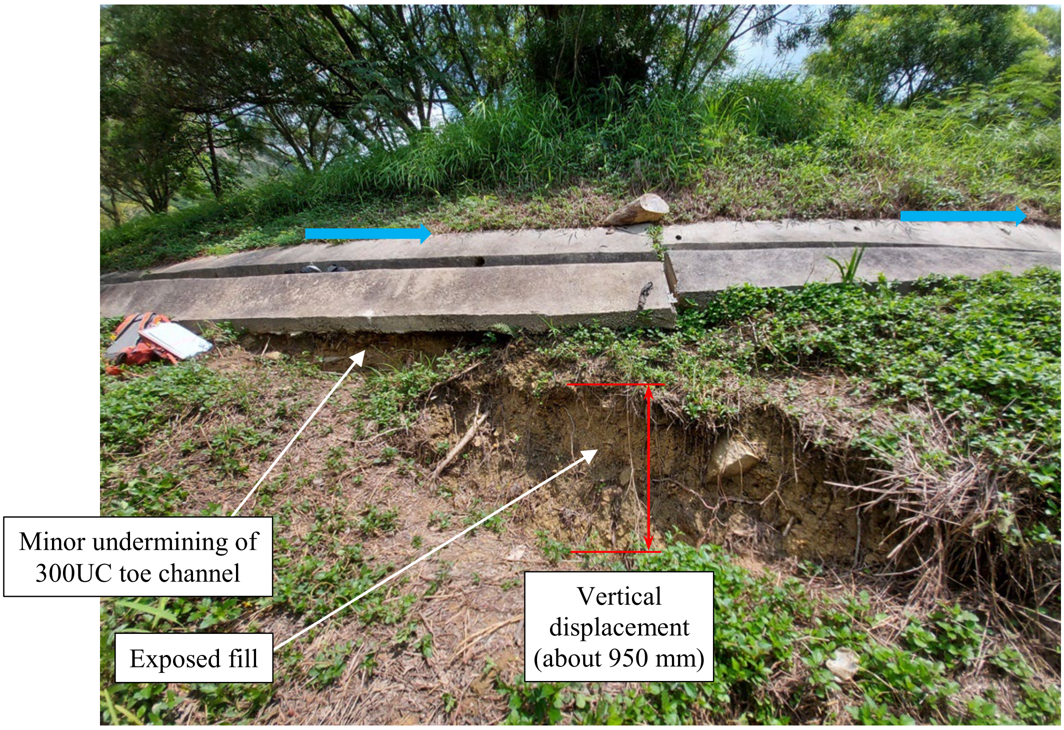
The landslide debris that entered the rigid barrier primarily accumulated to the rear of containment basin and over the planter behind the central core wall. Towards the central core wall, the deposition thickness was relatively even ranging from about 1 m thick on either side of the planter to a debris impact height up to 1.6 m at the rear of the gabion wall (i.e. about 0.6 m above the planter). A minor amount of soil and rock fragments ran round the sides of the central core wall, reaching the outer wall. Minor amount of washout materials and a few rock fragments deposited at the downstream face of the central core wall. No apparent damage to the barrier or deformation of the gabion wall was observed. Above the crest of the barrier, the debris was about 1 m thick, extending back about 5 m over the natural slope.

5.3.3 Upslope Terrain

Directly above the landslide location, the natural slope changes to gently sloping, planar-slightly convex morphology and is densely vegetated by trees. Three tension cracks (T2 to T4) were observed on the gentle slope of about 25° inclination immediately below the toe of fill slope No. 11SW-C/F64 (Figure 5.2, 5.13 and 5.14).



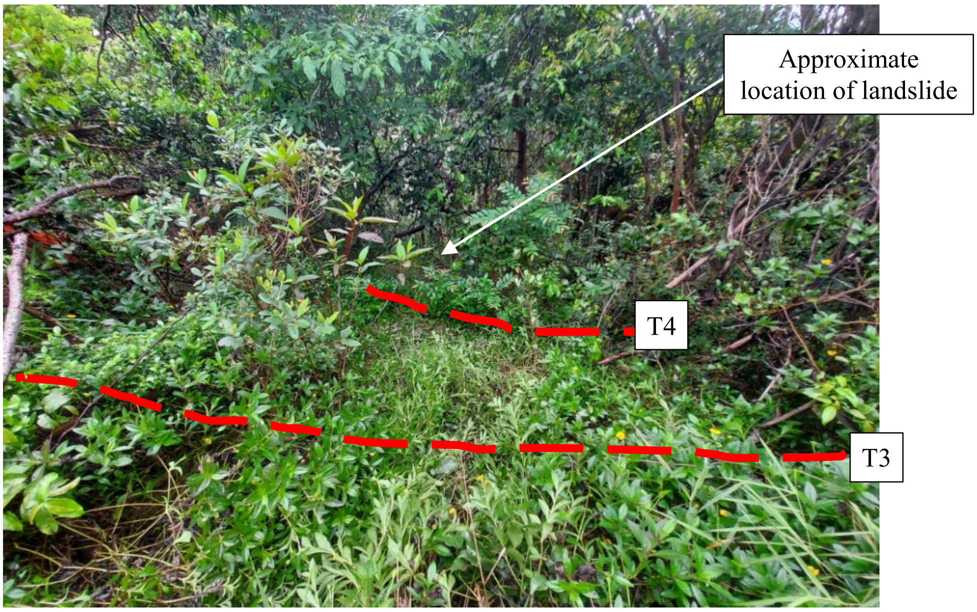
(a) Tension crack T2



(b) Tension crack T2

Note: Photographs taken on 6 September 2021 after vegetation clearance and channel unblocking.

Figure 5.13 Tension Crack T2 (Photographs Taken on 6 September 2021)



(a) Tension cracks T3 and T4

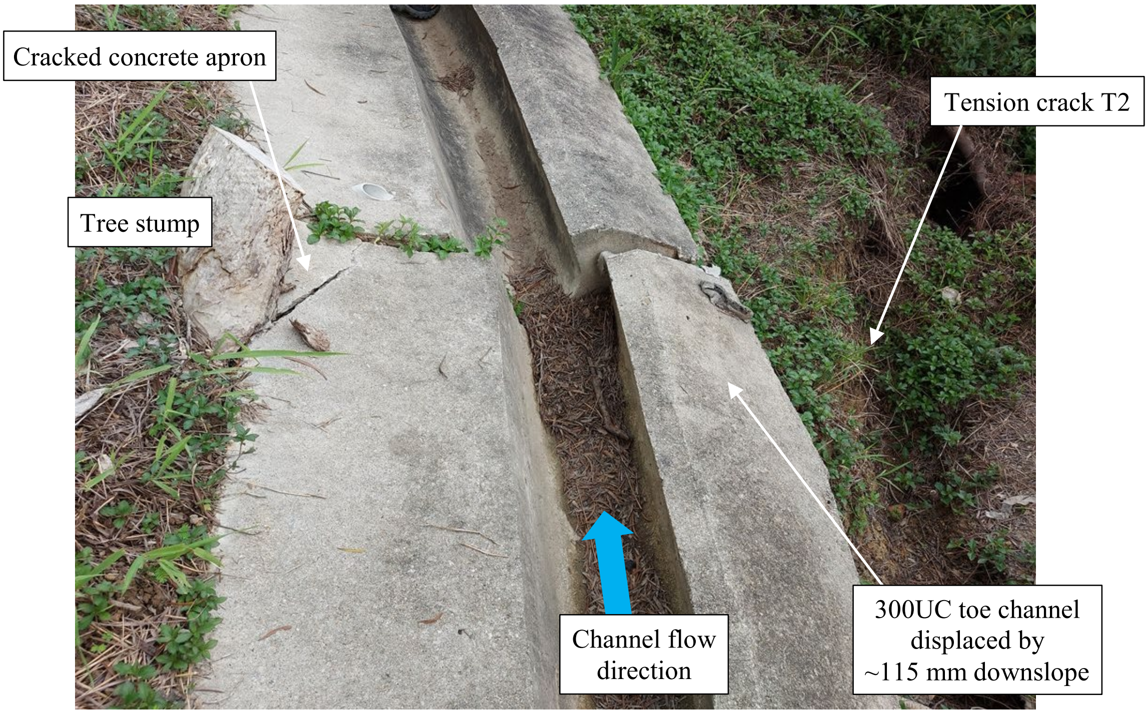
(b) Close-up view of tension crack T3

(c) Close-up view of tension crack T4

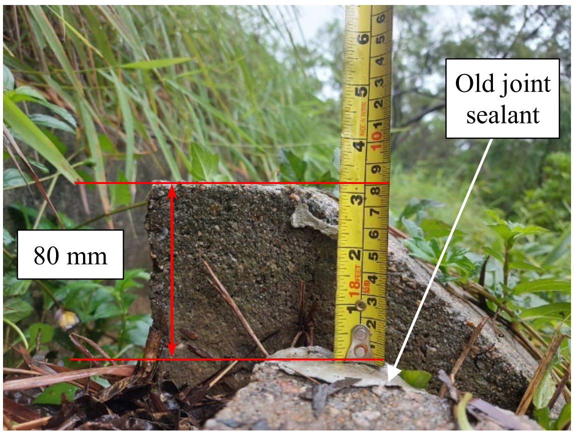
Figure 5.14 Tension Cracks T3 and T4 (Photographs Taken on 4 August 2021)

The largest tension crack, T2, was measured 10 m in length with a vertical displacement of about 0.5 m exposing fill materials (Figure 5.13). Tension cracks T3 and T4 were located downslope and broadly parallel to tension crack T2. T3 and T4 were measured about 9 m and 6 m in length respectively with a maximum vertical displacement of about 0.1 m (Figure 5.14).

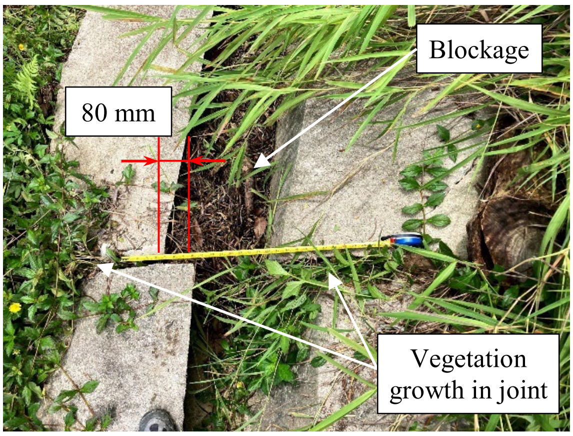
Tension crack T2 had slightly undermined a section of the 300UC toe channel of the fill slope. At this affected section of the channel, a displaced expansion joint and partial blockage of the channel was observed (hereafter referred to as "defective 300UC section") (Figure 5.15). The displaced channel expansion joint had exhibited an overall movement of about 115 mm (80 mm vertically and 80 mm laterally). A tree stump of an apparently previously felled tree was observed above the displaced joint together with cracking of the concrete apron. It is possible that the joint displacement had resulted from tree root action although the relative timing of the tree felling and joint displacement could not be established. Nevertheless, the joint displacement could have developed some time prior to the incident as evidenced by the vegetation growth within the expansion joint (Figure 5.15).



(a) Defective 300UC section of toe channel (Photograph taken after vegetation clearance)



(b) Vertical channel displacement (looking downstream)



(c) Lateral channel displacement (looking upstream)

Note: Photograph (a) taken on 6 September 2021, (b) taken on 3 August 2021 and (c) taken on 4 August 2021.

Figure 5.15 Defective 300UC Section (Photographs Taken on 3 August, 4 August and 6 September 2021)

Evidence of vegetation stripping, rill erosion and recent sediment build-up was observed on the hillside area between the tension cracks and the crest of the landslide, indicative of possible overland flow (Figure 5.16).

The defective 300UC section of the fill slope toe channel, the distressed ground below in the form of the three broadly parallel tension cracks (T2 to T4) and evidence of possible overland flow were all observed to be aligned directly above the landslide location indicating the defective 300UC section as a likely point of conveying the observed concentrated surface runoff to the landslide location.

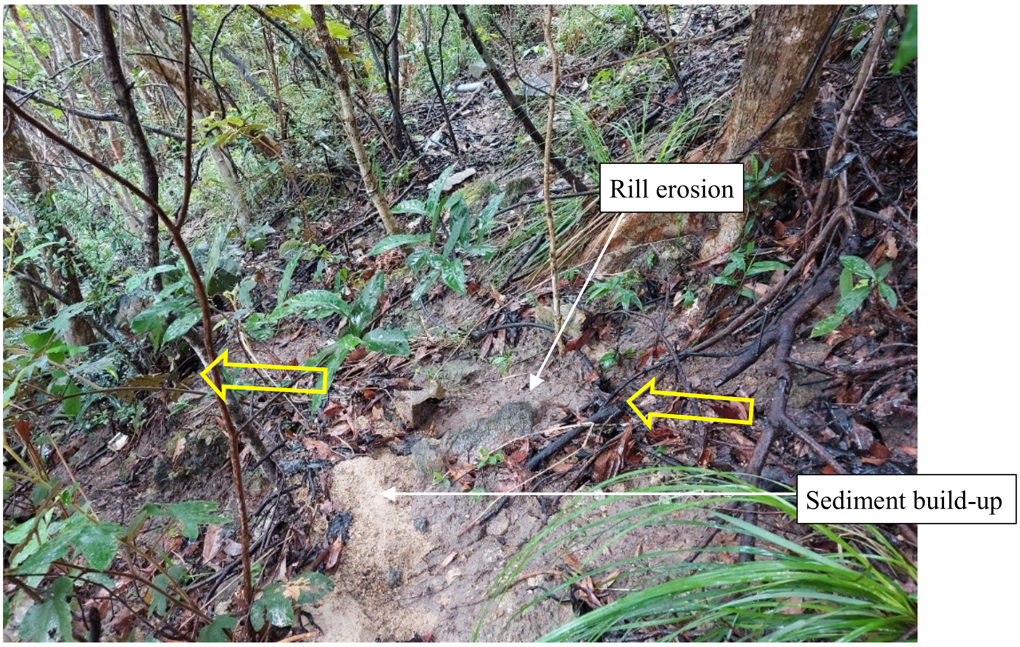


Figure 5.16 Evidence of Overland Flow Directly above the Landslide Location (Photograph Taken on 3 August 2021)

5.3.4 Surface and Subsurface Drainage on Fill Slope No. 11SW-C/F64

In connection with the defective 300UC section above the landslide location, the overall layout and condition of the drainage system of fill slope No. 11SW-C/F64 were reviewed. The slope surface drainage system comprises a crest channel (300UC), toe channels (225UC & 300UC), connecting stepped channels (300SC) and catchpits (Figure 5.17). On the crest platform above the underground water tank, U-channels (150UC) discharge into the crest channel of the fill slope. The fill slope drainage ultimately discharges into the ephemeral drainage line located downslope of the central slope toe area.

The two 225 mm diameter subsurface FWSR washout pipes discharge into the drainage system of the fill slope (see section 2.4). The northern washout pipe discharges into a catchpit about 1.5 m below the slope crest and the flow is diverted to an adjacent 300SC conveying it, via a catchpit, to the 300UC toe channel including the defective 300UC section (Figure 5.18).

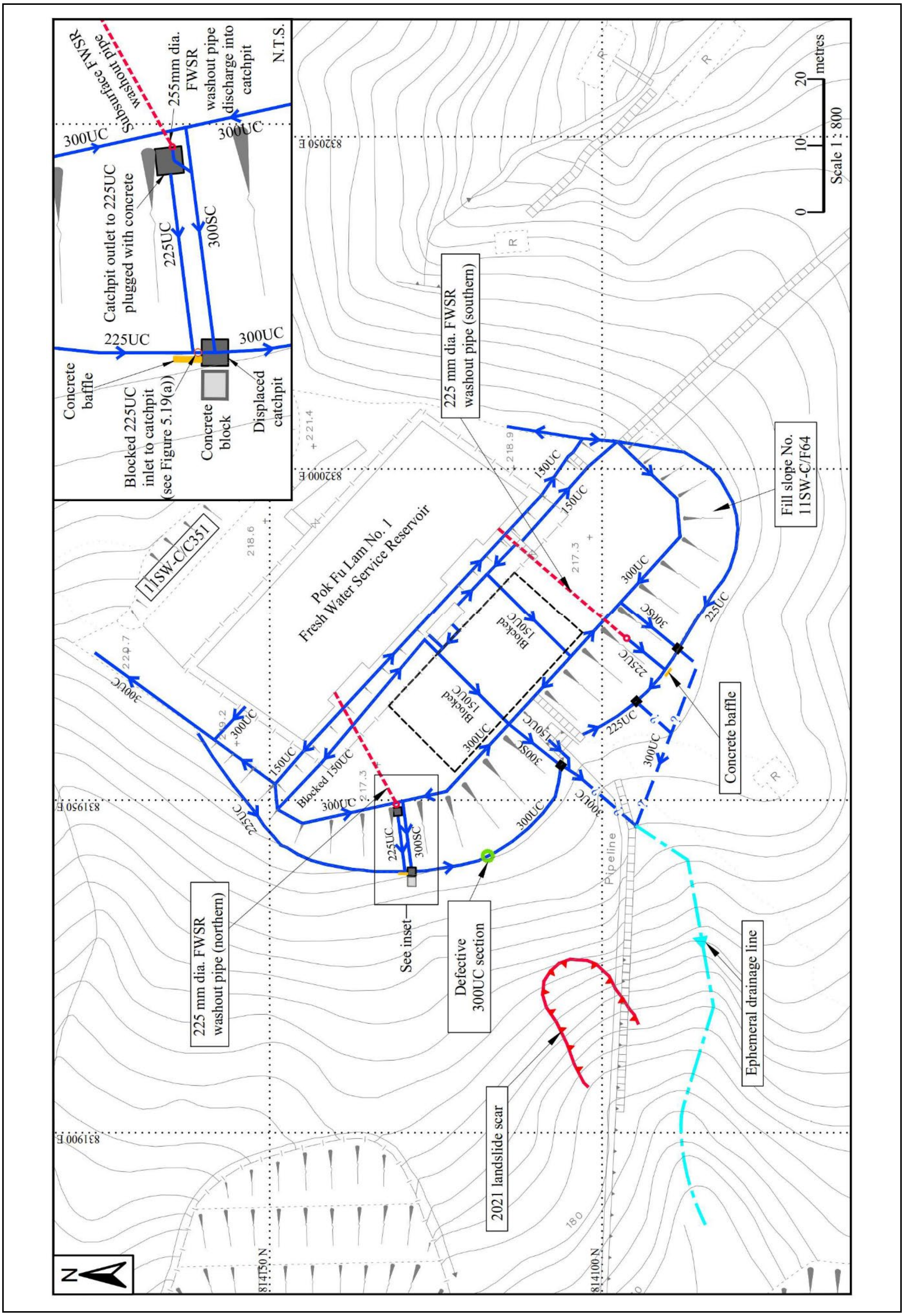
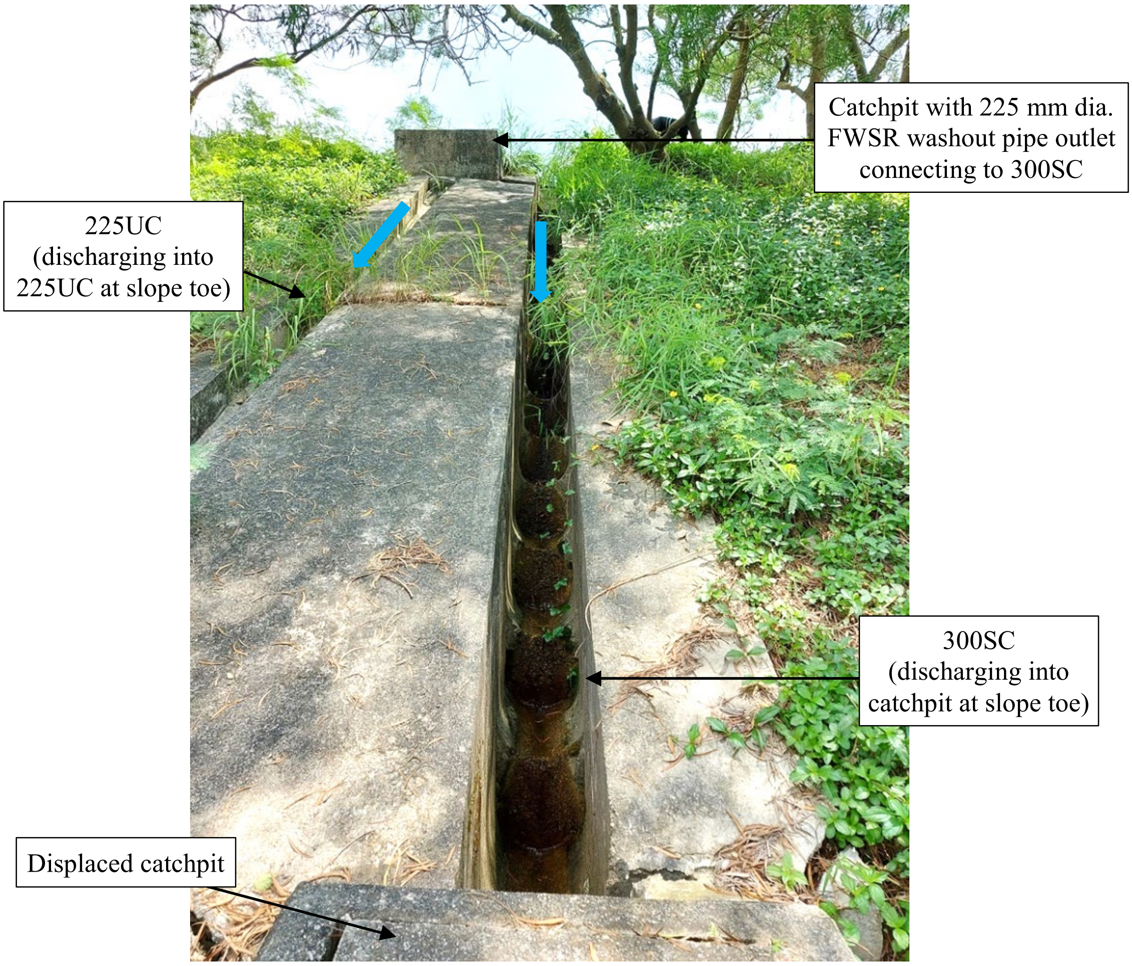


Figure 5.17 Drainage Layout of Fill Slope No. 11SW-C/F64

(a) 225 mm dia. washout pipe in catchpit



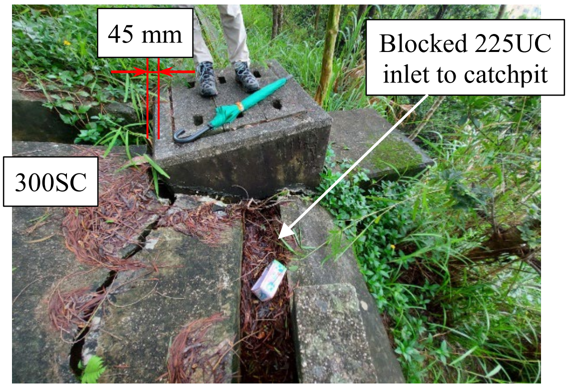
(b) Light flow in 300SC from 225 mm dia. FWSR washout pipe in upper catchpit

Note: Photographs (a) taken on 6 August 2021 and (b) taken on 6 September 2021.

Figure 5.18 Outlet of Northern 225 mm Diameter FWSR Washout Pipe (Photographs Taken on 6 August and 6 September 2021)

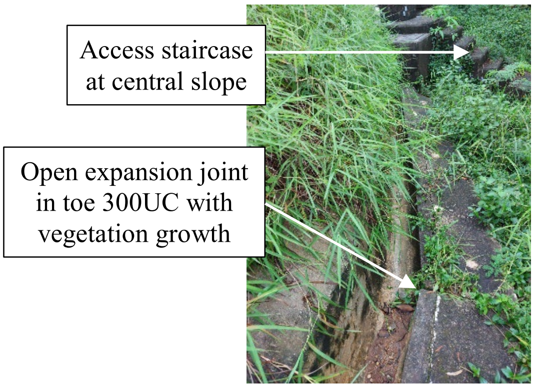
The southern FWSR washout pipe discharges at about 2 m below the slope crest directly into a down-the-slope 225UC connecting to a 225UC toe channel (Figure 5.17).

Apart from the blockage noted at the defective 300UC section, locally, the 225UC toe channel was heavily blocked at the catchpit inlet at the northern portion of the slope toe (Figures 5.17 and 5.19(a)). The remainder of the fill slope surface drainage system was generally clear. Other defects in the surface drainage system were observed including separation of the aforesaid catchpit from the connecting channels (by up to 45 mm), cracked channels and channel aprons, and loss of joint sealant at an expansion joint in the toe channel (Figure 5.19). Some of the defects appeared to have been present for some time as evidenced by vegetation growth and concrete discolouration. Signs of past repairs on the channels and aprons, possibly associated with previous maintenance works, were also apparent. It is noted that the routine maintenance inspections/works and the Engineer Inspection prior to the landslide were conducted in late 2020 and in April 2021 respectively.



(a) Separated catchpit and blocked 225UC at the northern slope toe

(b) Cracked 225UC along the northern slope toe



(c) Open joint in 300UC toe channel (loss of sealant)

(d) Cracking and separation of 300UC crest channel apron (possible tree root action)

Note: Photographs (a), (b) and (c) taken on 6 August 2021 and (d) taken on 6 September 2021.

Figure 5.19 Examples of Other Defects in the Surface Drainage on Fill Slope No. 11SW-C/F64 (Photographs Taken on 6 August and 6 September 2021)

Ponding was observed at the crest of the feature, which appeared to be confined to the surface extent roughly above the abandoned underground water tank, probably caused by a lack of gradient and blockage of the 150UCs in the crest platform (Figure 5.20).

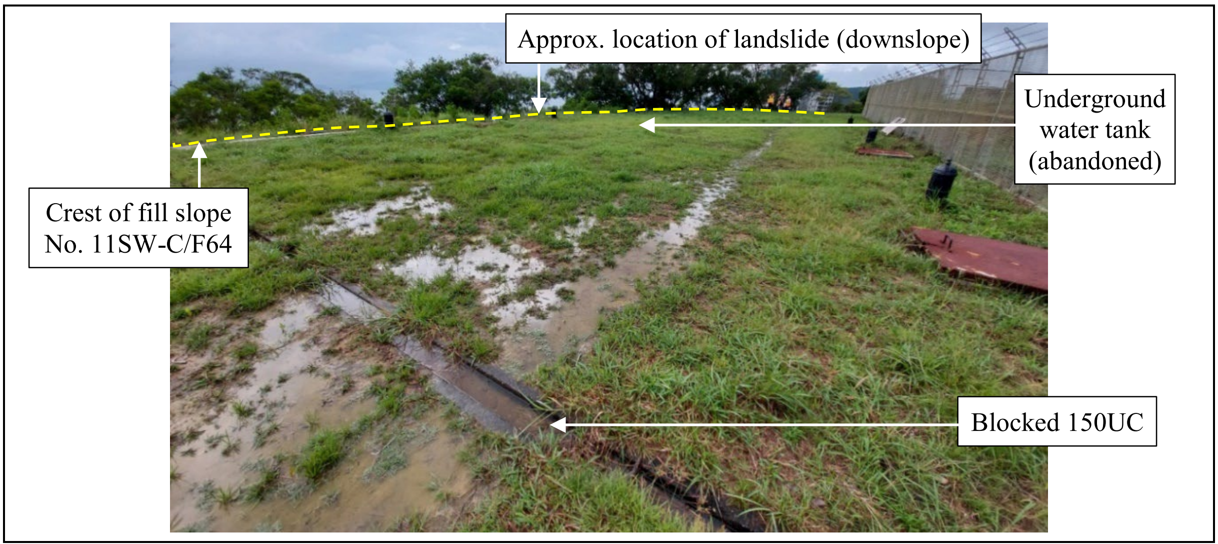


Figure 5.20 Ponding at Crest of Fill Slope No. 11SW-C/F64 (Photograph Taken on 3 August 2021)

6 Debris Mobility

Debris mobility analysis was carried out to evaluate the behaviour of the 2021 landslide and determine the probable apparent friction angle of the landslide debris. The analysis was carried out using DAN-W software, which was developed by Hungr (2010).

The modelled pre-landslide ground profile was derived from the 2020 LiDAR dataset and the as-built records of the rigid barrier (AECOM, 2014). The modelled profile has included the inclined rear wall and containment basin of the rigid barrier but omitted the central core wall and planter. The modelled source volume of 135 m^3 was adopted and no entrainment was considered based on the post-landslide observations. Sensitivity analysis was conducted with a range of apparent friction angles.

The travel distance from the head scarp to the furthest extent of debris deposition was about 50 m and the corresponding travel angle was approximately 35°, with the impedance of the rigid barrier (Figure 5.3). In order to discard the retarding effect of the central core wall and the planter, which were not considered in the model, the analysis results were gauged on the relative proportion of debris deposition on the natural slope above the barrier and that entering into the barrier for comparison with the post-landslide observations (Section 5.3.2). From the analyses, an apparent friction angle of 32° has yielded results best simulating the measured debris distribution and such angle is within the typical range of OHFs in Hong Kong (GEO, 2012b). Details of the debris mobility analyses are presented in Appendix C.

7 Analysis of Rainfall Records

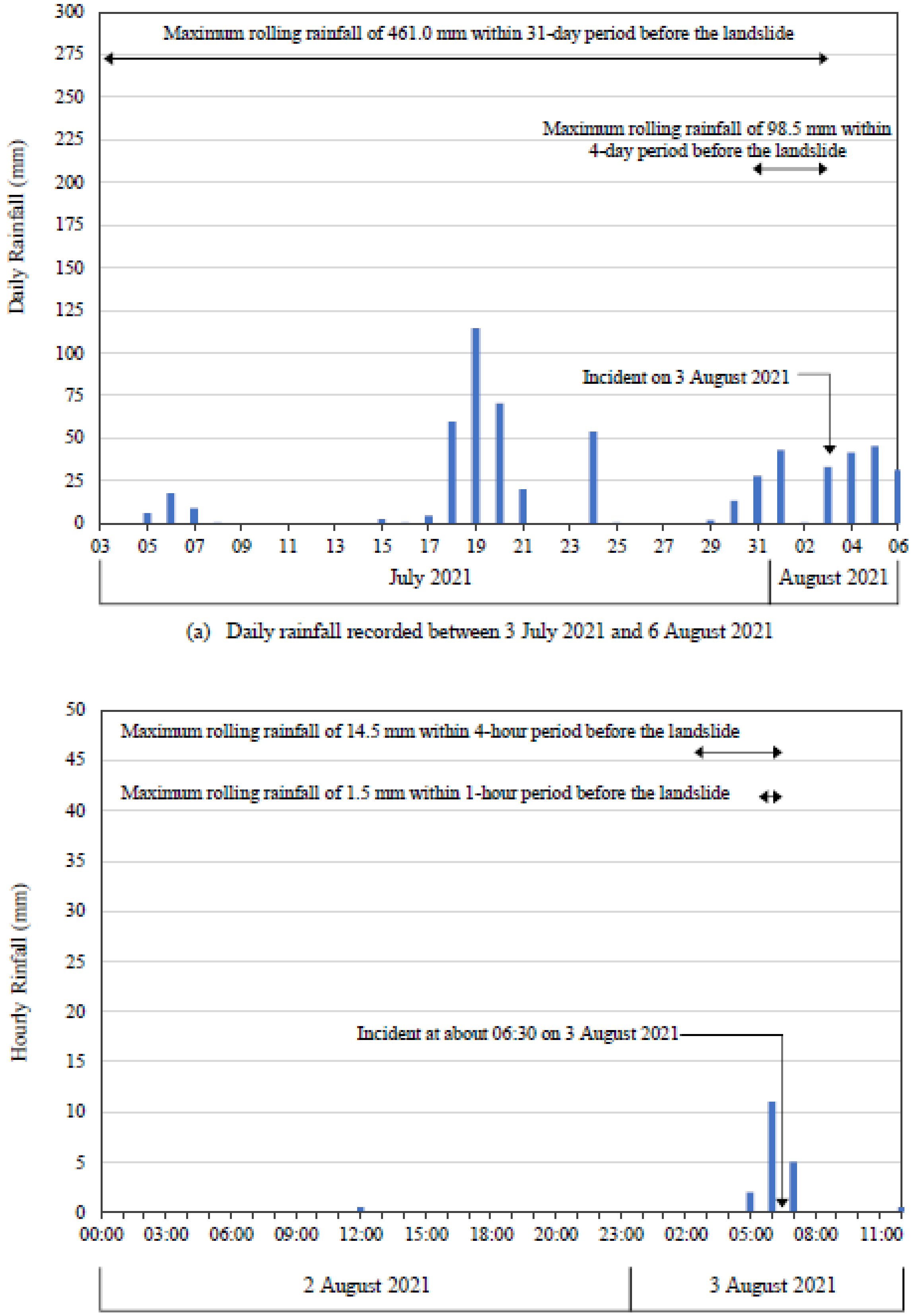
The nearest raingauge to the landslide location is GEO Raingauge No. H03, located at Block 44, Baguio Villa, Pok Fu Lam, about 520 m south of the incident location (Figure 1.1). The raingauge was established in 1978. It records and transmits rainfall data to the GEO and the Hong Kong Observatory (HKO) at 1-minute and 5-minute intervals respectively. The daily rainfall recorded over the month preceding the landslide and the hourly rainfall recorded for the period between 0:00 a.m. on 2 August 2021 and 12:00 p.m. on 3 August 2021 are presented in Figure 7.1. No Rainstorm Warning Signal or Landslip Warning Signal was in effect at the time of the landslide.

The rainfall analysis was carried out by estimating the maximum rolling rainfall preceding the time of occurrence of the landslide for various durations from 5 minutes to 31 days. Results of the rainfall analysis based on the rainfall data recorded by GEO Raingauge No. H03 are presented in Table 7.1. The maximum rolling rainfall for 2 hours, 4 hours, 12 hours, 24 hours, and 48 hours is 14.5 mm, 14.5 mm, 14.5 mm, 15.0 mm and 18.5 mm respectively (Table 7.1).

Table 7.1 Maximum Rolling Rainfall at GEO Rainguage No. H03 for Selected Durations Preceding the 3 August 2021 Landslide and the Estimated Return Periods

Duration	Maximum Rolling Rainfall (mm) (1)(2)	End of Period (3)	Estimated Return Period (years) (4)
5 Minutes	1.5	6:30 a.m. on 3 August 2021	< 2
15 Minutes	1.5	6:30 a.m. on 3 August 2021	< 2
30 Minutes	1.5	6:30 a.m. on 3 August 2021	< 2
1 Hour	1.5	6:30 a.m. on 3 August 2021	< 2
2 Hours	14.5	6:30 a.m. on 3 August 2021	< 2
4 Hours	14.5	6:30 a.m. on 3 August 2021	< 2
12 Hours	14.5	6:30 a.m. on 3 August 2021	< 2
24 Hours	15.0	6:30 a.m. on 3 August 2021	< 2
48 Hours	18.5	6:30 a.m. on 3 August 2021	< 2
4 Days	98.5	6:30 a.m. on 3 August 2021	< 2
7 Days	101.5	6:30 a.m. on 3 August 2021	< 2
15 Days	308.5	6:30 a.m. on 3 August 2021	< 2
31 Days	461.0	6:30 a.m. on 3 August 2021	< 2

Notes:
(1) Maximum rolling rainfall was calculated from 5-minute interval rainfall data.
(2) The nearest raingauge to the landslide location is GEO Raingauge No. H03 (in operation since 1978) located at Block 44, Baguio Villa, Pok Fu Lam, about 520 m south of the landslide location.
(3) The landslide occurred at about 6:30 a.m. on 3 August 2021.
(4) Return periods were estimated based on the method described by Tang & Cheung (2011).



(a) Daily rainfall recorded between 3 July 2021 and 6 August 2021

(b) Hourly rainfall recorded between 00:00 on 2 August 2021 and 12:00 on 3 August 2021

Figure 7.1 Daily and Hourly Rainfall Recorded at GEO Raingauge No. H03

An analysis of the return periods for various durations of rolling rainfall recorded by GEO Raingauge No. H03 was made with reference to the historical rainfall data recorded at the raingauge (Tang & Cheung, 2011). The analysis has shown that the rainfall was not intense and corresponded to a return period of less than two years for all the durations assessed (Table 7.1).

8 Possible Sources of Water

8.1 Surface Runoff Associated with Rainfall

Information from the eye-witnesses has shown that concentrated surface runoff was flowing from above the crest of the landslide into the landslide scar around the time of the landslide on 3 August 2021 (Figure 5.4). With reference to the upslope drainage catchment, a drainage assessment was conducted to estimate the surface runoff that could have reached the landslide location at the time of the landslide in association with rainfall (Appendix D). The runoff could have involved channel overflow from the defective 300UC section on fill slope No. 11SW-C/F64 (Section 5.3.3) and the surface runoff from the natural slope immediately above the landslide location.

The assessment was based on the rainfall data and the drainage conditions observed on site. The catchment area contributing to channel flow along the defective 300UC section is delineated in Figure 8.1. The blocked 150UC channels at the crest platform were neglected due to the lack of functionality at the time of the landslide. Although the blocked 225UC and displaced catchpit on the slope toe (Figure 5.19(a)) would have likely resulted in overspill onto the natural slope north of the landslide location, no loss of channel flow was conservatively assumed.

Based on the assessment, the surface runoff possibly collected by the slope drainage system which could have overflowed at the defective 300UC section, plus the runoff from the natural slope associated with rainfall at the time of the landslide is about 0.7 l/s which is relatively insignificant and does not liken to the observed condition of the prominent concentrated surface flow over the crest of the landslide as noted from the videographic evidence captured shortly after the landslide.

8.2 Service Reservoir Installations and Operations

Following the landslide, information pertaining to the reservoir installations and operations were sought from WSD. According to WSD, the function of the two 225 mm diameter washout pipes is for draining off water at the FWSR during cleaning operations which are typically carried out at 12- to 18-month intervals. The last drain off operation prior to the landslide was carried out between 7 and 10 July 2021. No drain off operation was being undertaken near the time of the landslide. The FWSR had been emptied since late July 2021 pending inspection. The water depth within the FWSR had remained constant at about 0.11 m since around 24 July 2021, showing no abnormal change prior to and during the landslide.

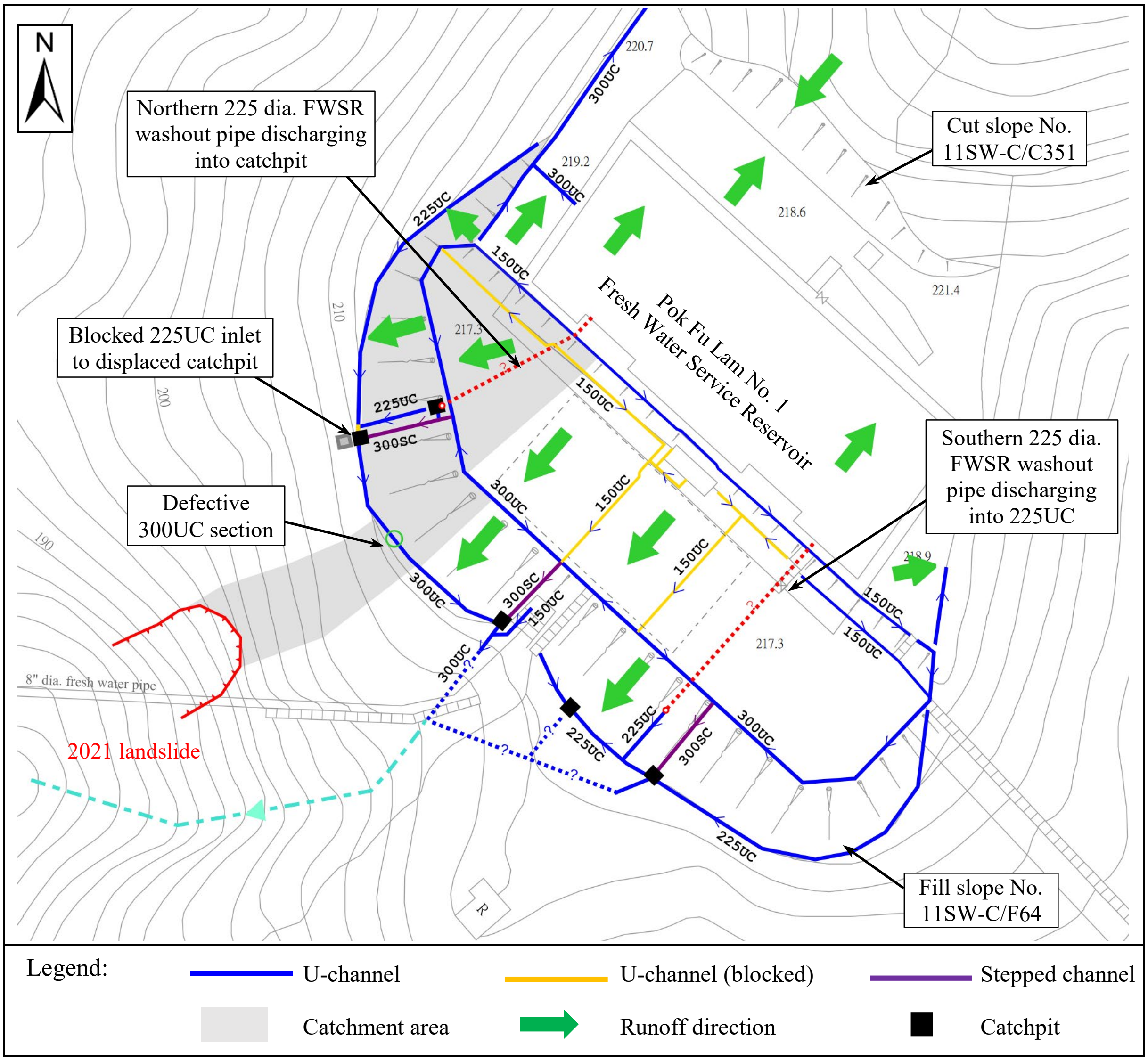


Figure 8.1 Catchment Area in Surface Runoff Review

Following the landslide, WSD has conducted a review of the layout of the water mains near FWSR. Their review has confirmed no overflow, leakages or discharges associated with the reservoir infrastructure (including among others the water pipes, valves, sub-soil drains, outlet points, etc.) as well as any activities being the possible source of water collected by the fill slope surface drainage system in relation to the incident.

9 Diagnosis of Probable Causes of the Landslide

The 3 August 2021 landslide involved a sliding failure on a steep natural terrain (about 40° to 45°). The area at which the landslide initiated is underlain by highly to moderately decomposed rock at shallow depth. Within the thin soil mantle (primarily colluvium), a greater proportion of the near-surface groundmass was susceptible to saturation. Subsequently, a loss in suction and a build-up of transient water pressure in the thin soil mantle could have led to the sliding initiation.

10 Discussion

The landslide was a sliding failure promoted primarily by subsurface flow reaching the landslide location. The locally steepened area and shallow rockhead at the landslide location rendered the groundmass particularly vulnerable to landsliding.

It is postulated that the localised defective slope drainage system of the fill slope and tension cracks on the natural slope had constituted to enhanced infiltration and subsurface flow above the landslide location. The localised defects in the slope drainage system, including separation of a catchpit from the connecting channels, cracked channels and the displaced channel section would have promoted water ingress into the natural slope. Given the non-convergent hillside setting, the observed concentrated surface flow was likely to have originated from overflow of the defective 300UC section directly upslope of the landslide location. Signs of overland flow were evidenced between the defective 300UC section and the landslide location. The tension cracks that existed along the probable concentrated surface flow path could have further promoted infiltration into the natural slope and hence the subsurface flow.

The subject incident highlights that defective slope drainage can lead to unintended surface runoff and increased infiltration, and consequently can result in landsliding events even at some distance from the slope extent. The importance of slope maintenance is reiterated. Based on the post-landslide inspection, defects in the fill slope drainage system appeared to have been present for some time. It was observed that there was no adequate access along the slope toe channel, where defects were identified at the time of the landslide. The latest Engineer Inspection conducted prior to the landslide in April 2021 (Atkins, 2021) recorded a similar observation and therefore provision of maintenance access along the toe channel was recommended to be carried out as part of the preventive maintenance works and such works were being arranged. Inadequate access for maintenance inspection may have been a factor in the condition and performance of the surface drainage system contributing to the landslide. The implication of accessibility for drainage maintenance to drainage/slope performance is highlighted.

In respect of the source of water, given the minimal rainfall preceding the incident, the runoff collected within the surface drainage system of the fill slope is not likely to have resulted solely from the rainfall associated runoff. The surface runoff assessment (Section 8.1) has indicated that the rainfall associated runoff is relatively insignificant and does not liken to the observed prominent concentrated surface flow leading to the landslide location. Whilst the flow was sourced from the upslope areas, it is considered unlikely to be related to any isolated human activities judging from the flow rate and volume. The primary water source that could have contributed to the landslide remains suspicious. Although WSD's review of the FWSR installations and operations did not identify any potential water source contributory to the landslide, the possibility of any unknown leakage from the reservoir services/facilities cannot be precluded.

The susceptibility of HLC No. 11SW-C/DF9 to the natural terrain landslide hazards, including OHFs as in the subject incident, was previously identified in the Stage 3(H) Study under the LPMitP. Incidentally, the 2021 landslide occurred on the locally steepened area below the defective 300UC section where the study identified that OHF could occur. The rigid barrier constructed had satisfactorily arrested all the landslide debris that had entered the containment basin and the downslope facilities were not affected. Whilst some minor debris reached the outer wall, the configuration of the key barrier components prevented any debris from going beyond the rigid barrier. The debris mobility was largely reduced when the debris reached the levelled containment basin at the toe of the inclined rear wall. It is noted that the majority of the debris entering the containment basin had accumulated at the toe of the inclined rear wall. The actual amount of debris impact on the central core wall is limited (viz. a thin veneer of debris generally less than 0.6 m thick above the planter). The barrier structure was found subjected to negligible deformation or damage following the landslide. In fact, the volume of debris reaching the barrier in the current incident (about 68 m^3) was much less than that considered in the Stage 3(H) Study (485 m^3). The apparent friction angle of the landslide debris as determined (32°) was significantly higher than the one considered for OHFs in the Stage 3(H) Study (20°), revealing a conservative design adopted in the early days before the guidelines on debris mobility assessment has become more mature (GEO, 2012b). The performance of the barrier is yet to be tested by a more sizeable and/or mobile landslide event.

11 Conclusions

The 3 August 2021 landslide (GEO Incident No. 2021/08/3020) involved an OHF which occurred under light rainfall on the natural hillside above Block 3 of Middleton Towers, 140 Pok Fu Lam Road. Some of the landslide debris had deposited on the hillside. The remaining landslide debris was fully arrested by the rigid barrier at the toe of the catchment rendering no adverse consequence to the downslope facilities. No noticeable deformation nor damage were observed on the barrier. As the scale and mobility of the landslide are far from the previous design considerations, the performance of the barrier is yet to be tested.

The landslide occurred on a locally steepened area and was probably caused by the build-up of transient water pressure within the thin soil mantle above the shallow rockhead. Enhanced infiltration associated with localised defects in the surface drainage on a fill slope at some distance above the landslide location was diagnosed to have contributed to the landslide. The importance of slope maintenance is reiterated. In addition, the implication of accessibility for drainage maintenance to drainage/slope performance is highlighted.

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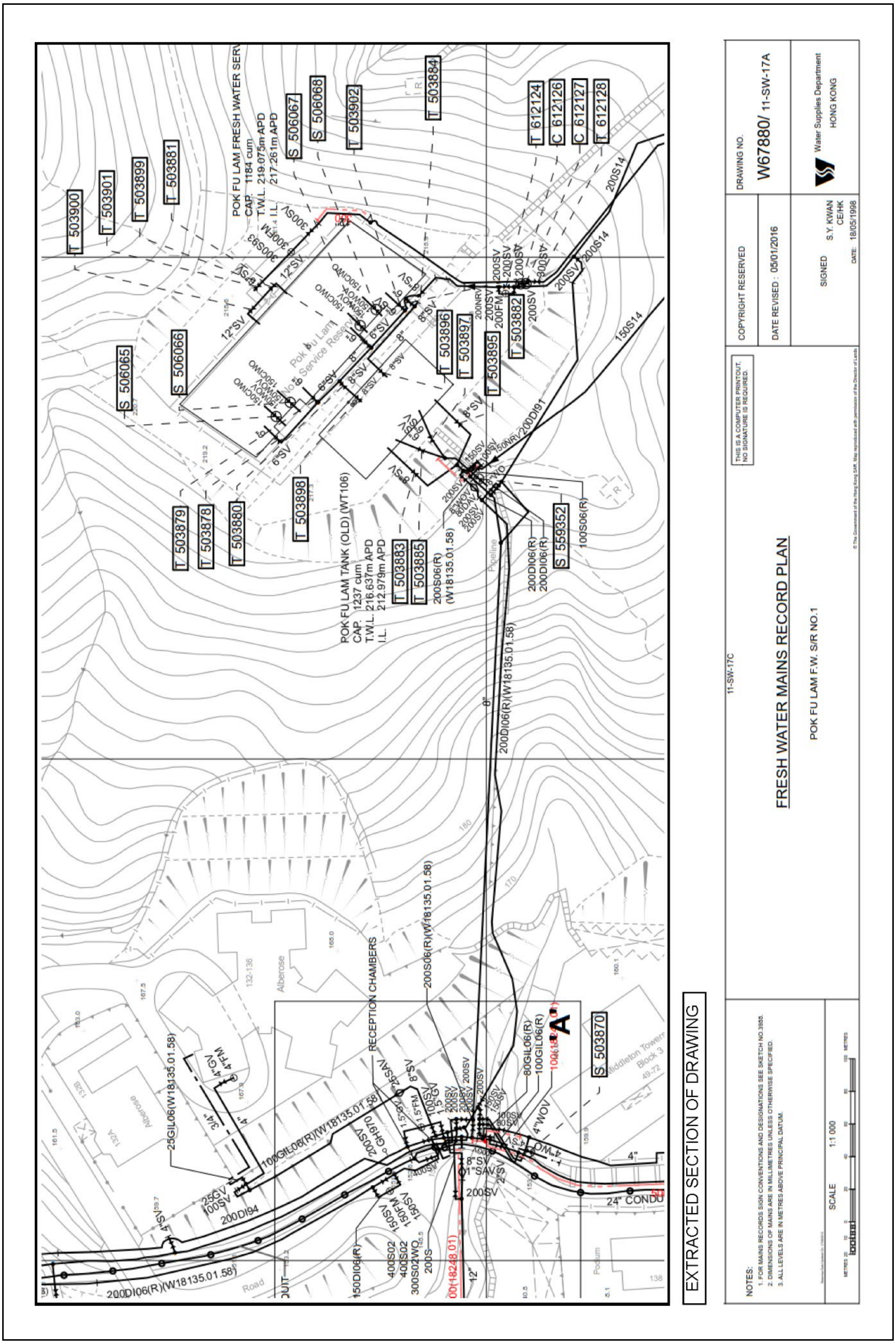
Appendix A

Record Drawings of Pok Fu Lam No. 1 Fresh Water Service Reservoir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11-SW-17C
DRAWING NO.
W67880/ 11-SW-17A
COPYRIGHT RESERVED
DATE REVISED : 05/01/2016
SIGNED S.Y. KWAN CE/HK
DATE: 18/05/1998
Water Supplies Department HONG KONG
THIS IS A COMPUTER PRINTOUT. NO SIGNATURE IS REQUIRED.
SCALE 1:1 000
NOTES:
POK FU LAM FRESH WATER SERV
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T.W.L. 219.075m APD
I.L. 217.261m APD
POK FU LAM TANK (OLD) (WT106)
CAP. 1237 cum
T.W.L. 216.637m APD
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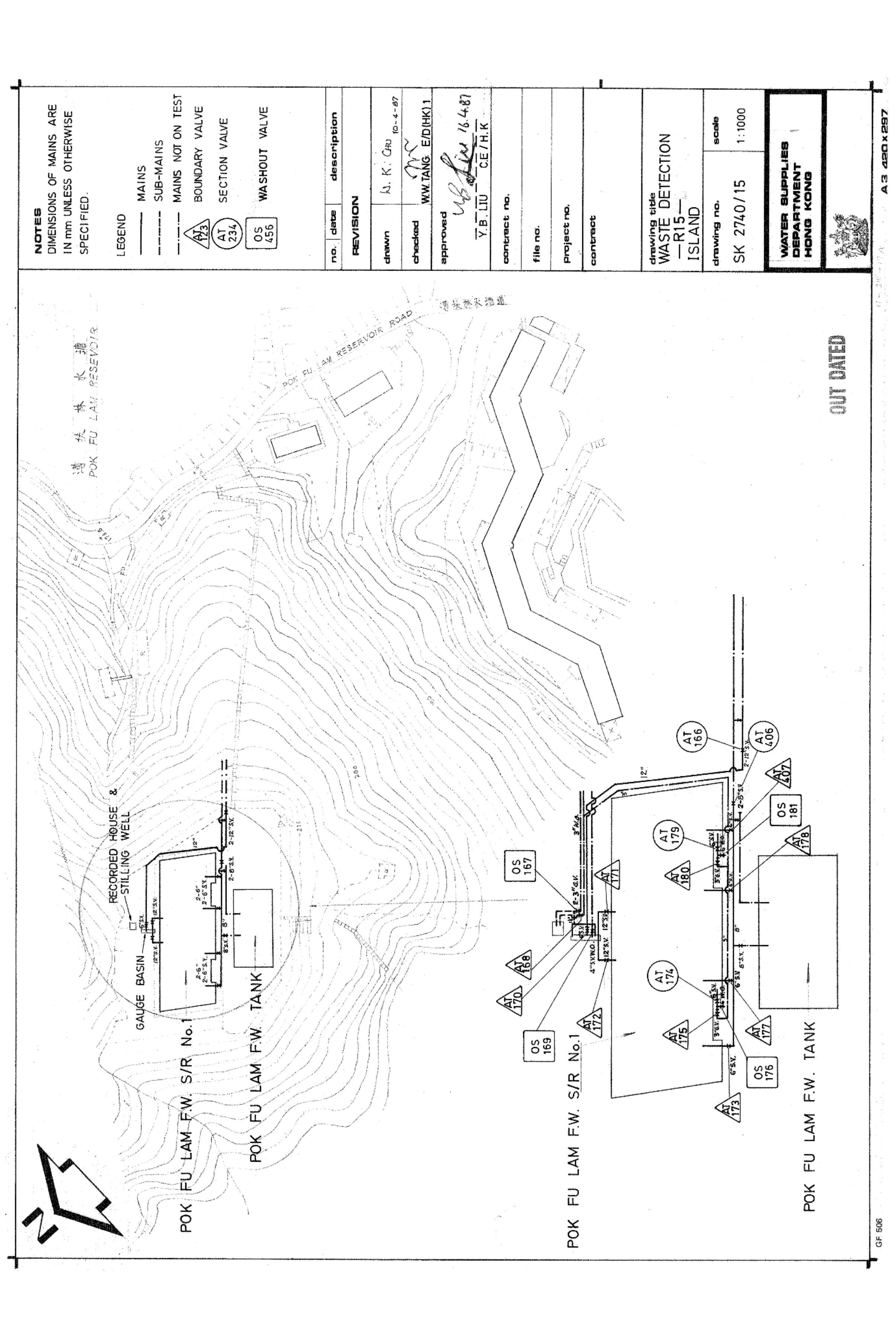
RECEPTION CHAMBERS
200DI06(R)(W18135.01.58)
Alberose
Middleton Towers Block 3



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AT 234
SECTION VALVE
OS 456
WASHOUT VALVE
no.
date
description
REVISION
drawn
checked
W.W. TANG E/D(HK)1
approved
Y.B. LIU CE/H.K
contract no.
file no.
project no.
contract
drawing title
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drawing no.
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POK FU LAM RESERVOIR
POK FU LAM RESERVOIR ROAD
薄扶林水塘道
RECORDED HOUSE & STILLING WELL
GAUGE BASIN
POK FU LAM F.W. S/R No.1
POK FU LAM F.W. TANK
OS 167
OS 169
OS 176
OS 181
AT 166
AT 406
AT 407
AT 179
AT 180
AT 171
AT 178
AT 168
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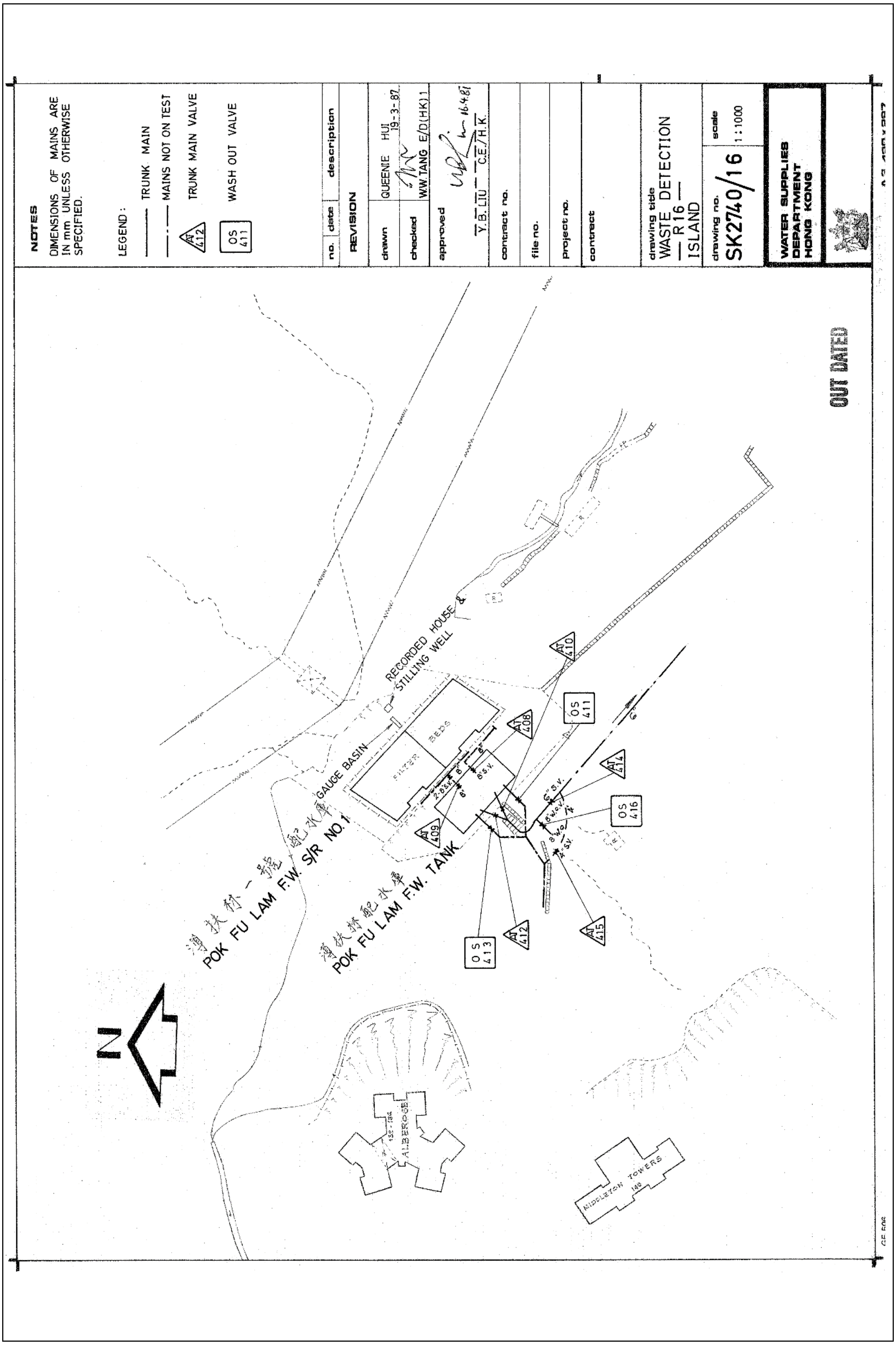
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OS 411 WASH OUT VALVE
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checked W.W. TANG E/D(HK)1
approved Y.B. LIU C.E./H.K.
contract no.
file no.
project no.
contract
drawing title
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— R16 —
ISLAND
drawing no.
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FILTER BEDS
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POK FU LAM F.W. S/R NO.1
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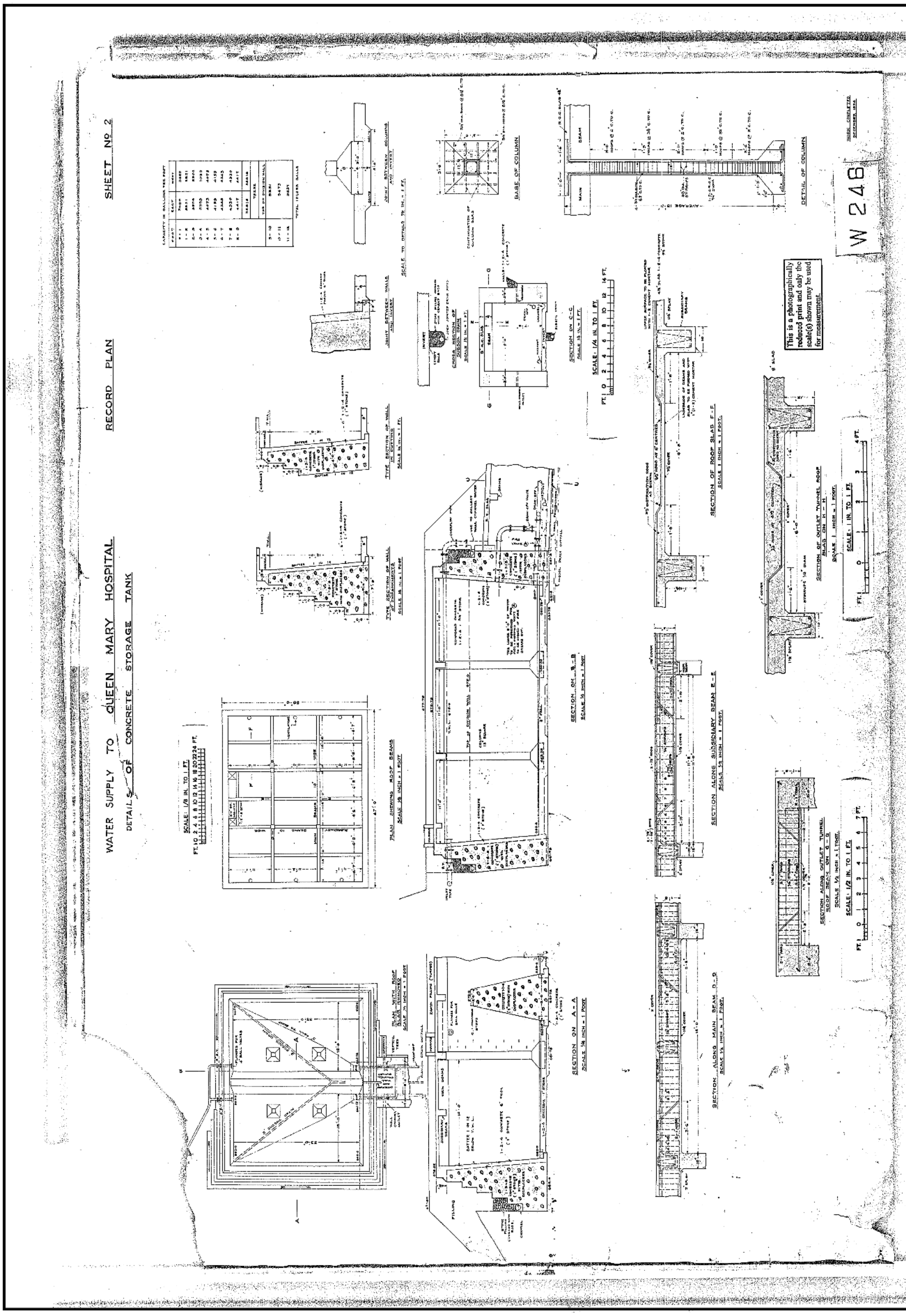

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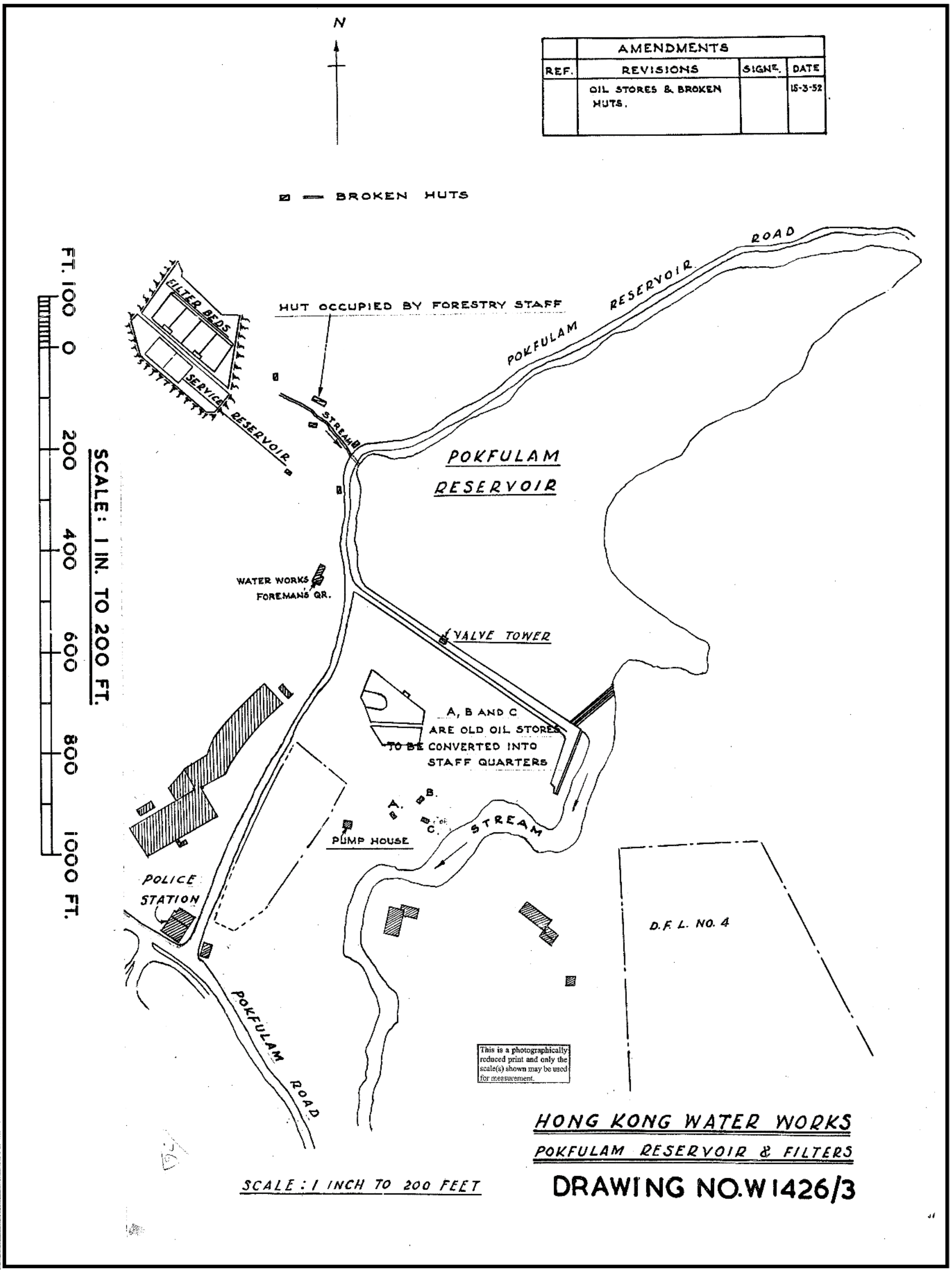
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AMENDMENTS
REF.
REVISIONS
SIGNE.
DATE
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15-3-52
BROKEN HUTS
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FILTER BEDS
SERVICE RESERVOIR
STREAM
POKFULAM RESERVOIR ROAD
POKFULAM RESERVOIR
WATER WORKS FOREMANS QR.
VALVE TOWER
A, B AND C ARE OLD OIL STORES TO BE CONVERTED INTO STAFF QUARTERS
A.
B.
C.
PUMP HOUSE
STREAM
POLICE STATION
D.F. L. NO. 4
POKFULAM ROAD
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SCALE: 1 IN. TO 200 FT.
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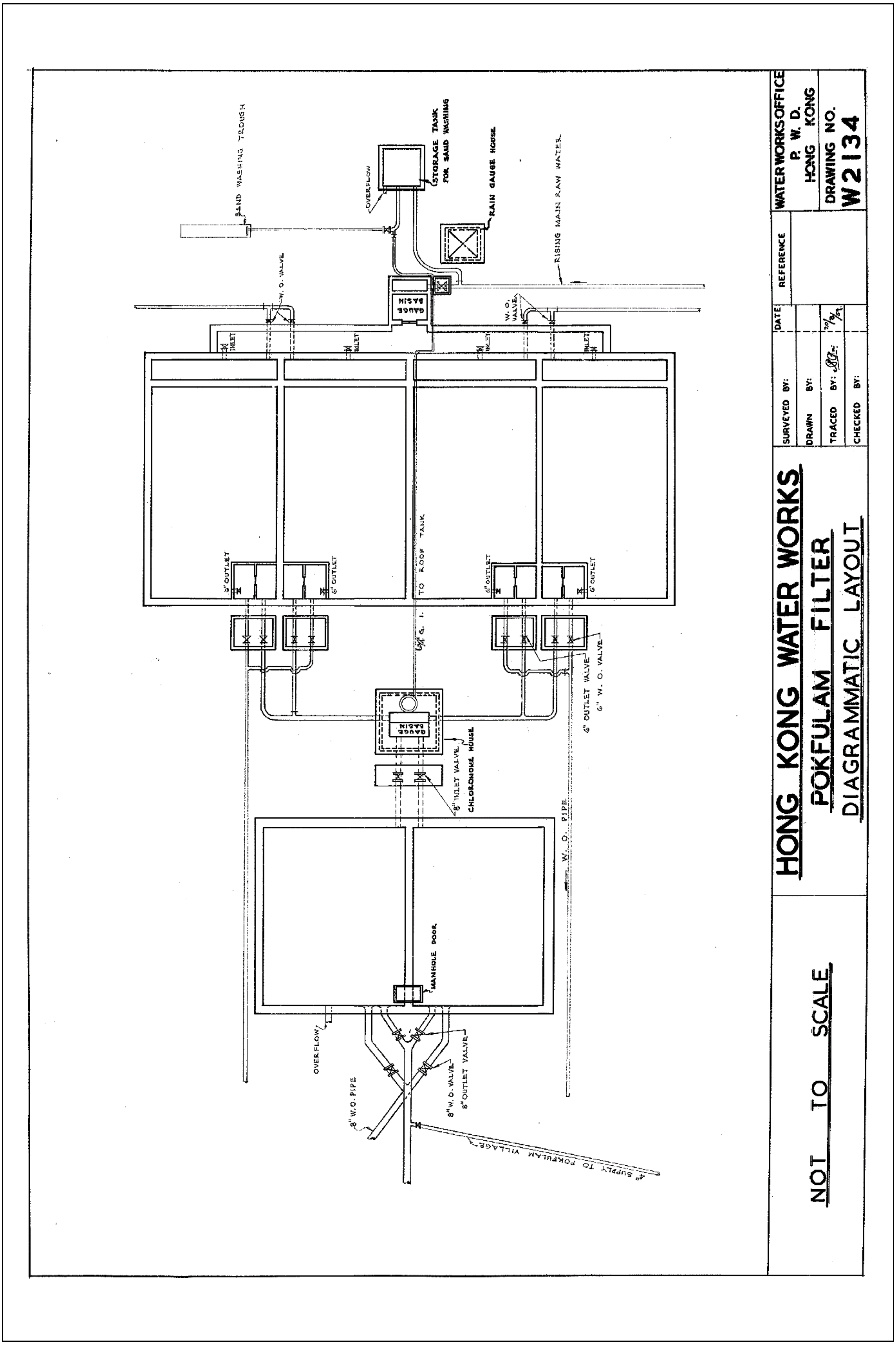
SCALE: 1 INCH TO 200 FEET
DRAWING NO.W1426/3



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CHECKED BY:
DATE
REFERENCE
WATER WORKS OFFICE
P. W. D.
HONG KONG
DRAWING NO.
W2134
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OVERFLOW
STORAGE TANK FOR SAND WASHING
RAIN GAUGE HOUSE
RISING MAIN RAW WATER
W. O. VALVE
GAUGE BASIN
INLET
6" OUTLET
TO ROOF TANK
6" OUTLET VALVE
6" W. O. VALVE
CHLORONOME HOUSE
8" INLET VALVE
W. O. PIPE
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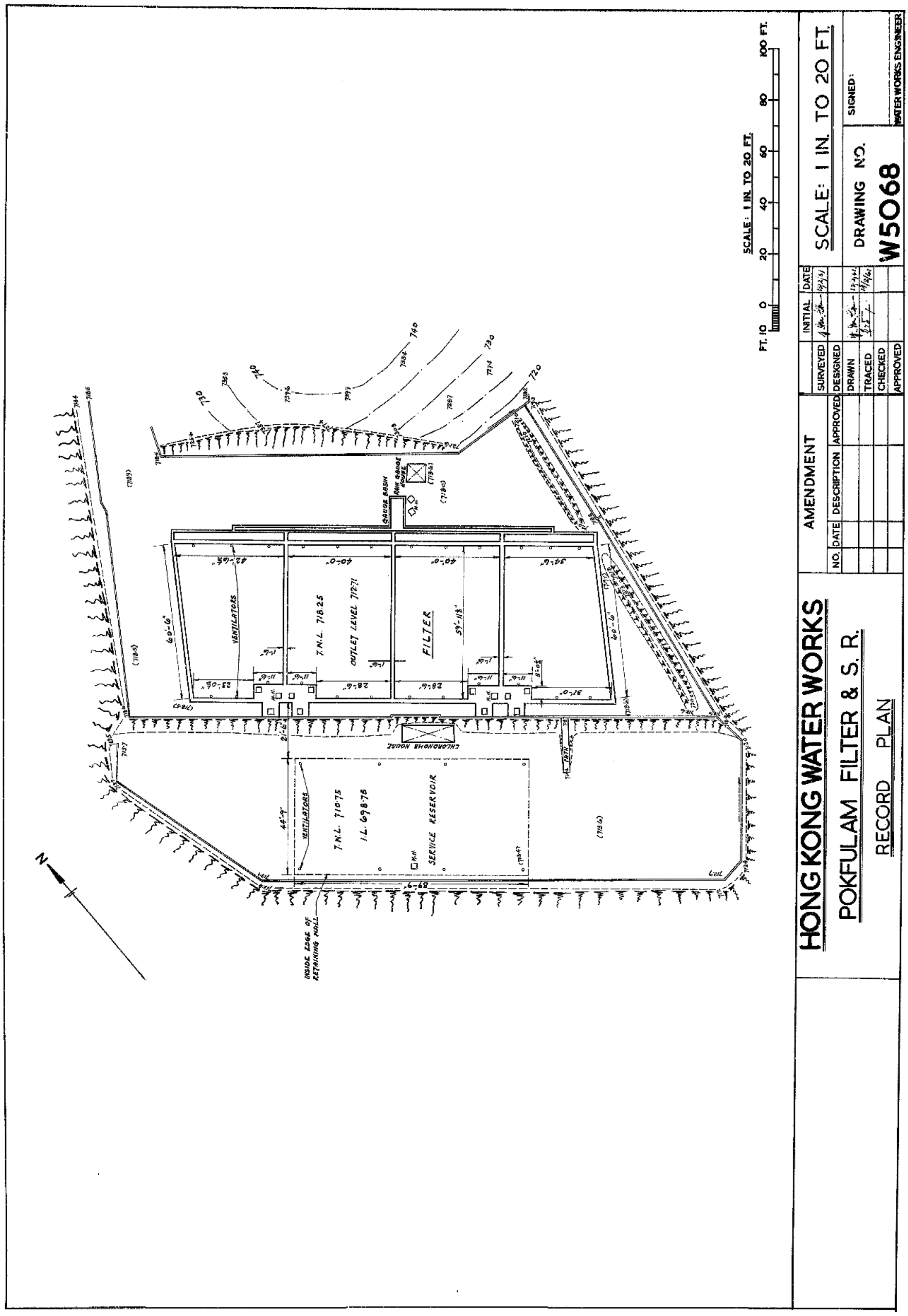
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I.L. 698.75
CHLORONOME HOUSE
INSIDE EDGE OF RETAINING WALL
N

Appendix B

Aerial Photograph Interpretation

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B.1 Introduction

This Appendix presents an aerial photograph interpretation (API) of the August 2021 landslide location and its vicinity to identify a detailed site history including geomorphological characteristics and past instabilities. More than 65 pairs of aerial photographs have been reviewed covering the period from 1924 to 2021 (Table B1). Pertinent observations from the API are summarised in Figure B1.

B.2 Summary

The earliest available aerial photographs in 1924 show natural terrain at and above the 2021 landslide location with ongoing construction at the toe of the catchment. In 1945, a westerly trending ephemeral drainage line is apparent within a valley which characterises catchment on which the landslide occurred. As observed in 1963, the small valley is bounded to the north and south by steep southwest sloping, rounded spurlines, and to the east by a steeply sloping planar sideslope. The sideslopes that form the valley are steep concave-planar and incised, generally facing north, south and west. A change-in-slope is apparent above the 2021 landslide location, on the west-facing sideslope, from gently sloping convex morphology at the crest, to steeply sloping and planar-concave toward the toe.

Since the earliest available photographs in 1924, the upper and lower parts of the catchment have undergone development for Pok Fu Lam No. 1 Fresh Water Service Reservoir (FWSR) and Middleton Towers respectively. The mid-part of the catchment, where the 2021 landslide originated, has remained largely unaffected by the development.

The FWSR with the associated cut and fill slopes (Feature Nos. 11SW-C/C351 and 11SW-C/F64) and pipelines traversing the catchment were constructed between 1924 and 1945. Construction of Middleton Towers started in 1963 and was completed in 1972. Upgrading works to fill slope No. 11SW-C/F64 below the FWSR was carried out in 1999. Construction of rigid barrier No. 11SW-C/ND14 at the toe of the catchment started in 2012 and was completed by 2013.

From 1945 to 2013, areas of erosion were observed at or directly upslope of the 2021 landslide location, possibly associated with localised instability, anthropogenic activity or faunal disturbance. Much of the catchment was masked by dense vegetation since 1963, with occasional vegetation clearance carried out on the fill slope throughout the years. In 1976, ENTLI No. 11SW-C0587E is clearly visible as a landslide scar on the north-facing sideslope below the southern spurline. In 2000, a gully feature, observed as a linear break-in-slope was apparent downslope of the toe of fill slope No. 11SW-C/F64, possibly associated with erosion and/or instability. In 2005, landslide Incident No. 2005/08/0369 occurred on the slope near the toe of the catchment, below the southern spurline on the north-facing sideslope, which was subsequently shotcrete covered. Minimal changes were observed at the 2021 landslide location from the earliest aerial photographs to 2017. From 2017 to the latest photographs (2021), signs of potential ongoing erosion and/or instability were observed as mentioned in Section B.3.

B.3 Detailed Observations

Year Observations

1924 High level (unknown altitude) single aerial photograph of moderate quality. Construction of the FWSR and Middleton Towers have not yet started. Alberose is under construction to the north of the Middleton Towers location. Small areas of high reflectance are apparent upslope of the incident location, possibly associated with anthropogenic activity, erosion and/or instability. The catchment is masked by moderately dense shrub/grassy vegetation. A footpath is visible along the northern spurline leading to the location of the FWSR.

1945 High level (20000 ft) stereopair of good quality. The catchment on which the landslide occurred is characterised by a small valley bounded to the north and south by steep southwest sloping, rounded spurlines, and to the east by a steeply sloping, west-facing, planar sideslope. A westerly trending ephemeral drainage line is apparent within the valley. The north- and south-facing sideslopes that form the valley are steep concave-planar and incised. The north-facing sideslope is obscured by shadow cover. A prominent footpath is apparent on the southern spurline. A change-in-slope is apparent on the west-facing sideslope from gently sloping planar-convex morphology at the crest, to steeply sloping and planar-concave toward the toe. The FWSR was constructed with a surrounding large area of high reflectance associated with the fill platform and a fill slope (Feature No. 11SW-C/F64). A drainage channel is visible along the outer edge of the fill platform observed as a band of high reflectance. A drainage channel is also visible beneath the location of the northern 225 mm diameter FWSR washout pipe. A linear band of higher reflectance is apparent traversing the site along a similar alignment to the 8" diameter fresh water pipe, leading to the culvert located at the mid-point of fill slope No. 11SW-C/F64 beneath the abandoned underground water tank. This is the first observation of the fresh water pipe which ruptured during the 2021 landslide. Two small areas of high reflectance are visible upslope of the fresh water pipe, split by a gully, possibly associated with anthropogenic disturbance, shallow erosion and/or instability (E1). A footpath connects both areas. Larger areas of high reflectance are apparent upslope of the gully feature, also connected by footpaths, probably associated with anthropogenic disturbance. Alberose is constructed with the initial formation of cut slope No. 11SW-C/C92.

1956 High level (16700 ft) stereopair of good quality. Partial coverage of the area of the FWSR. The location of the 2021 landslide is not visible.

Year	Observations
1963	Low level (2700 ft) stereopair of excellent quality. The 8" diameter fresh water pipe is apparent traversing the site with vegetation cleared along its extent. The incident location appears to be defined by a sharp change-in-slope (E2) masked by a line of dense vegetation. Two minor depressions (E3) are present on the north-facing sideslope at the approximate location of subsequent landslides in 1976 (L1) and 2005 (L2). Small footpaths/tracks are observed below fill slope No. 11SW-C/F64 and upslope of the 2021 landslide location. Alberose is redeveloped with expansion works on cut slope No. 11SW-C/C92. Much of the catchment is becoming masked by trees. Site formation works at the location of Middleton Towers Block 2 are ongoing.
1964	High level (12500 ft) single aerial photograph of moderate quality. No significant changes in the catchment area are apparent, except that Blocks 1 and 2 of Middleton Towers are under construction.
1967	Medium level (6250 ft) stereopair of good quality. An area of high reflectance is apparent on the southern spurline below fill slope No. 11SW-C/F64 probably associated with dumping activity. Narrow footpaths are still visible around the toe of the fill slope, above the 2021 landslide location. The FWSR is now covered by a roof constructed of multiple quonset rows. Construction of Blocks 1 and 2 of Middleton Towers appears to be complete. Minor vegetation clearance and slope cutting works are visible at the location of Block 3 Middleton Towers.
1968	Low level (2000 ft) stereopair of excellent quality. Two small square areas of high reflectance are apparent on the northern portion of the service reservoir fill platform, with one located just above a drainage channel. These may be associated with construction works. The 2021 landslide location appears lighter in colour compared to the surrounding terrain, probably associated with less vegetation growth. Narrow footpaths are still present at and above the 2021 landslide location. Construction of Middleton Towers Block 3 appears to be nearly complete.
1972	High level (13000 ft) stereopair of good quality. No significant changes except that the catchment is becoming densely vegetated. Block 3 Middleton Towers appears to be complete.
1973	High level (12500 ft & 3000ft) stereopair of good quality. No significant changes are apparent.
1974	High level (12500 ft) stereopair of good quality. No significant changes are apparent.
1975	High level (12500 ft) stereopair of good quality. No significant changes are apparent.

Year	Observations
1976	Low level (4000 ft) stereopair of good quality. At the location of the northern FWSR washout pipe outlet, a drainage pipe is apparent over fill slope No. 11SW-C/F64. The footpaths above the 2021 landslide location are no longer apparent.
1976	High level (12500 ft) stereopair of good quality. A landslide scar (ENTLI No. 11SWC0587E) is apparent in an existing concave depression on the southern sideslope within the catchment (L1), observed as a wide linear area of high reflectance with vegetation removed along its extent. The landslide debris appears to terminate within the ephemeral drainage line.
1977	Low level (4000 ft) stereopair of good quality. The landslide (L1) observed in 1976 is more clearly visible. An area of high reflectance (E4) is apparent between the culvert and the 2021 landslide location, possibly associated with erosion and/or instability. Footpaths were previously identified in this area.
1979	Low level (5500 ft) stereopair of good quality. No significant changes are apparent. The recent landslide scar observed in 1976 is still visible. North of the 2021 landslide location, a linear high reflective feature is apparent connecting to the drainage pipe first observed in 1976, possibly associated with water diversion. Small areas of high reflectance are apparent throughout the fill slope above the 2021 landslide location possibly associated with anthropogenic activity or faunal disturbance.
1980	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except that the horizontal linear feature connected to the drainage pipe north of the incident location is no longer visible. A footpath is visible below the culvert.
1981	Low level (4000 ft) single photograph of good quality. No significant changes are apparent.
1982	High level (10000 ft) stereopair of good quality. No significant changes are apparent.
1983	High level (10000 ft) stereopair of good quality. No significant changes are apparent.
1984	Low level (4000 ft) stereopair of good quality. No significant changes are apparent.
1985	High level (10000 ft) stereopair of good quality. No significant changes are apparent.

Year	Observations
1986	Low level (4000 ft) stereopair of good quality. No significant changes are apparent.
1987	Low level (4000 ft) stereopair of good quality. Small areas of high reflectance (E5, E6 and E7) are apparent below fill slope No. 11SW-C/F64 on the vegetated slope, possibly associated with anthropogenic or faunal disturbance.
1988	Low level (4000 ft) stereopair of good quality. No significant changes are apparent.
1989	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except narrow trails are apparent below fill slope No. 11SW-C/F64, upslope of the incident location. These trails may be faunal or man-made in origin.
1989	High level (10000 ft) stereopair of good quality. Fill slope No. 11SW-C/F64 appears to have undergone vegetation clearance over the full slope extent.
1990	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except that small areas of high reflectance (E5, E6 and E8) are apparent below the toe of fill slope No. 11SW-C/F64, possibly associated with faunal disturbance, erosion and/or instability.
1991	Low level (4000 ft) stereopair of good quality. At the southern portion of fill slope No. 11SW-C/F64, a linear area of high reflectance is apparent along the toe. A linear channel within the high reflectance is probably associated with the construction of the 200 mm diameter buried fresh water pipe connecting the FWSR and the exposed 8" diameter fresh water pipe. A footpath extends from the crest of cut slope No. 11SW-C/C92 across the 2021 landslide location to the area of the construction works.
1992	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except small areas of high reflectance (E7 and E8) are apparent at the toe of the fill slope possibly associated with erosion and/or instability or faunal/anthropogenic disturbance. Vegetation clearance is apparent over fill slope No. 11SW-C/F64.
1993	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except that the construction works first observed in 1991 are now covered by dense vegetation. The disturbed areas observed in 1992 are still visible.
1994	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except the disturbed areas observed in 1993 are becoming masked by dense vegetation. The catchment remains obscured by dense vegetation cover including the footpath seen in 1992.

Year	Observations
1995	Low level (3500 ft) stereopair of good quality. No significant changes are apparent except that vegetation clearance is apparent on fill slope No. 11SW-C/F64.
1996	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except that fill slope No. 11SW-C/F64 is covered by dense grass vegetation.
1997	Low level (4000 ft) stereopair of good quality. Four prominent areas of high reflectance are apparent on fill slope No. 11SW-C/F64 and another one is apparent on the fill platform. These five areas are associated with ground investigation works (trial pits) carried out in connection with the fill slope upgrading works.
1998	Low level (4000 ft) stereopair of good quality. No significant changes are apparent at the 2021 landslide location. To the southeast, a haul road is constructed below the fill slope and construction works are ongoing on the slope. The former trial pit locations are still visible on the fill slope.
1999	Medium level (5000 ft) stereopair of moderate quality. Fill slope No. 11SW-C/F64 appears to have undergone upgrading works with reconstruction of the surface drainage system, including the addition of a drainage channel along the toe of the slope. On the northern portion of the slope, a westerly aligned drainage channel connects the crest channel to the toe channel. At this location, an adjacent drainage channel is also aligned across the slope but terminates below the slope crest at the location of the northern 225 mm diameter FWSR washout pipe. The westerly aligned drainage channels are at the location of the previous drainage pipe first observed in 1976. Vegetation has been removed beyond the toe channel onto the natural hillside below. The haul road is still clearly visible. No significant changes to the 2021 landslide location are apparent.
2000	Low level (4000 ft) stereopair of good quality. A gully feature (E9), observed as a linear break-in-slope is apparent directly below and broadly parallel to the northern toe channel on fill slope No. 11SW-C/F64. An area of lighter colour is observed just below the break-in-slope, possibly associated with erosion and/or instability. No significant changes to the 2021 landslide location are apparent.

Year	Observations
2001	Low level (4000 ft) stereopair of good quality. On the northern portion of the slope, a catchpit is constructed above the westerly aligned drainage channel which terminates below the slope crest. An area of high reflectance is apparent on the platform just above the catchpit, possibly associated with connection of the northern 225 mm diameter FWSR washout pipe to the new catchpit. An area of high reflectance is observed on the slope below the catchpit connecting the westerly aligned drainage channel to the toe channel, possibly associated with erosion and/or instability or construction of a concrete support block. Erosion control matting is apparent below the crest channel of the fill slope. Trees are starting to grow on the fill slope. No significant changes to the 2021 landslide location are apparent.
2002	Low level (3500 ft) stereopair of moderate quality. No significant changes to the 2021 landslide location are apparent.
2003	Low level (4000 ft) stereopair of good quality. No significant changes are apparent except the area below the fill slope toe channel is becoming densely vegetated by grass and trees. The fill slope is also becoming more vegetated.
2004	Low level (2500 ft) stereopair of good quality. No significant changes are apparent.
2005	Medium level (6000 ft) stereopair of moderate quality. A landslide (Incident No. 2005/08/0369) is apparent near the toe of the catchment within an existing concave depression below the southern spurline (L2). The landslide is in the shadow of Block 3 Middleton Towers and is partially covered by trees, obscuring the extent of the landslide scar and debris trail. No other significant changes to the area are apparent.
2006	Low level (4000 ft) stereopair of good quality. The landslide scar visible in 2005 appears to be covered by shotcrete. No other significant changes are apparent.
2007	Low level (3000 ft) stereopair of good quality. No significant changes are apparent.
2008	Medium level (6000 ft) stereopair of good quality. No significant changes are apparent except a small area of high reflectance (E10) is apparent on the northern portion of the fill slope, possibly associated with erosion and/or instability. The catchment becomes completely covered by dense vegetation by March 2008.
2009	Low level (3000 ft) stereopair of good quality. No significant changes are apparent.
2010	Medium level (6000 ft) stereopair of good quality. No significant changes are apparent.

Year	Observations
2011	Medium level (6000 ft) stereopair of good quality. A small area of vegetation clearance (E11) is observed in the catchment on the southern spurline, south of the 2021 landslide location, possibly associated with erosion and/or instability.
2012	Medium level (6000 ft) stereopair of good quality. A large area of vegetation clearance is apparent at the toe of the catchment, associated with the start of construction works on rigid barrier No. 11SW-C/ND14.
2013	High level (8000 ft) stereopair of good quality. Construction of rigid barrier No. 11SW-C/ND14 appears to be complete.
2013	Low level (2000 ft) stereopair of good quality. Small areas of high reflectance (E12) are apparent on the fill slope observed as brown spots. These may be associated with erosion and/or minor instability.
2014	Medium level (6000 ft) stereopair of good quality. No significant changes are apparent except construction works appear to have been carried out at the crest platform at the southern end of fill slope No. 11SW-C/F64.
2015	Medium level (6000 ft) stereopair of good quality. No significant changes are apparent.
2016	Medium level (6000 ft) stereopair of good quality. No significant changes are apparent.
2017	Medium level (6000 ft) stereopair of good quality. A small area of cleared vegetation (E13) is apparent below the incident location, possibly associated with erosion and/or instability.
2018	Medium level (6900 ft) stereopair of good quality. The small area of cleared vegetation possibly associated with erosion and/or instability observed in 2017 has expanded upslope (E13). Vegetation clearance is apparent along the lower portion of the fill slope with the removal of trees above and below the toe channel. Vegetation cover continues to become denser across the catchment.
2019	Medium level (6000 ft) stereopair of moderate quality. No significant changes are apparent except the cleared area observed in 2017 and 2018 remains visible. The fill slope is masked by dense grass cover.

Year	**Observations**
2021	A low-level UAV-derived orthophotograph and oblique aerial photographs taken by CEDD Survey Division. The 2021 landslide is apparent. Some landslide debris is deposited on the lower portion of the hillside above rigid barrier No. 11SW-C/ND14 with the remaining debris arrested by the barrier. A section of the 8" diameter fresh water pipe has been ruptured by the landslide and the detached pipe segment is visible in the debris at the crest of the rigid barrier. Soil, rock fragments and trees are visible in the debris. Rock outcrops are apparent in the landslide scar above the pre-failure alignment of the fresh water pipe. The concrete staircase and adjacent shotcrete areas are visible on the southern side of the scar but are covered by debris on the northern side. Directly upslope of the landslide, the displaced section of the fill slope toe channel is apparent. Some bare areas are also apparent on the northern portion of the fill slope (E12).

Table B1 List of Aerial Photographs (Sheet 1 of 2)

Date of Photograph (dd/mm/yyyy)	Photograph Number [(1)]	Altitude (ft)
1924	Y00044	-
11/11/1945	Y00466 &Y00465	20000
27/12/1956	Y3175 & Y3176	16700
01/02/1963	Y07241, Y07242 & Y07243	2700
13/12/1964	Y12828	12500
16/05/1967	Y13274, Y13275 & Y13276	6250
1968	Y14084 & Y14085	2000
03/10/1972	2297, 2298, 2303 & 2304	13000
24/10/1973	5464 & 5465	12500
12/12/1973	7048	3000
21/11/1974	9691 & 9692	12500
19/12/1975	11701 & 11702	12500
28/01/1976	12653 & 12654	4000
04/11/1976	15918 & 15919	12500
21/12/1977	20469, 20470 & 20471	4000
30/11/1978	23835 & 23836	4000
05/12/1978	23879 & 23880	4000
28/09/1979	27094 to 27097	5500
16/04/1980	32026 & 29827	4000
28/11/1982	33417 & 33418	10000
18/05/1981	37411	4000
26/10/1981	39014 & 39015	10000
10/10/1982	44473 & 44474	10000
30/11/1983	51342 & 51343	10000
03/02/1984	53677 & 53678	4000
07/07/1985	A01703 & A01704	10000
20/09/1986	A06015, A06016 & A06017	4000
21/12/1986	A08246 & A08247	10000
09/09/1987	A10363 & A10364	4000
27/09/1988	A14502 & A14503	4000
16/08/1989	A17779, A17780 & A17781	4000
16/08/1989	A17779, A17780 & A17781	4000
20/11/1989	A19394 & A19395	10000
20/03/1990	A20830 & A20831	4000
02/10/1991	A27809 & A27810	4000

Note: (1) Photographs numbered with CN, CW, CS, or E are in colour. All others are black and white.

Table B1 List of Aerial Photographs (Sheet 2 of 2)

Date of Photograph (dd/mm/yyyy)	Photograph Number [1]	Altitude (ft)
12/05/1992	A30951 & A30952	4000
09/07/1993	A35413 & A35414	4000
17/11/1994	CN8113 & CN8114	4000
07/12/1995	CN12686 & CN12687	3500
23/10/1996	CN15568 & CN15569	4000
23/07/1997	CN17662 & CN17663	4000
23/10/1998	CN21121, CN21122 & CN21128	4000
03/11/1999	CN24041, CN24042 & CN24043	5000
16/09/2000	CN28255 & CN28256	4000
22/08/2001	AW52349 to AW52351	4000
17/04/2002	CW39562 & CW39563	3500
11/05/2003	CW47102 & CW47103	4000
11/06/2004	CW57866 & CW57867	2500
23/11/2005	RW06464 & RW06465	6000
15/05/2006	CW71604 & CW71605	4000
12/07/2007	CW77089 & CW77090	3000
01/03/2008	CS11671 & CS11672	6000
25/07/2008	CS14147 & CS14148	6000
26/08/2009	CW83527 & CW83528	3000
23/10/2009	CS22957 & CS22958	6000
09/11/2010	RS01104 & RS01105	6000
04/07/2011	CS32550, CS32551 & CS32552	6000
07/06/2012	CS36594 & CS36595	6000
05/01/2013	CW100326 & CW100327	8000
01/06/2013	CW103864 & CW103865	2000
01/01/2014	CS47347 & CS47348	6000
01/01/2015	CS54879, CS54880 & CS54881	6000
01/01/2016	CS62456, CS62457 & CS62458	6000
14/09/2017	E30044C, E030045C & E30046C	6000
05/10/2018	E047646C, E047647C & E047648C	6000
03/10/2019	E071014, E071015C & E071016	6000
04/08/2021	Orthophotograph / Oblique photographs	-

Note: (1) Photographs numbered with CN, CW, CS, or E are in colour. All others are black and white.

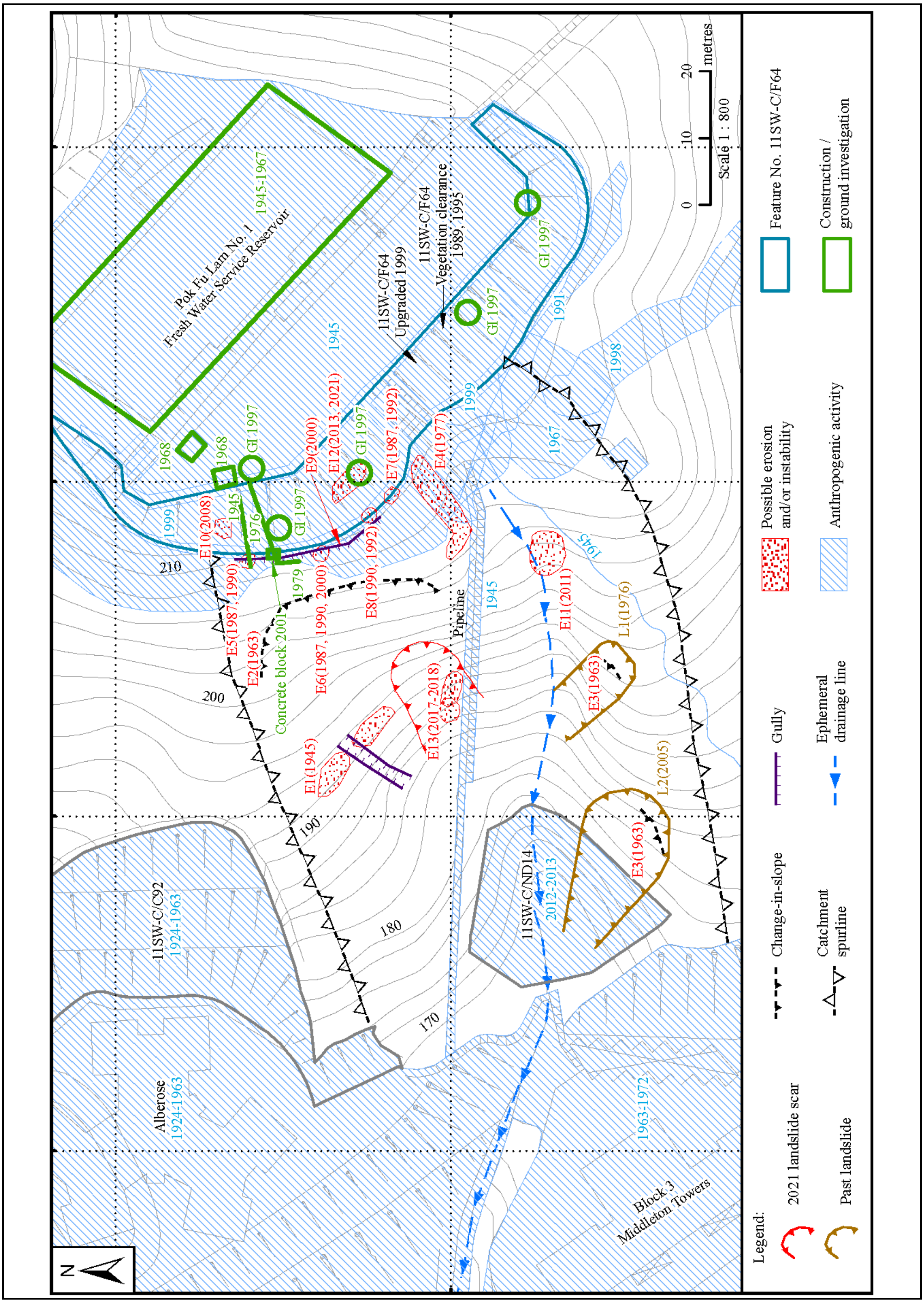

Figure B1 Summary of API Observations

Appendix C

Debris Mobility Analyses

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C.1 General

This Appendix presents the results of debris mobility analyses for the 2021 landslide. The analyses were carried out to determine the probable apparent friction angle of the landslide debris with reference to the relative proportion of debris volumes that could have naturally deposited on the natural hillside above the crest of the rigid barrier and that accumulated within the basin of the rigid barrier. The computer programme DAN-W (release 10) developed by O. Hungr Geotechnical Research Inc. (Hungr, 2010) was used to model the motion of the landslide debris. It implements a Lagrangian solution of the equations of motion for a mass of earth material which starts from a prescribed static configuration and flows according to one of several rheological relationships.

C.2 Methodology

Field mapping and analysis of the handheld laser scanning (HLS) point cloud model aided apportioning the total landslide debris volume of about 135 m³, of which about half had deposited on the natural hillside and half had deposited within the containment basin of the rigid barrier.

The pre-landslide profile was inferred from the 2020 LiDAR dataset and the as-built records of the rigid barrier (AECOM, 2014). As observed in the field mapping, the furthest extent of debris deposition was impeded by the central core of the rigid barrier. For the purpose of the analyses, the modelled profile included the inclined rear wall and containment basin of the rigid barrier but omitted the central core wall, gabion wall and planter to simulate the pre-landslide slope profile. The input data used for the analysis are shown in Table C1.

Sensitivity analyses were carried out by varying the apparent friction angles to estimate the probable apparent friction angle of the landslide debris, which was then compared against the volume of debris deposition above and within the rigid barrier as inferred from the field mapping.

Table C1 Input Data for Debris Mobility Back Analyses

Item	Input Data	Remarks
Soil unit weight	19 kN/m³	Based on S3(H)R 5/2010 parameters
Modelled source volume	135 m³	Based on field mapping and HLS on landslide debris volume
Rheological model	Frictional	OHL (GEO Report No. 104)
Apparent friction angle	31°, 32°, 33°	Sensitivity analyses
Internal friction angle	35°	Based on S3(H)R 5/2010 parameters
Debris trail width	8 m	Based on field mapping and HLS
Pre-failure profile	2020 LiDAR data	-
Observation point	CH40.0	CH40.0 - Crest of inclined rear wall

C.3 Results

The debris mobility analysis results comparing the landslide debris distribution obtained by field mapping are presented in Table C2 and Figure C1. An apparent friction angle of 32° was determined as being the most representative of the distribution of debris on the hillside and in the containment basin of the rigid barrier and is within the typical range for open hillslope failures (GEO, 2012).

Table C2 Results of Debris Mobility Analyses

Apparent Friction Angle	Debris Distribution		
	Length over Natural Slope	Volume on Natural Slope	Volume in Rigid Barrier
31°	8.4 m	58 m^3	77 m^3
32°	8.7 m	65 m^3	70 m^3
33°	9.1 m	72 m^3	63 m^3
Field mapping results	5 m	68 m^3	67 m^3

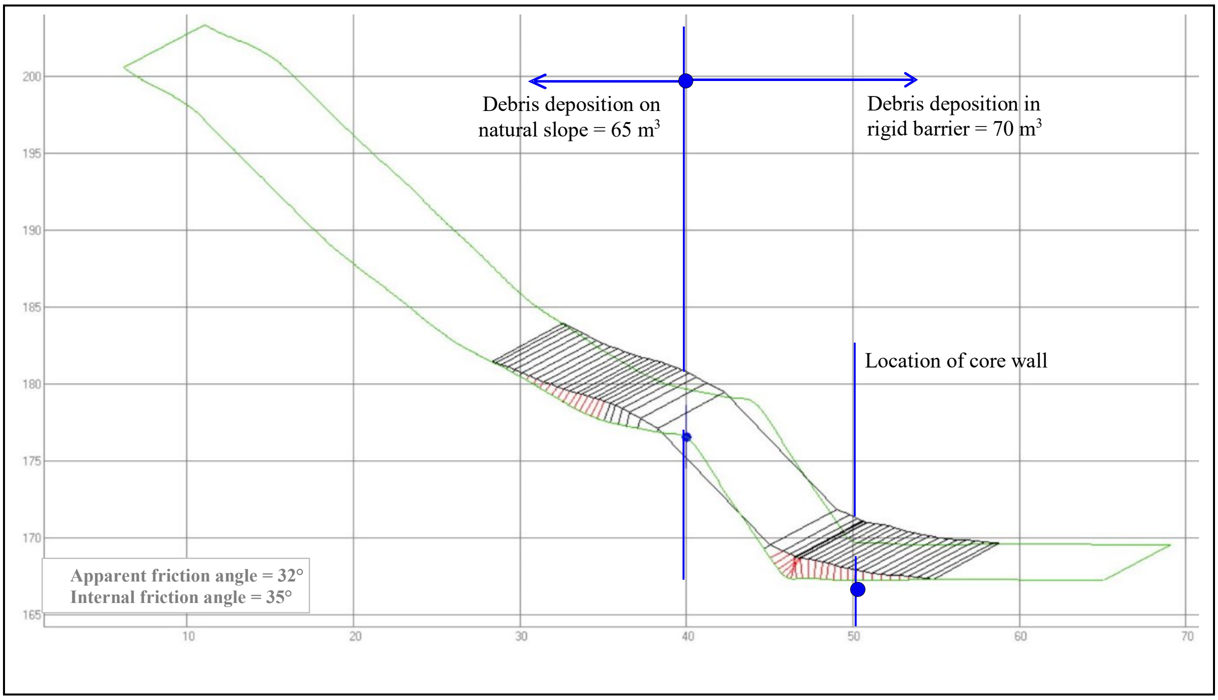

Figure C1 Results of Debris Mobility Analysis

C.4 References

AECOM (2011). S*tudy Area No. 11SW-C/SA3 (Hillside Catchment Nos. 11SW-C/DF9, 11SW-C/DF9a, 11SW-C/OH12 and 11SW-C/OH12a) Pok Fu Lam, Southern District (Stage 3(H) Study Report No. S3(H)R 5/2010).* AECOM Asia Co. Ltd. Report to the Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong, 215 p.

AECOM (2014). *Feature Nos. 11SW-C/ND14, /ND15, /ND16, /NS17, /NS18 & /NS19 Near Middleton Towers, Pok Fu Lam, Southern District* (*Maintenance Manual No. MM (H) 026/2014)*. AECOM Asia Co. Ltd. Report to the Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong, 90 p.

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

Hungr, O. (2010). *DAN-W Dynamic Analysis of Landslides*. O. Hungr Geotechnical Research Inc., 61 p.

Appendix D

Review of Rainfall Associated Surface Runoff

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D.1 General

This Appendix presents the assessment of surface runoff associated with rainfall that could have reached the 2021 landslide location at the time of the landslide. The catchment area that could contribute to surface runoff at the landslide location is shown in Figure D1. The surface runoff could have comprised both overflow from the defective 300UC section of fill slope No. 11SW-C/F64 (Areas 1 to 4) and the surface runoff from the natural slope immediately upslope of the landslide location (Area 5).

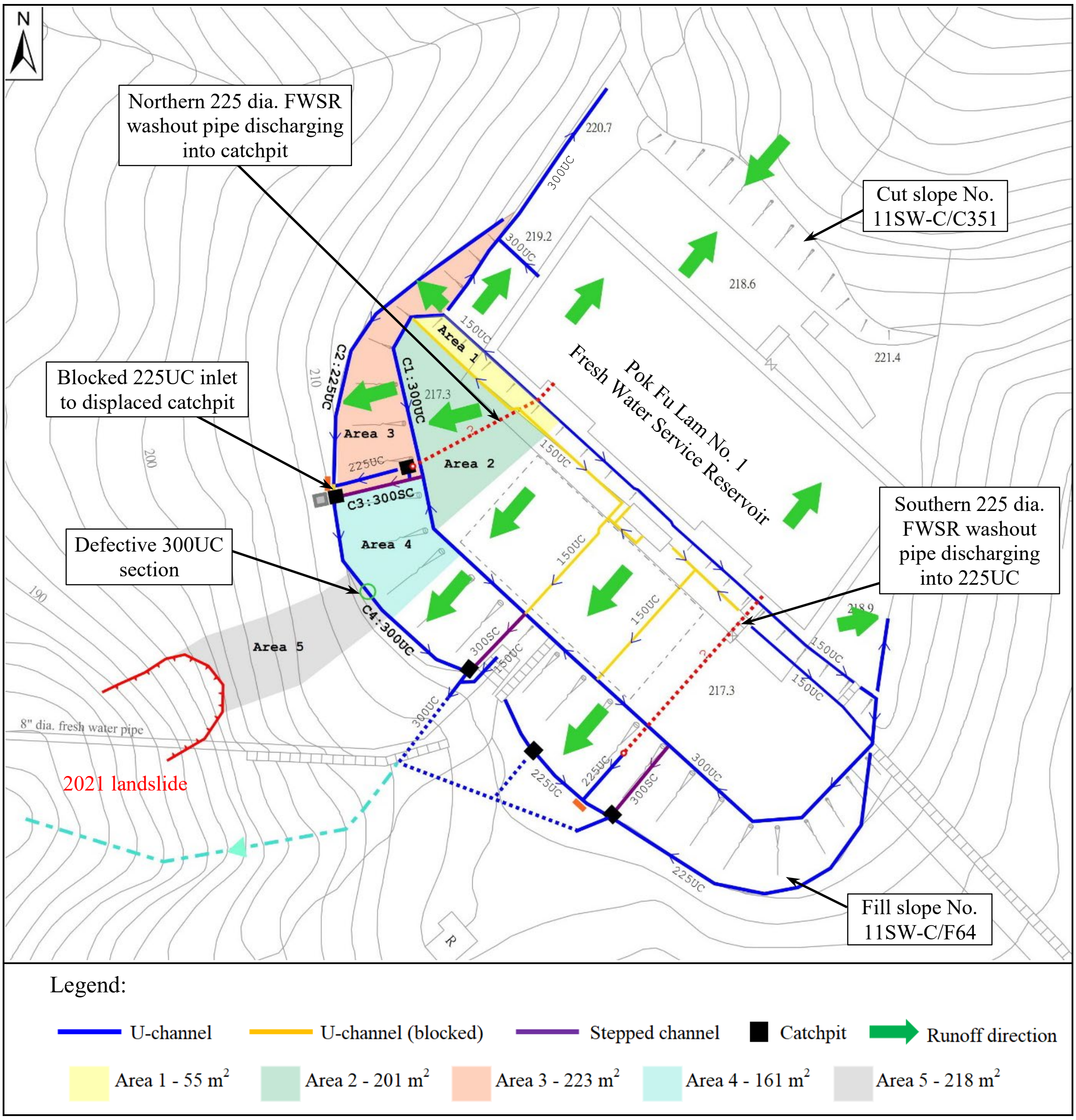

Figure D1 Catchment Area for the Defective 300UC Section and Landslide Head Scarp

D.2 Methodology

Surface runoff associated with rainfall at the time of the landslide has been estimated in accordance with Geotechnical Manual for Slopes (GCO, 1984) and Stormwater Drainage Manual (DSD, 2018).

The surface runoff associated with rainfall has been calculated based on the rational method and time of concentration for overland flow has been based on the modified Bransby-Williams equation according to the above references where:

$$Q = \frac{KiA}{3600} \qquad \text{(D1)}$$

$$t = 0.14465 \left[\frac{L}{H^{0.2}\, A^{0.1}}\right] \qquad \text{(D2)}$$

where
Q = maximum runoff (in l/s)
i = intensity of rainfall (in mm/hr)
A = area of catchment (in m^2)
K = runoff coefficient (dimensionless)
t = time of concentration (in min)
L = distance on the line of natural flow between design section and that point of the catchment from which water would take the longest time to reach the design section (in m), and
H = average fall from the summit of the catchment to the point of design (in m per 100 m)

The time of concentration for each sub-area of the catchment has been estimated based on the summation of the time for overland flow determined in accordance with Equation D2 and the time for flow within the drainage system determined in accordance with the flow velocities derived from Figure 8.7 of the Geotechnical Manual for Slopes (GEO, 1984). The maximum surface runoff has been estimated based on the rainfall intensity at the time of the landslide (taking into account the time of concentration) in accordance with Equation D1.

The input parameters for the time of concentration are summarised in Tables D1 to D3 and the input parameters for the estimation of surface runoff are given in Table D4.

Table D1 Time of Concentration for Overland Flow

Parameter	Catchment Sub-area [(1)]				
	Area 1	Area 2	Area 3	Area 4	Area 5
Area, A (m^2)	55	201	223	161	218
Distance of overland flow, L[(2)] (m)	2.8	17.2	12.5	13.5	26.6
Slope angle (deg)	32	1	30	30	33
Change in elevation, ΔE (m)	1.48	0.30	6.25	6.75	14.49
Average fall, H (m / 100 m)	52.99	1.75	50.00	50.00	54.46
Time of concentration, t_o (min)	0.12	1.31	0.48	0.54	1.01

Notes:
(1) See Figure D1 for plan of catchment sub-areas.
(2) For Area 5, the distance of overland flow is the line of natural flow between the furthest point of the catchment sub-area and the crest of the landslide.

Table D2 Time of Flow in Drainage System

Parameter	Drainage Channel [(1)]			
	Channel 1	Channel 2	Channel 3	Channel 4
Channel size	300UC	225UC	300SC	300UC
Channel gradient	1:60	1:6	1:1.7	1:36
Flow velocity [(2)] (m/s)	2.36	6.10	8.00 [(3)]	3.14
Channel length (m)	20.8	44.0	12.5	18.0
Time of flow, t_f (s)	8.8	7.2	1.6	5.7
Time of flow, t_f (min)	0.15	0.12	0.03	0.10

Notes:
(1) See Figure D1 for plan of surface drainage system.
(2) Flow velocity in U-channels is determined from Figure 8.7 of the Geotechnical Manual for Slopes (GEO, 1984).
(3) Assumed flow velocity in stepped channel.

Table D3 Overall Time of Concentration to Reach the Landslide Head Scarp

Catchment Sub-area	Elements of Time for Overland Flow (t_o) and Flow in Drainage System (t_f)	Overall Time of Concentration, t (min)
Area 1	$t_o(A1) + t_o(A2) + t_f(C1) + t_f(C3) + t_f(C4) + t_o(A5)$	2.72 (Max.)
Area 2	$t_o(A2) + t_f(C1) + t_f(C3) + t_f(C4) + t_o(A5)$	2.60
Area 3	$t_o(A3) + t_f(C2) + t_f(C4) + t_o(A5)$	1.71
Area 4	$t_o(A4) + t_f(C4) + t_o(A5)$	1.65
Area 5	$t_o(A5)$	1.01

Note: The overall time of concentration for each sub-area of the catchment is based on the time of concentration for overland flow within a catchment sub-area (A#) given in Table D1 and time for flow within the drainage channels (C#) given in Table D2 in order for the surface runoff to reach the landslide headscarp.

Table D4 Estimated Surface Runoff at the Landslide Head Scarp at the Time of the Landslide

Parameter	Value
5-minute rolling rainfall intensity at the time of the landslide, i [(1)(2)] (mm / 5 min)	1.5
Runoff coefficient, grassland, sandy soil, flat, K (Area 2 - 24%)	0.15
Runoff coefficient, grassland, sandy soil, steep, K (Areas 1, 3, 4, 5 - 76%)	0.20
Weighted runoff coefficient, K	0.19
Catchment area (assuming a 50% reduction in Area 1 and Area 2), A (m^2)	730
Estimated runoff, Q [(3)(4)] (l/s)	0.7

Notes:

(1) The estimated runoff is based on the 5-minute rolling rainfall intensity based on the overall time of concentration of 2.72 minutes (< 5 minutes).

(2) The 5-minute rolling rainfall intensity is based on rainfall data from GEO Raingauge No. H03 (in operation since 1978) located at Block 44, Baguio Villa, Pok Fu Lam, about 520 m south of the landslide location.

(3) The 5-minute rolling rainfall data is for the period ending 6:30 a.m. on 3 August 2021.

(4) The estimated runoff is determined in accordance with Equation D3.

D.3 Assumptions in the Surface Runoff Estimation

In the estimation of surface runoff associated with rainfall reaching the 2021 landslide location, the following assumptions have been made:

(a) Rainfall intensity has been determined from the 5-minute rainfall data at GEO Raingauge No. H03 located approximately 520 m from the landslide location, with the time of incident at 6:30 a.m. on 3 August 2021.

(b) The surface runoff has been estimated using the recommended runoff coefficients given in the Stormwater Drainage Manual (DSD, 2018) which have been weighted based on the proportional catchment topography as given in Table D4.

(c) The surface drainage condition is based on site inspections undertaken in the days following the landslide:

(i) The blocked 150UC channels at the crest platform of the fill slope are neglected due to the lack of functionality at the time of the incident.

(ii) The surface runoff from the reservoir beds, cut slope No. 11SW-C/C351 and upslope natural terrain is considered to flow into the surface drainage system surrounding the FWSR and is conveyed away from the catchment affecting the landslide crest area.

(iii) Since Area 2 is generally a flat platform, possible runoff from Area 1 and Area 2 itself is expected to pond due to the lack of surface fall of Area 2. This assumption matches with the site observation of 3 August 2021. Therefore, a 50% reduction of the runoff from Area 1 and Area 2 is assumed to have entered the slope drainage system.

(iv) Although the blocked 225UC and displaced catchpit on the slope toe would have likely resulted in overspill onto the natural slope north of the landslide location, no loss in the channel flow has been conservatively assumed.

D.4 Results

For each sub-area of the catchment, the estimated time of concentration for overland flow and flow within the surface drainage system are given in Table D1 and Table D2 respectively. The overall time of concentration based on the summation of overland flow and flow within the surface drainage channels is given in Table D3. The overall time of concentration is estimated to be 2.7 minutes. Given the time of concentration is less than

5 minutes, the 5-minute rolling rainfall of 1.5 mm has been used to determine the rainfall runoff by modification of Equation D1 as follows:

$$Q = \frac{KiA}{300} \quad \text{(D3)}$$

where Q = maximum runoff (in l/s)
i = intensity of rainfall (in mm/5-min)
A = area of catchment (in m^2)
K = runoff coefficient (dimensionless)

Based on the overall time of concentration and the rainfall intensity at the time of the landslide, the maximum surface runoff has been estimated as 0.7 l/s as shown in Table D4. The estimated surface runoff over the crest of the landslide scar does not liken to the observed condition of the concentrated surface flow over the crest of the landslide as noted from the videographic evidence captured shortly after the landslide.

D.5 References

DSD (2018). *Stormwater Drainage Manual, Planning Design and Management (5th Edition)*. Drainage Services Department, Hong Kong, 193p.

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