REPORT ON THE 22 MAY 2013 DISTRESS AT A REINFORCED FILL WALL AT A CONSTRUCTION SITE ABOVE SHUN ON ROAD, SAU MAU PING

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

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(minor amendments made in November 2020)

Executive Summary

This report presents the findings of an investigation of distress of a reinforced fill wall, Wall R22 above Shun On Road, Sau Mau Ping on 22 May 2013. The wall was under construction as part of the Development at Anderson Road (DAR) project. No casualty was reported as a result of the incident.

The incident involved the dislodgement of 78 facing panels with a total soil loss of about 1,300 m^3. The majority of washout debris was deposited over the hillside in front of the wall with a minor amount of debris overspilling the culvert below the wall onto Shun On Road. The incident resulted in temporary closure of a section of Shun On Road for 18 days.

The key objectives of this study were to establish the probable causes and mechanism of the incident. The study included interviewing eye-witnesses, field inspections, ground investigation, and review of related design and construction records of the DAR project.

Based on the findings, the incident was a piping-related distress at some tier openings. It resulted from the inability of the site drainage system to cope with the surface runoff arising from the intense rainfall in the early morning of 22 May 2013. This led to excessive ingress of surface runoff to the wall via an exposed drainage layer at the backyard of the wall. High water pressure could build up at and in the vicinity of the drainage layer near the wall face. The high water pressure would have initiated piping at the tier openings at three locations of the wall. This was followed by soil loss and resulted in panel dislodgement in two of the three locations.

Contents

1 Introduction

In the early morning of 22 May 2013, a distress involving dislodgement of facing panels and loss of soil (Incident No. 2013/06/1367) occurred at a reinforced fill (RF) wall (Wall R22) at the construction site for the Development at Anderson Road (DAR) project, above Shun On Road, Sau Mau Ping (Figure 1.1 and Plates 1 and 2). The wall was under construction at the time of the incident.

The incident involved a 1,300 m^3 loss of soil and a distressed groundmass of 5,500 m^3. The majority of washout debris was deposited over the hillside in front of Wall R22 with a minor amount of debris overspilling the culvert below the wall onto Shun On Road. The incident resulted in temporary closure of a section of Shun On Road for 18 days. No casualty was reported as a result of the incident.

Fugro Scott Wilson Joint Venture (FSW) has been engaged by the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) to establish the probable causes and mechanism of the incident.

The investigation was conducted from May 2013 to November 2013 and comprised the following key tasks:

(a) review of all known relevant documents relating to the design and construction of the site,

(b) interviews with eye-witnesses of the incident,

(c) detailed observations and measurements in the vicinity of the incident,

(d) interpretation of aerial photographs relating to the site,

(e) execution of ground investigation to establish the subsurface conditions,

(f) analysis of rainfall records,

(g) engineering analyses of the site drainage provisions at the time of the incident, and

(h) diagnosis of the causes of the incident.

This report documents the findings. The findings have been reviewed by an independent reviewer, Professor John Burland of Imperial College London. On 22 May 2013, a failure involving a fill slope also occurred in the DAR site. The investigation of the slope failure is covered in a separate report.

2 Site Description

2.1 General

The DAR project is to provide usable land of about 20 hectares for constructing public housing, and government and public facilities at the site. Under the project, site formation and associated infrastructure works, including roads, drains and upgrading of existing slopes, were being carried out. The DAR site is bounded by Anderson Road to the northeast, Sau Mau Ping Road to the southwest, Po Lam Road to the south, and Lee On Road and Shun On Road to the west (Figure 1.1). Construction works for the DAR project commenced in January 2008 and are scheduled for completion in 2014. At the time of the incident, some works were still under construction including formation of Platforms C1 and C2, the construction of Roads L1, L2 and L3, permanent site drainage works and works for Wall R22.

The DAR project is managed by the Civil Engineering Office of the CEDD. The Contractor and the Consultant for the DAR project are China State Construction Engineering (HK) Limited (CSCE) and Ove Arup and Partners Hong Kong Limited (OAP) respectively.

2.2 Site Setting

Wall R22 is located below the proposed Platform C1 at the western part of the DAR project site (Figures 1.1 and 2.1). It is situated over a westerly to southerly sloping terrain, in the vicinity of two drainage lines (Figure 2.1). Adjoining the northern end of Wall R22 is another reinforced fill wall (Wall R26). A cascade (with an adjacent staircase) serving as the discharge point for the northwestern part of the DAR site is located in front of Wall R26 and the northern end of Wall R22 (Figure 2.1). The cascade feeds via a streamcourse into a culvert underneath Shun On Road for discharge (Figure 2.1). There are other surface drainage measures along the toe of Wall R22.

Wall R22 is a 300 m long reinforced fill wall with a curved alignment on plan (Figure 2.1). Upon its completion, it would have a maximum height of 36.5 m, comprising four tiers, namely the top tier, upper tier, middle tier and lower tier (Figure 2.2). Each tier is set back from the lower one, forming a 2 m wide berm and opening (referred to as 'tier opening' in the report). The wall is sub-divided longitudinally from Bay 1a to Bay 22b (Figure 2.2). Further description of Wall R22 is given in Section 7.

At the time of the incident, the top tier of the wall was under construction, with the top surface of the compacted fill (referred to as 'backyard' in the report) at about +146 mPD as shown in Figure 2.2 (see also Plate 3).

3 Description of the Incident

The following description of the incident has been collated from field observations together with witness accounts and records and photographs from the CEDD, CSCE and OAP.

The incident probably occurred in the early morning of 22 May 2013. At about 4:50 a.m., a bus was halted by washout debris on the northbound lane of Shun On Road near the culvert below Wall R22. According to another bus driver who passed the same location some 10 to 15 minutes earlier, he did not observe any debris at that time. Shortly before 5:00 a.m., a delivery truck was stopped by washout debris that had overspilled the culvert below Wall R22 on the southbound lane of Shun On Road. The drivers were not aware of the distress of the wall above. It is probable that the incident started to occur some time after the commencement of heavy rainfall at 3:30 a.m. and before the observations of debris on the road at 4:50 a.m. In estimating the time of the incident, the washout debris would have first blocked the culvert below Wall R22 prior to the overspilling being observed on Shun On Road. At around 6:30 a.m. when the first CEDD staff attended the scene, the wall distress had occurred and no further distress was noted.

According to resident site staff of the DAR project, there was no indication of incipient distress at Wall R22 when it was last inspected at about 3:45 p.m. on 21 May 2013 (Plate 3).

The distress of the wall was confined to the area between Bay 4 and Bay 9 of Wall R22, from the middle tier up to the top tier. It generally comprised three localized areas of distress at the interfaces between Bays 4 and 5, between Bays 6 and 7 and between Bays 8 and 9 as shown in Plates 2 and 4 and Figures 3.1 and 3.2.

The localized distress at the interface between Bays 4 and 5 involved the dislodgement of 40 panels at the middle and upper tiers, with approximately 510 m^3 of soil loss behind the dislodged panels and their adjoining panels (Plates 4 and 5). The extent of soil loss appeared to be confined to the zone within 2 m from the panels. There was no sign of dislodgement or observable displacement of the top tier panels. The bottommost panel involved in this localized distress happened to be the one dislodged in a previous incident on 24 July 2012 (see Section 8).

The localized distress at the interface between Bays 6 and 7 involved the dislodgement of 38 panels from the middle to the top tiers (Plates 4 and 6). Approximately 340 m^3 of soil loss was observed immediately behind the dislodged panels and their adjacent panels. Loss of soil was mainly limited to within a distance of 2 m away from the panel. At the backyard of the wall, a sinkhole measuring approximately 8 m wide by 12.5 m long on plan, extending up to 9 m deep and with an approximate volume of 450 m^3 was observed (Plate 7). Photographic records indicate that the central part of the soil loss appeared to extend deeper and would have likely connected to the sinkhole (Plates 6 and 7).

The localized distress at the interface between Bays 8 and 9 involved a relatively small scale of soil loss (approximately 5 m^3) immediately behind the panels at the top of the upper tier (Plates 4 and 8). Soil debris of around 5 m^3 was deposited on the top of the middle tier below the location where loss of soil was noted. No signs of dislodgement or notable movement of panels was observed at the affected facing panels (Plate 8).

The dislodged panels either fell into the reinforced fill body or hung by the reinforcement straps attached to the panels. None of the dislodged panels fell off from the wall.

4 Analysis of Rainfall Records

Rainfall data was obtained from the nearest GEO automatic raingauge No. K04 which is located about 0.93 km northwest of the location of Wall R22 (Figure 1.1). The raingauge records rainfall data at 5-minute intervals. The daily rainfall recorded by raingauge No. K04 from 22 April 2013 to 22 May 2013 and the hourly rainfall readings from 0:00 a.m. on

21 May 2013 to 10:00 a.m. on 22 May 2013 are shown in Figure 4.1. In addition, the DAR site also has its own raingauge which is located further away, at about 1 km southeast of the location of Wall R22, and only records rainfall data at 15-minute intervals (Figure 1.1). Therefore, data from this raingauge have not been used in the rainfall analysis.

Table 4.1 presents the estimated return periods for the maximum rolling rainfall for various durations recorded by raingauge No. K04 following the approach described by Tang & Cheung (2011). The results of the analyses show that during the incident the return period corresponding to a 1-hour maximum rolling rainfall of 135 mm was more than 200 years.

The maximum rolling rainfall of the 22 May 2013 rainstorm has been compared with previous major rainstorms recorded at rainguage No. K04 (Figure 4.2). The 1-hour intensity of the 22 May 2013 rainstorm during the incident was the most severe rainstorm recorded by raingauge No. K04 since it came into operation in 1980.

5 Site Catchment and Temporary Site Drainage Arrangement

5.1 Catchment of the Site

Assessment of the site topography shows that the catchment area contributing surface runoff to Wall R22 covered Catchment 1 and Catchment 2 as shown in Figure 5.1.

Catchment 1 comprised Platform B and adjacent slopes within the DAR site (77 % of Catchment 1), a section of Anderson Road (3% of Catchment 1) and part of the site for Anderson Road Quarry (20 % of Catchment 1), with a total catchment area of about 93,100 m^2. Post-incident investigation revealed that there is no evidence of other significant source of water coming from the Anderson Road Quarry including the quarry lagoon (Plate 9), which is used to store surface runoff within the quarry.

Catchment 2 was mainly the backyard of Wall R22 and Wall R26 and its adjoining uphill slope with an estimated area of 12,800 m^2.

5.2 Temporary Site Drainage Arrangements

Based on the Contractor's latest temporary drainage design prior to the incident (submitted to the Consultant on 9 May 2013), a 600 mm U-channel was to be constructed along the back of Wall R22 to discharge runoff offsite via the cascade (Figure 5.2). However, this channel had not yet been constructed at the time of the incident. According to OAP, a temporary earth bund was reportedly provided over the southern end of Platform B behind Wall R26 and Bay 1 of Wall R22 to keep runoff from accumulating at the rear of Wall R22.

At the time of the incident, the main drainage constructed near Wall R22 comprised a series of U-channels (ranging in size from 525 mm to 750 mm) and intervening sand traps along the periphery of Platform B (Figure 5.3). These drainage measures were part of the permanent drainage system for the DAR project (Figure 5.3). At Platform B, the U-channels generally have a fall of less than 1 in 220 in a herringbone fashion towards the sand traps (Figure 5.4). The sand traps are intended to discharge flow into the drainage network under

Road L2 as part of the permanent drainage system (Figure 5.3). Limited drainage works under Road L2 were constructed at the time of the incident. Only one of the constructed sand traps (ST15 in Figures 5.3 and 5.4, Plate 10) was connected to the cascade in front of Wall R22 and Wall R26 (Figure 5.4). Given the as-built fall direction of these U-channels, surface flow against the invert fall would occur at some sections of U-channels (Figure 5.4), hampering the flow efficiency and capacity of these channels under the temporary drainage condition. Signs of blockage of the drainage system were observed days before the incident (Plate 11).

In the morning of 22 May 2013, significant overland flow originating from Platform B over the location of the temporary earth bund was observed (Figure 5.5 and Plate 12) flowing down a haul road towards the back of Wall R22. Based on photographic records, the temporary earth bund between the haul road and sand trap ST16 was estimated to be around 500 mm high. The temporary earth bund was not effective in controlling the surface runoff as evidenced by the overland flow in the morning of 22 May 2013 as well as erosions scars below the reported bund extent observed several days prior to the incident.

At the time of the incident, the top surface of the compacted fill (the backyard) was slightly graded away from the wall face (Plate 3). The backyard at Bays 4 to 7 of the wall was a topographical low point in the vicinity, as evidenced by water ponding observed on the day before the incident (Plate 13). No temporary surface drainage was provided at this location (Plate 4). The top end of the drainage layer at the back of Wall R22 was exposed in this area (Plate 13). This allowed any surface water that accumulated at the backyard to get inside Wall R22. Discussion of the drainage arrangement of Wall R22 is given in Section 7.1.2.

6 Subsurface Flow Conditions

The location of Wall R22 is situated on sloping terrain that encompassed two drainage lines (Figure 2.1). Underneath the northern end of the wall was a major perennial drainage line within a valley which had since been filled as part of the DAR project. The other, a minor ephemeral drainage line, was located upslope of Bays 5 and 6. The ground where this drainage line was situated had been modified under the DAR project and the subsurface flow of the drainage line could have been altered.

During the construction of Wall R22, continued seepage (measured as 0.84 litres per second in April 2010) was observed at the temporary cut of Bay 1 (Plate 14), whereas the temporary cut at the back of Bays 3 to 7 showed relatively minor seepage above some weathered weak seams (Plate 14). No flow measurement was taken at these seepage locations. The seepage levels were around or below the base level of the reinforced fill portion of the wall.

Records of groundwater monitoring from previous ground investigation (GI) in the vicinity of Wall R22 were reviewed (Figure 6.1). At the northern end of the wall close to where the major drainage line was located, the highest groundwater level monitored was +127.84 mPD, i.e. 4.3 m above the base of the reinforced fill during the period of June 2008 to January 2010. Near Bay 8 of Wall R22, the highest groundwater level monitored was at +133.78 mPD, 0.9 m below the base of the reinforced fill, during the monitoring period of

June 2008 to September 2008. At the time of the 22 May 2013 incident, the groundwater level in front of Bay 10 (SP-41 in Figure 6.1) was noted to have risen by around 2 m, reaching +123.51 mPD.

Following the removal of the panels affected by the 22 May 2013 incident and the soil backfill behind as part of the urgent remedial works, steady light seepage flow had been observed from the lower part of the temporary rock cut behind Bays 5 and 6. Standing water up to 80 mm deep was also observed on the mass concrete foundation of Bay 4.

The groundwater table in the vicinity of the wall is generally low and there is no evidence to indicate that the subsurface flow to the wall is significant.

7 Wall R22

7.1 Design of Wall R22

7.1.1 Structural Arrangement and Overall Stability of Wall R22

Under the Contract, RE walls, including Wall R22, were to be designed and constructed by CSCE. CSCE appointed VSL Hong Kong Limited as the specialist sub-contractor for the wall construction and internal stability design of the RE walls and Golder Associates Limited (formerly under the name of Geotechnical Consultants Group) were appointed to design and analyse the external stability of the RE walls. CSCE also appointed Atkins China Limited as the Independent Checking Engineer (ICE) for checking both internal and external stabilities of the RE walls. The permanent design of RE walls was accepted by OAP and subsequently checked by GEO.

According to the design records (Appendix A), Wall R22 typically comprises mass concrete foundations supporting a reinforced fill body. The mass concrete foundations are configured in a stepped profile along the alignment of the wall (Figure 2.2). On top of the reinforced fill body, there would be an L-shaped reinforced concrete retaining wall (Figure 7.1).

The reinforced fill body is composed of an elemental system of concrete facing panels with a typical size of 1.6 m high by 2.5 m wide. Non-standard panel sizes are utilized to suit the curvature of the wall at some locations. Each concrete facing panel is tied back by rows of metal reinforcement straps ranging from 4.6 m to 19.5 m in length (Figure 7.2). Behind the panels are compacted fill materials which provide anchorage for the reinforcement straps to support the concrete facing panels. The lowermost tier of the concrete facing panels are generally founded on the mass concrete foundations whilst the panels of the tiers above are generally founded on the compacted fill materials with 300 mm wide by 150 mm high strip peg footings. Socket joints are provided to interlock the panels to adjacent panels. Geotextile is placed behind the panel joints to prevent soil loss. Some of the concrete facing panels are secured to the front face of the mass concrete foundations (referred to as 'dummy panels'), with a 300 mm wide separation with concrete infill (Figure 7.2).

The wall is designed as a tiered structure, with a 2 m wide tier opening created at the top of the lower, middle and upper tiers. The soil near the top surface of the tier opening has a low overburden pressure in comparison to the surcharge created at the base of the tier above and is assumed not to be subject to any build-up of high water pressure. The design does not have provisions to guard against any soil loss through the tier opening. At the time of the incident, a thin layer of gravel was placed on the top of the tier opening for planting.

The checking of internal and external wall stabilities was undertaken on a bay-by-bay approach at a critical section of each bay. The design groundwater level was taken as one-third of the retained height in the checking of external stability of Wall R22. In the design against internal instability, it was assumed that groundwater would be intercepted by drainage layers surrounding the wall and along the temporary cut surface with no saturation or build-up of water pressure within the reinforced fill body.

7.1.2 Drainage Arrangement of Wall R22

The drainage arrangement of the wall typically comprises two drainage layers at the back of the wall: a vertical one directly behind the reinforced fill body and an inclined one resting on the surface of the temporary cut as shown in Figure 7.1. There is also a base drainage layer overlying the mass concrete foundations at the base of the recompacted fill body. All three drainage layers are connected (Figure 7.1).

At the steps of the mass concrete foundations, the adjacent base drainage layers are connected to each other by vertical drainage layers which are referred to in the report as '*vertical connecting drainage layer*' (Figure 2.2). The inclined drainage layer at the back of the wall was designed to extend up to two-thirds of the retained height of the reinforced fill body.

All the drainage layers were prescribed as 500 mm thick, comprising granular materials. A layer of geotextile was provided as a filter at the interfaces of the inclined and vertical drainage layers with adjacent ground. The drainage layers are much more permeable than the compacted fill materials. The thickness of the drainage layers was found to be variable. Photographic records show the drainage layers at some locations at the rear of the wall were thicker than 500 mm whilst localised exposure of the base drainage layer above the Bay 4 mass concrete foundation varied from 300 mm to 400 mm in thickness. Contamination of the drainage layers with finer soil particles was observed in the local exposures of the base drainage layers over Bays 4 to 6 and the '*vertical connecting drainage layer*' at the interface between Bays 4 and 5.

The drainage design arrangement of the wall results in the '*vertical connecting drainage layers*' at the interfaces between Bays 4 and 5, between Bays 6 and 7, and between Bays 8 and 9 being in close proximity to a tier opening (see Figure 7.3). Over the portion of the reinforced fill wall under construction, such arrangement was unique at these three wall locations, which were observed to be coincident with the location of the three localised distressed zones. The implication of this wall arrangement is further discussed in Section 9.

Water collected in the vertical and inclined drainage layers at the back of the reinforced fill body would flow along the base drainage layer within Wall R22 until it reaches an outlet. There were 4 main outlets for Wall R22 comprising direct outflow from the base drainage layers at Bay 1 and Bays 21 to 22 and via 150 mm and 225 mm diameter half-perforated subsoil drain pipes prescribed at Bay 9 and Bay 15 respectively. A 250 mm diameter toe drain was buried underneath the footpath in front of the wall discharging the direct outflow from the base drainage layer. Additionally, a row of weepholes (100 mm diameter at 2.5 m horizontal spacing) were prescribed at the concrete facing panels along the base drainage layer at Bay 5, Bay 6, Bays 12 to 14 and Bays 18a to 19b (Figure 2.2).

Following the incident on 24 July 2012 (see Section 8), additional 100 mm diameter weepholes at the joints of dummy panels were prescribed at Bays 5 and 6 and an additional 250 mm diameter half-perforated subsoil drain pipe embedded sub-horizontally at the '*vertical connecting drainage layer*' at the interface between Bays 4 and 5 was prescribed. This outlet pipe was fed by three sub-vertical 250 mm diameter half-perforated subsoil drain pipes installed at the back of Bays 2 to 6. Underneath the 250 mm diameter subsoil drain outlet pipe was a layer of 600 mm thick compacted soil fill (Figure 3.3 and Plate 15).

The provisions of the drainage arrangement of the wall appeared to be on a prescriptive basis. No assessment can be found to show the adequacy of the drainage arrangement of the wall or the possible impacts of a large amount of surface water ingress to the wall through the drainage layers. CSCE had checked and concluded that the 500 mm thick drainage layer was adequate to cope with the observed seepage recorded in Bay 1 in April 2010 (see Section 6), but this checking did not consider possible longitudinal flow of water along the base drainage layer from adjacent bays.

7.2 Construction of Wall R22

At the time of the incident, the construction of the reinforced fill portion of the wall between Bay 2 and Bay 16 was on-going. The wall was generally constructed in accordance with the engineering design as mentioned above, except that the inclined and vertical drainage layers at the back of the wall were constructed as a single combined layer between Bay 3 and Bay 11 (Plate 16, Figures 3.3 to 3.5).

Based on the review of construction records and the field inspections, vibratory rollers were generally used for the compaction of the fill materials, and in-situ density tests were conducted by the Government Public Works Laboratories to confirm that the compacted fill materials complied with the specifications. At the local areas (about 1.5 m wide) immediately behind the panels, light hand-operated equipment was used for compaction.

Generally, there was no evidence suggesting that the materials used for the construction of Wall R22, including concrete facing panels, reinforcement straps and their connections, etc. deviated from the specifications. Occasional oversized fill fragments were identified at Bay 4 during the post-incident ground investigation. These fragments were generally not observed in the reinforced soil mass throughout the excavation for the urgent remedial works. Variation in the thickness of the drainage layers was also observed locally and inferred from photographic records.

7.3 Monitoring of Wall R22

A series of movement markers was erected at the top panel of each tier along the wall alignment with measurements taken since 19 July 2012 at typically fortnightly intervals. The maximum movement recorded over the affected bays prior to the incident was 20 mm vertical settlement at the upper tier of Bay 4 and 18 mm outward horizontal movement at the middle tier of Bay 7. The recorded movements of the affected bays were all within the allowable tolerances.

Instrumentation installed in the wall included strain gauges, piezometers and inclinometers, but none were installed in Bays 4 to 9 that exhibited distress in the 22 May 2013 incident.

Based on available site records, seepage flows issuing from the wall face since May 2012 were noted (Figure 7.4 and Plate 17). Seepage was mainly observed between Bays 1 and 5 as well as Bay 9 of the wall. Both clear and muddy seepages have been noted with varying degrees of intensity. Most of the seepage was through the joints of the dummy panels (i.e. at a level at or below the base of the base drainage layer). Limited water seepage points were observed at Bays 6 and 7.

7.4 Post-incident Ground Investigation

The post-incident ground investigation was undertaken by GI contractor, DrilTech Ground Engineering Ltd, from August 2013 to September 2013 following the urgent remedial works. The GI comprised 15 GCO probes tests and excavation of five inspection pits at various locations to identify the nature and condition of the materials involved in the 22 May 2013 incident. The locations of the post-incident ground investigation stations are shown in Figure 7.5.

The GCO probe tests indicate that the GCO probe values ranged from 0 to 94 with an average value of 17. The GCO probe results did not appear to vary as a consequence of the adopted compaction techniques (vibratory rollers and light hand-operated equipment). At the interface between Bays 8 and 9, an average probe value of 2.5 was encountered at GCO probe No. G15 over the depth of the upper tier beneath the void. However, 2 m away from the void, GCO probe Nos. G3 and G4 recorded an average value of 22.4 over the same depth of the upper tier. The results of GCO probe tests indicate the loosening of soil around the interface between Bays 8 and 9.

Sizes of inspection pits were generally limited in order to avoid any potential disturbance to the peg footings. In general, no significant observations were made in most inspection pits, except in inspection pit No. IP3. Occasional cobble-sized fragments were encountered in inspection pit No. IP3, which was located near the exposed peg footing of middle tier at Bay 4.

8 Previous Distress of Wall R22

The construction of Wall R22 commenced in mid-2010. Prior to the 22 May 2013 incident, Wall R22 suffered a dislodged panel in 2012.

In the morning of 24 July 2012, after Typhoon Vicente had hit Hong Kong, a panel was found dislodged and collapsed into the wall at Bay 4 (Figures 8.1 to 8.3, Plates 18 and 19). The three panels above showed signs of downward and inwards movement. Approximately 40 m^3 of soil loss was apparent immediately behind the panels, in the vicinity of the '*vertical connecting drainage layer*' at the interface between Bays 4 and 5, as well as in the backyard of the wall. At that time, the wall was formed up to a level of about +135 mPD, with the height of reinforced fill about 10 m.

The rainfall recorded at the nearest raingauge K04 before the 24 July 2012 incident was not particularly intense (Figure 8.4), with a return period generally of two years or less for various durations considered. The maximum hourly and 24 hours rolling rainfall preceding the incident were about 29 mm and 241 mm respectively.

Site records showed that, at the time of the 24 July 2012 incident, there was no temporary drainage in the backyard of Bays 4 and 5. Water ponding in this area was observed shortly after the incident suggesting that it was a local low point (Plate 19). Similar to the 22 May 2013 incident, the upper end of the combined vertical/inclined drainage layer in the backyard of Bays 4 and 5 was exposed. Such arrangement could allow significant ingress of surface water into Wall R22 during rainstorms.

It was probable that ingress of surface water via the exposed drainage layer at the back of the wall was a key contributory factor of the distress. The Contractor’s investigation (CSCE, 2012) also concluded that "*the failure was due to the flow of surface water towards the lowest point of the current backfilled level and flow through the back slope filter layer down to the surface of the mass concrete block which washed out the fill along its path*".

Discussion of the postulated distress mechanism of the 24 July 2012 incident is covered in Section 9.

Before the incident, some seepage flow was noted through the joints of the panels near the interface between Bays 4 and 5 (Plate 17c). Following the 24 July 2012 incident, the wall was partially removed from Bay 2 to Bay 6 in a stepped profile down to the level of the collapsed panel (Figure 8.5). Additional internal drainage measures as mentioned in Section 7.1.2 were provided (Figure 8.6). CSCE and OAP also carried out field inspections to identify any seepage under heavy rainfalls subsequent to the 24 July 2012 incident.

Following the 24 July 2012 incident, OAP had urged CSCE to make improvements to the temporary surface drainage arrangements to ensure protection of granular filter materials and wall backfill materials against surface runoff during construction.

9 Diagnosis of the 22 May 2013 Incident

Based on available information, the 22 May 2013 incident probably occurred sometime before 4:50 a.m. when there was heavy rainfall. In view of the mode of distress and the close correlation of the time of the incident with rainfall, the incident is considered to be rain-induced.

The site drainage provisions at Platform B at the time of the incident were not efficient in conveying surface runoff offsite (Section 5.2). Engineering assessment shows that, under the intense rainfall of the 22 May 2013, the site drainage provisions at Platform B were inadequate to cope with the surface runoff generated, resulting in overflow of surface water towards Wall R22 (Appendix B). This was supported by field observation several hours after the incident. This overflow, together with surface runoff collected at the backyard of Walls R22 and R26, were the primary sources of water reaching the wall on 22 May 2013. The main source of surface water was generated from within the DAR site. The contribution from Anderson Road and the Anderson Road Quarry was considered relatively minor.

At the time of the incident, there was no temporary drainage provision at the backyard of Bays 4 to 7 to drain away any surface runoff that would have accumulated at this local low point. The exposed drainage layer at the back of the reinforced fill body remained unguarded against surface runoff and allowed water ingress at times of rainfall over this area. This exposed drainage layer would allow a large amount of water to percolate into the base drainage layers of Wall R22. Engineering analyses show that the water ingress exceeded the flow capacity of the drainage outlets in the area (Appendix B). As a result, this ingress invalidated the design assumptions of no groundwater pressure build-up inside the wall. High water pressures could have built up in the base drainage layers as well as in the '*vertical connecting drainage layers*'.

Figure 7.3 is a three-dimensional depiction of the arrangement of the subsurface drainage layers and tiers between Bays 4 and 9. It can be seen from the various sections shown in Figure 7.3 that the lowest tier openings are all located above the base drainage layers. In particular it should be noted that at the sections coinciding with the vertical steps in the mass concrete foundations (denoted by an asterisk) the tier openings are almost coincident with the '*vertical connecting drainage layers*'. The sections in Figures 3.3, 3.4 and 3.5 show that the thickness of soil cover between the tier openings and the '*vertical connecting drainage layers*' was very thin.

The overburden pressure exerted by the soil layers at the tier openings would have been very small. The build-up of high water pressures at the underlying drainage layer would have exceeded the overburden pressures causing hydraulic uplift of the soil layer and piping at the tier opening. Given the configuration of the wall, it is also possible that the soil in the vicinity of the tier openings was subject to high local stress ratio (shear/effective vertical stress) and is susceptible to local failure should there be a build-up of high water pressure in the vicinity.

It is probable that the large cross-sectional area of the '*vertical connecting drainage layers*' at a single location meant that much larger upward flows of water could take place above these layers than elsewhere above the base drainage layer. Therefore, once loss of soil was initiated, upward flow of water would concentrate at these locations along the tier causing erosion and continued soil loss. This would lead to the formation of voids in the compacted fill near the tier opening. This continued erosion process could allow the upward migration of voids (ravelling) combined with slumping of the compacted fill into the underlying voids. The phenomenon is supported by the void observed at the top of a tier (i.e. the upper tier) at Bays 8 and 9, together with soil debris deposited on the tier opening below (i.e. the middle tier). The post-incident ground investigation works involving GCO probes shows loosening of the soil beneath the void (Section 7.4).

The ravelling process which involved slumping of the fill could induce tensile forces in the reinforcement straps attached to the panels. When the induced tensile forces were large enough to shear off the socket connections at the joints of the panels, as well as to overcome the available earth pressure of the fill behind the panels, panel dislodgement could occur. The observed damage on the panels at Bays 4 and 5, and Bays 6 and 7 where the front part of the panel sockets had been sheared off whilst the rear part of the socket generally remained intact (Figures 9.1 and 9.2) supports this postulated onset mechanism of the panel dislodgement.

The distress would proceed with displacement or even dislodgement of the panels above due to loss of support by the supporting panels below, which could further promote soil loss. The postulated progression of the distress mechanism at the interface between Bays 4 and 5 is summarized in Figure 9.3 with each stage being numbered and described. The distress at the interface between Bays 6 and 7 appears to be more developed than that between Bays 4 and 5, with the formation of a sinkhole at the back, which could be due to a larger amount of water ingress into the wall or due to the presence of a subsoil drain pipe at the latter location which could help to reduce the volume of water issuing out of the top of the tier.

It is probable that the 24 July 2012 incident underwent the same distress mechanism as that of the 22 May 2013 incident. The site settings at the time are similar with the presence of a low point at the backyard of the wall, the presence of exposed end of drainage layer at the backyard, together with the distressed location occurring at the interface with the '*vertical connecting drainage layer*' in close proximity to a tier opening. There is also the close correlation of the time of the incident with rainfall, as well as the similarity in the distress mode (i.e. dislodgement of panel with soil loss behind the panels and at the backyard). The smaller scale in distress observed in the 24 July 2012 incident could possibly be due to the less intense rainfall at the time of the incident and hence lower volumes of water discharging through the tier opening.

Review of design records indicates that the provisions of the drainage arrangement of the wall appeared to be on a prescriptive basis for a permanent condition where the drainage layer behind the reinforced fill body would be capped by compacted fill at the top. No assessment was made on the adequacy of the drainage provisions of the wall or the likely adverse impacts under excessive ingress of water into the wall, in particular during construction. The tiered structure of the wall was not designed to cater for build-up of high water pressure near the tier openings. No provisions were allowed to guard against soil loss in the tier opening.

Upon review of related design and construction records, there is no indication that the distress was caused by any fault in the permanent design or workmanship of the permanent works. However, the internal detailing involving a '*vertical connecting drainage layer*' adjacent to the step of mass concrete foundation, in the vicinity of a tier opening, is vulnerable to piping in the event of unintended ingress of a significant amount of water, which took place in this incident during an intense rainstorm while the wall was under construction.

10 Conclusions

The 22 May 2013 incident at Wall R22 was piping-related and initiated sometime before 4:50 a.m. during an intense rainstorm. The exact start time and duration of incident are not known.

The site surface drainage provisions at Platform B at the time of the incident were not efficient in conveying surface runoff offsite and were overwhelmed by the large volume of surface water during the intense rainfall, resulting in overflow of surface water towards Wall R22. The wall was under construction and the backyard at Bays 4 to 7 was a topographic low point. The temporary site drainage provisions were yet to be constructed at this location. The exposed drainage layer at the backyard of Wall R22 in this area was susceptible to ingress of surface water. Excessive water ingress through the exposed top end of the drainage layer behind the reinforced fill body probably generated high water pressure at and in the vicinity of the drainage layer near the wall face. The high water pressure would have initiated hydraulic uplift and piping at tier openings. The presence of the '*vertical connecting drainage layers*' beneath resulted in a large amount of locally concentrated water flowing through and eroding the drainage and fill materials within the wall.

Surface water that reached and accumulated at the exposed drainage layer during the severe rainstorm was probably the principal source of water leading to the distress. The contribution of subsurface water was probably insignificant. There is no indication that water discharged from Anderson Road Quarry and Anderson Road had any significant contribution to the distress.

There is no indication that the distress was caused by any fault in the permanent design or workmanship of the permanent works. However, the internal detailing involving a '*vertical connecting drainage layer*' adjacent to the step of mass concrete foundation, in the vicinity of a tier opening, is vulnerable to piping in the event of unintended ingress of a significant amount of water, which took place in this incident during an intense rainstorm while the wall was under construction.

11 References

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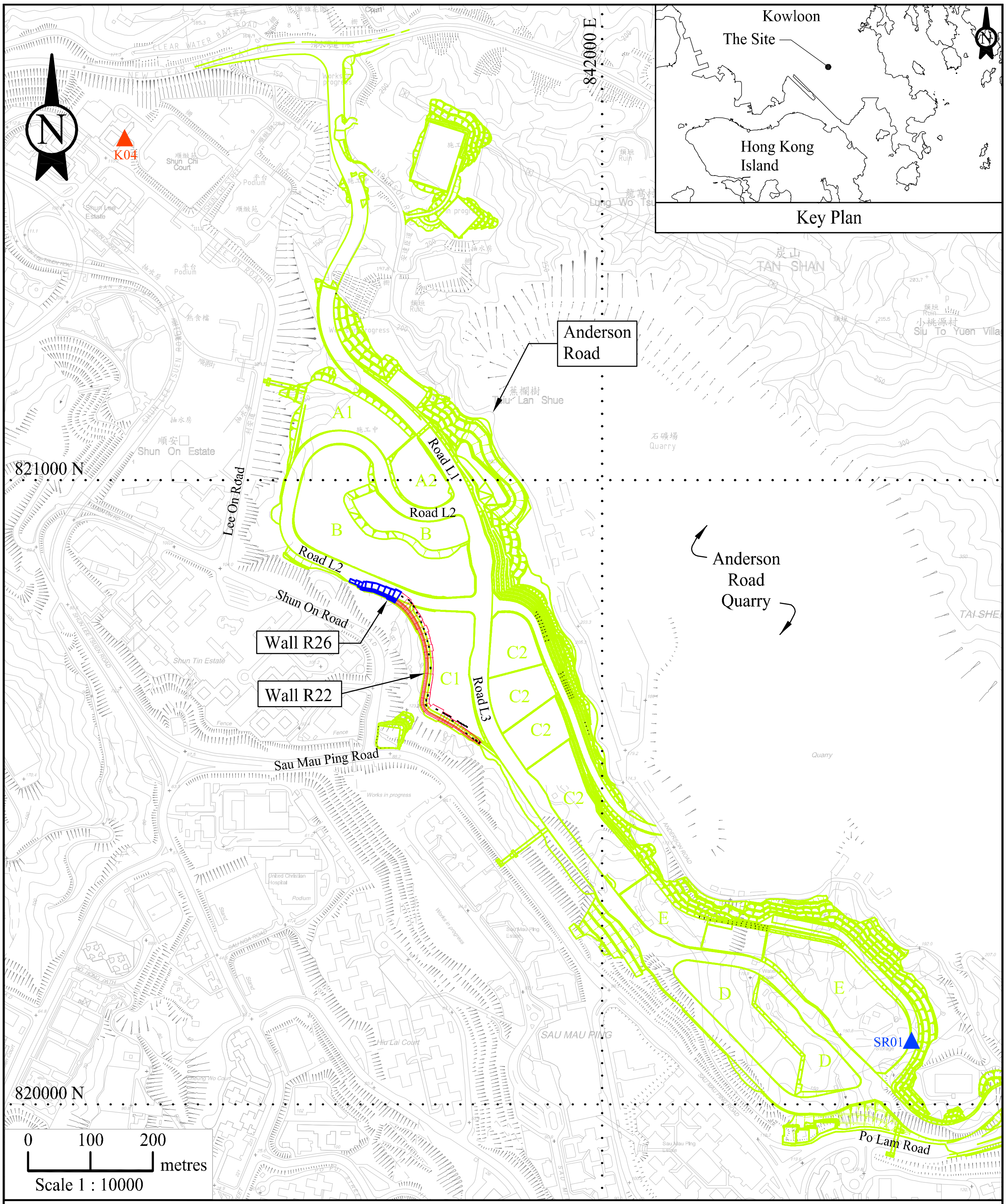
List of Tables

Table 4.1 Maximum Rolling Rainfall at GEO Raingauge No. K04 for Selected Durations Preceding the 22 May 2013 Incident and Estimated Return Periods

Duration	Maximum Rolling Rainfall (mm)	End of Period	Estimated Return Period (Years)
5 minutes	17.5	4:30 a.m. on 22 May 2013	19
15 minutes	45.0	4:30 a.m. on 22 May 2013	43
30 minutes	73.0	4:30 a.m. on 22 May 2013	33
1 hour	135.0	4:30 a.m. on 22 May 2013	228
2 hours	139.5	4:30 a.m. on 22 May 2013	13
4 hours	148.5	4:30 a.m. on 22 May 2013	4
12 hours	149.0	4:30 a.m. on 22 May 2013	<2
24 hours	169.0	4:30 a.m. on 22 May 2013	<2

Notes:
(1) Maximum rolling rainfall was calculated from 5-minute rainfall data.
(2) The DAR site raingauge recorded an hourly rainfall of 95.5 mm between 3:30 a.m. and 4:30 a.m. on 22 May 2013.
(3) Rainfall with durations more than 24 hours have a return period of less than 2 years.

List of Figures



Legend :

▲ K04	GEO Raingauge No. K04	B	Platform B within DAR site
▲ SR01	DAR Raingauge No. SR01		

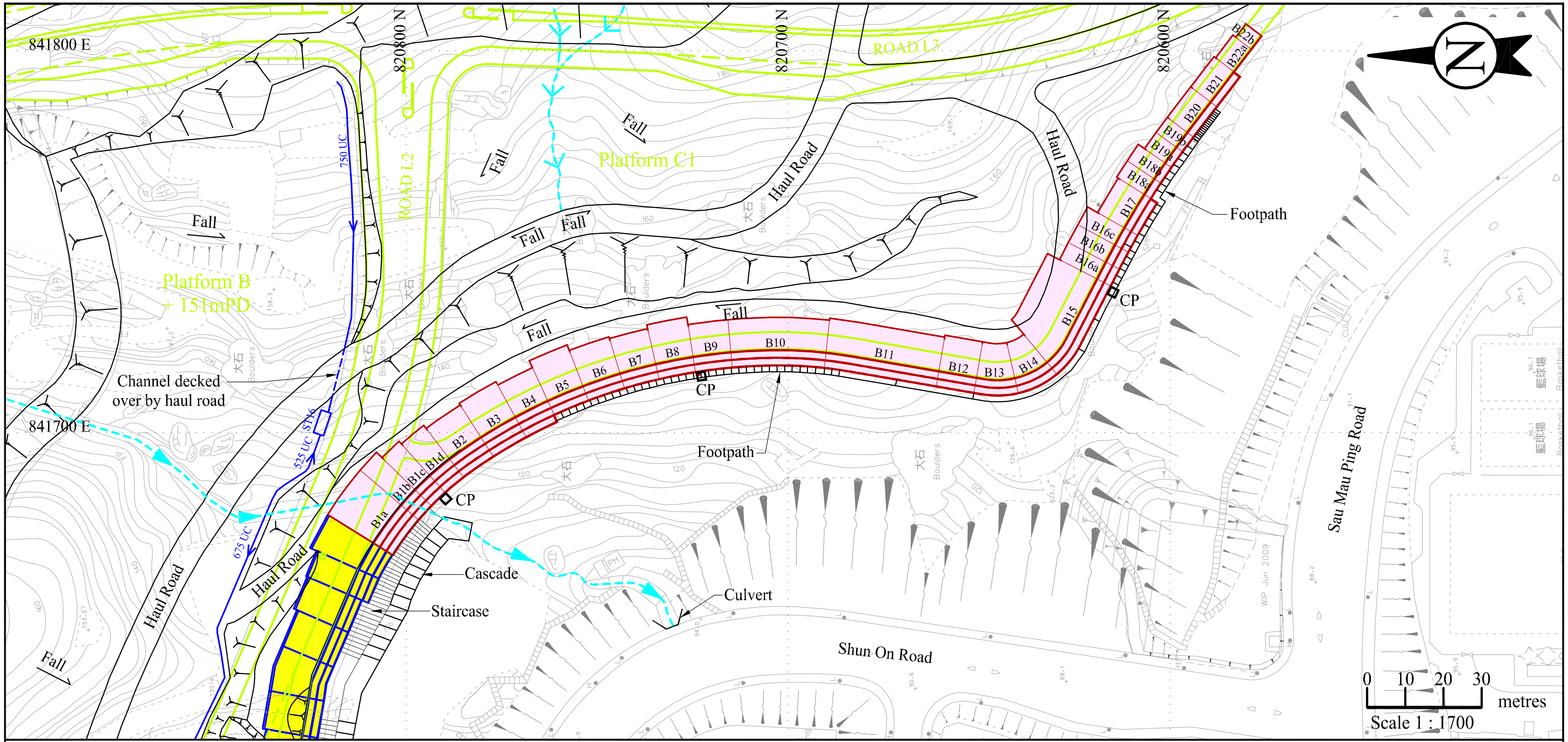
Notes :

(1) Base map is extracted from Survey Sheet Nos. 11NE-13B, 13D and 11NE-18B.

(2) Proposed development layout (in green) is extracted from CEDD plan provided by OAP.

(3) Proposed development works were partially completed at the time of the 22 May 2013 incident.

Figure 1.1 Key Plan for the Development at Anderson Road Project



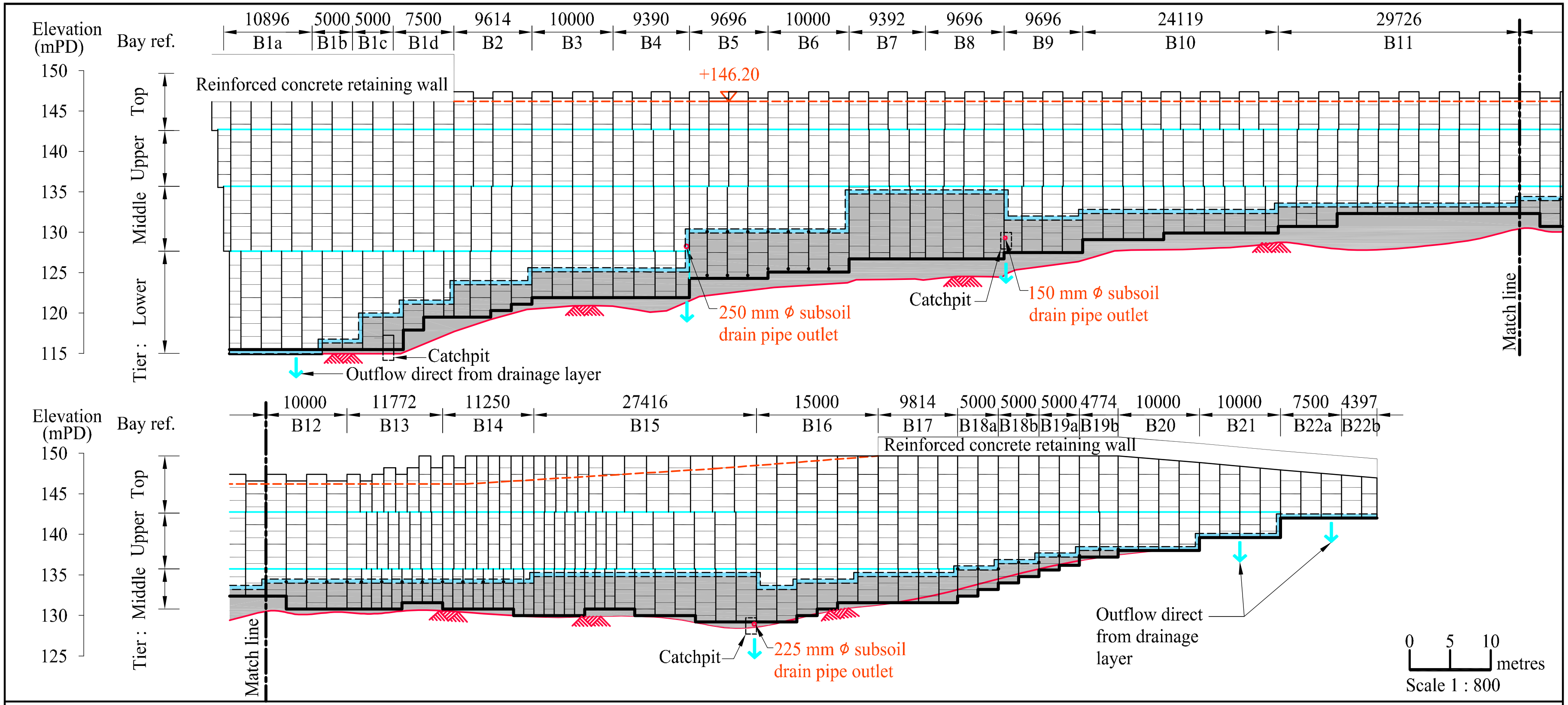
Legend :

▭	Wall R22	- - -▶- - -	Major perennial drainage line	750 UC →	750 mm U-channel	CP □	Catchpit
▭	Wall R26	- - -›- - -	Minor ephemeral drainage line	ST16 □	Sand trap No. ST16	B1a	Bay 1a for Wall R22

Notes :

(1) Base map is extracted from Survey Sheet Nos. 11NE13B & 13D.
(2) Proposed development layout (in green) is extracted from CEDD plan provided by OAP.
(3) Proposed development works for Platform C1 and Roads L1, L2 and L3 not completed at the time of the 22 May 2013 incident.

Figure 2.1 Layout Plan of Wall R22



Legend :

▨ Mass concrete foundation

▭ 500 mm thick drainage layer

↓ Drainage outlets

Grade III / IV or better rock

● 100 mm ϕ weepholes

○ Subsoil drain pipe outlet

— Top of tier

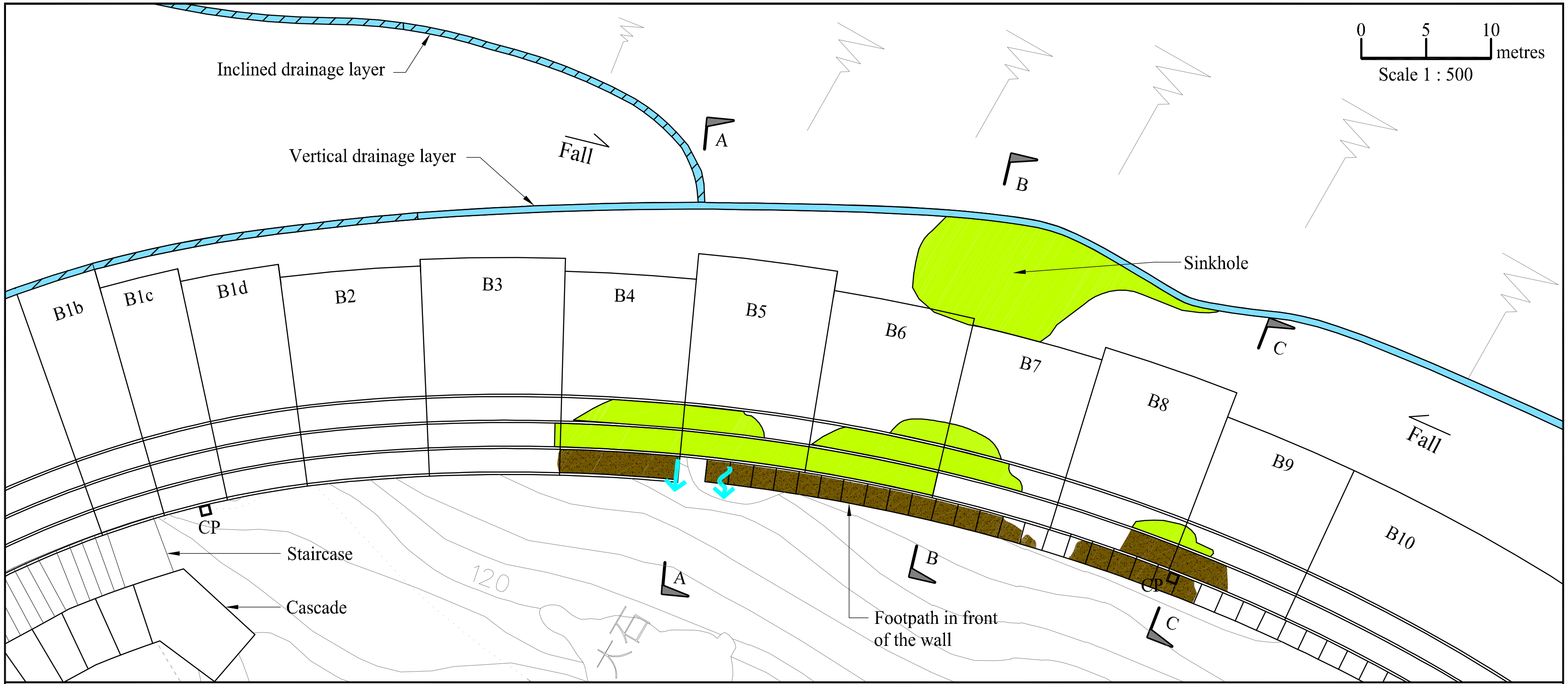
- - - Approximate level of backfill

━ Base of bottommost panel

Notes :

(1) Elevation is based on the merging of Drawing Nos. 2RE08054/CD/RE/R22/4001, 4003 to 4013 (Appendix A).
(2) All levels in mPD.
(3) Bay width dimensions shown are for the middle tier. Bay widths vary at each tier due to wall curvature and tier setback.
(4) 250 mm ϕ buried toe drain in front of the wall not shown.
(5) Grade III/IV or better rock profile is extracted from Drawing No. J385/RE/R22/002 (Appendix A).

Figure 2.2 Elevation of Wall R22



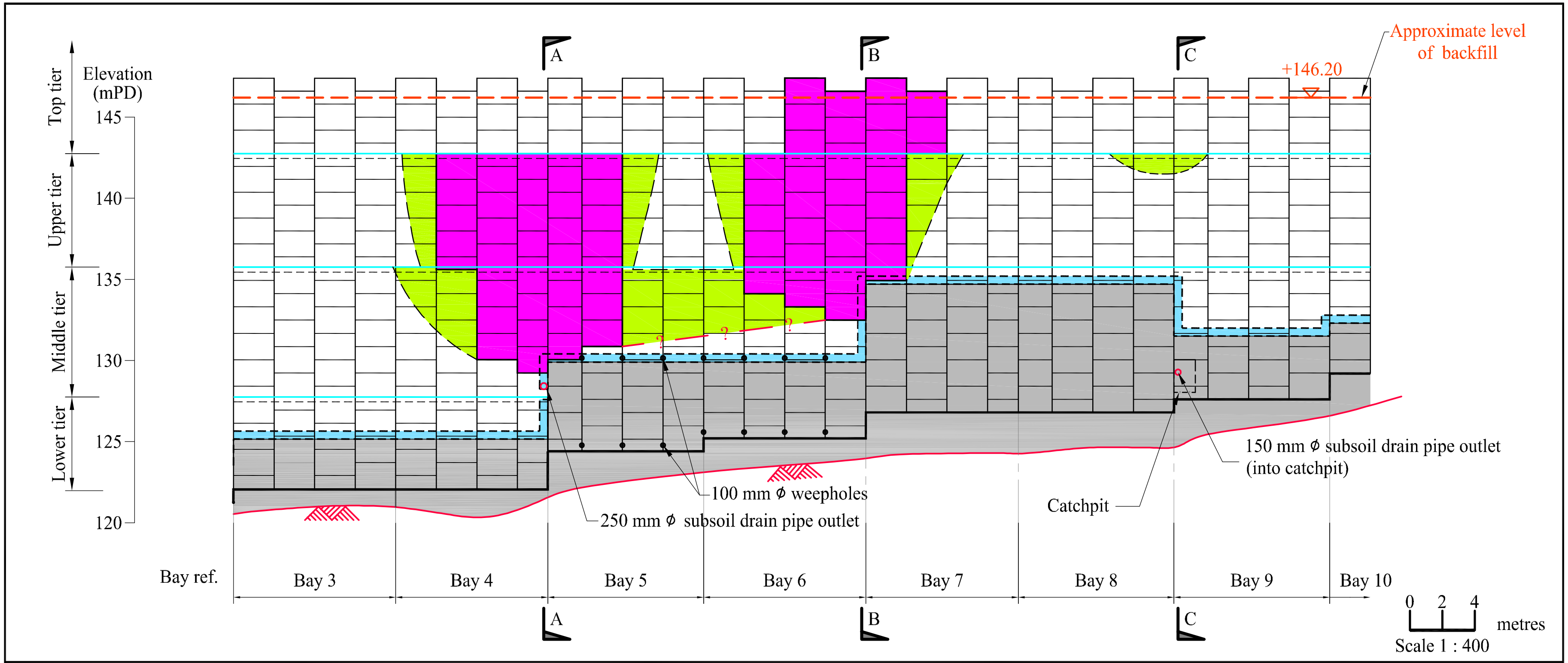
Legend :

🟩	Soil loss	↓	Water outflow from 250 mm ϕ subsoil drain pipe (22 May 2013, ~8:00 a.m.)	B3	Bay 3 for Wall R22	▨	500 mm thick drainage layer (capped by soil backfill)
🟫	Debris deposits	↓	Water outflow from dislodged panel (22 May 2013, ~8:00 a.m.)	CP ☐	Catchpit	▭	500 mm thick drainage layer
A A	Cross-section						

Notes :

(1) Extent and capping of drainage layers based on as-built drainage filter records (CSCE, 2013) and photographs.
(2) Debris deposits on wall tiers and footpath shown. Debris deposits over area beyond wall toe not shown.
(3) Inclined and vertical drainage layers are combined (coincident) over the lower portions of Bays 3 and 4 and over the full height of Bays 5 to 11.
(4) For cross-sections, see Figures 3.3 to 3.5.

Figure 3.1 Plan of the 22 May 2013 Incident at Wall R22



Legend :

▨ Mass concrete foundation

🟦 500 mm thick drainage layer

🟪 Dislodged panel

🟩 Loss of soil behind retained panels

Grade III/IV or better rock

A A Cross-section

Top of tier

Base of bottommost panel

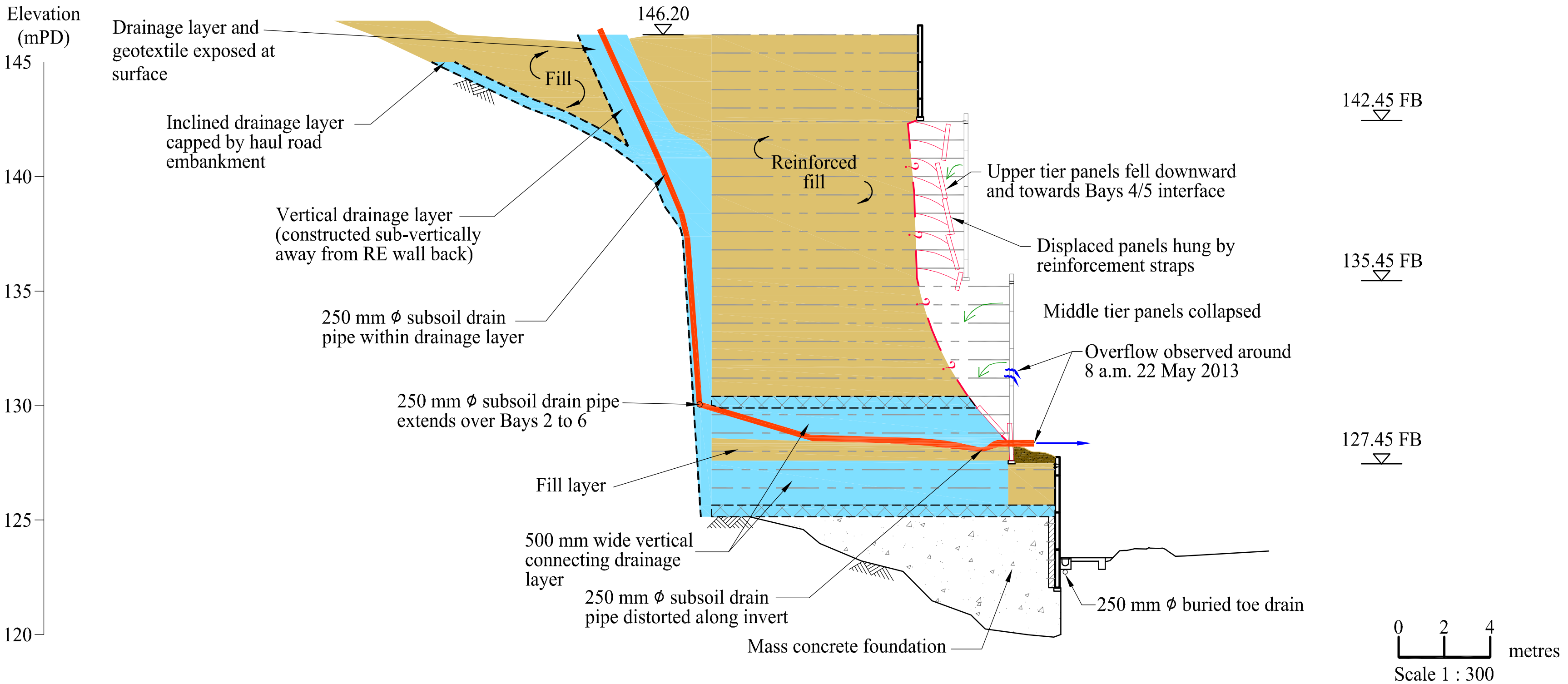
Base level of peg footing resting on compacted fill

○ Subsoil drain pipe outlet

Notes :

(1) Elevation is based on the merging of Drawing Nos. 2RE08054/CD/RE/R22/4001, 4003 to 4020 (Appendix A).
(2) All levels in mPD.
(3) Peg footings in Bay 7 and Bay 8 resting on mass concrete foundation not shown.
(4) 250 mm ϕ buried toe drain in front of the wall not shown.
(5) Grade III/IV or better rock profile is extracted from Drawing No. J385/RE/R22/002 (Appendix A).
(6) Top tier under construction at the time of the 22 May 2013 incident.
(7) For cross-sections, see Figures 3.3 to 3.5.

Figure 3.2 Elevation of the 22 May 2013 Incident at Wall R22



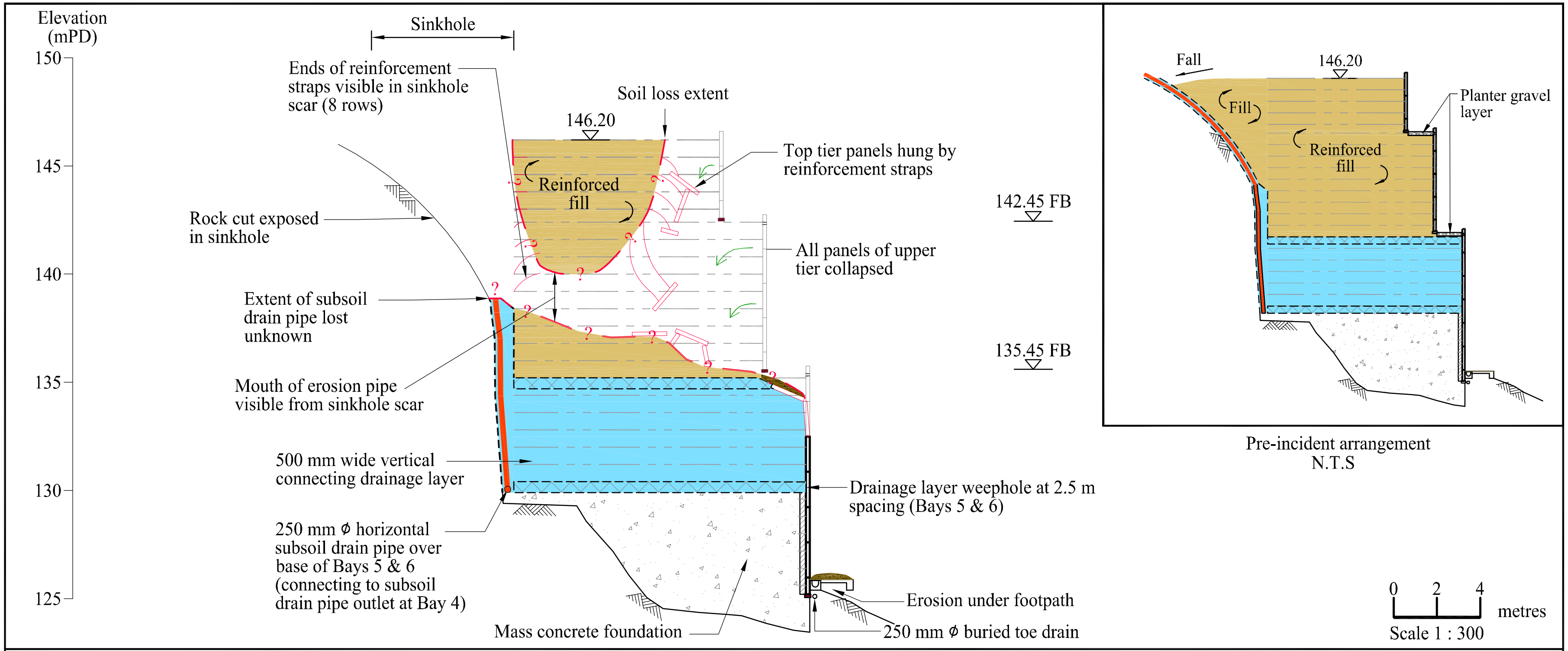
Legend :

🟦 Drainage layer
🟥 250 mm ϕ subsoil drain pipe wrapped in geotextile
🟫 Debris deposits
- - - - - - - - - Geotextile
▽ 135.45 FB Base level of peg footing resting on compacted fill
▯ Concrete fill
🟨 Fill
— ? — Denotes uncertainty
↙ Inferred overall panel displacement
▨ 500 mm thick base drainage layer over mass concrete foundations (connected by 500 mm wide vertical connecting drainage layer)

Notes :

(1) Cross-section based on Drawing Nos. J385/RE/R22/003 and 2RE08054/CD/RE/R22/4001, 4003 to 4030 (Appendix A), as-built drainage filter records (CSCE, 2013) and photographs.
(2) All levels in mPD.
(3) Top tier under construction at the time of the 22 May 2013 incident.
(4) For location of cross-section, see Figures 3.1 and 3.2.

Figure 3.3 Cross-section A-A of the 22 May 2013 Incident of Wall R22 at the Interface between Bays 4 and 5



Legend :

🟦 Drainage layer

🟥 250 mm ϕ subsoil drain pipe wrapped in geotextile

🟫 Debris deposits

- - - - - - - - - Geotextile

135.45 FB ▽ Base level of peg footing resting on compacted fill

▯ Concrete fill

🟨 Fill

— ? — Denotes uncertainty

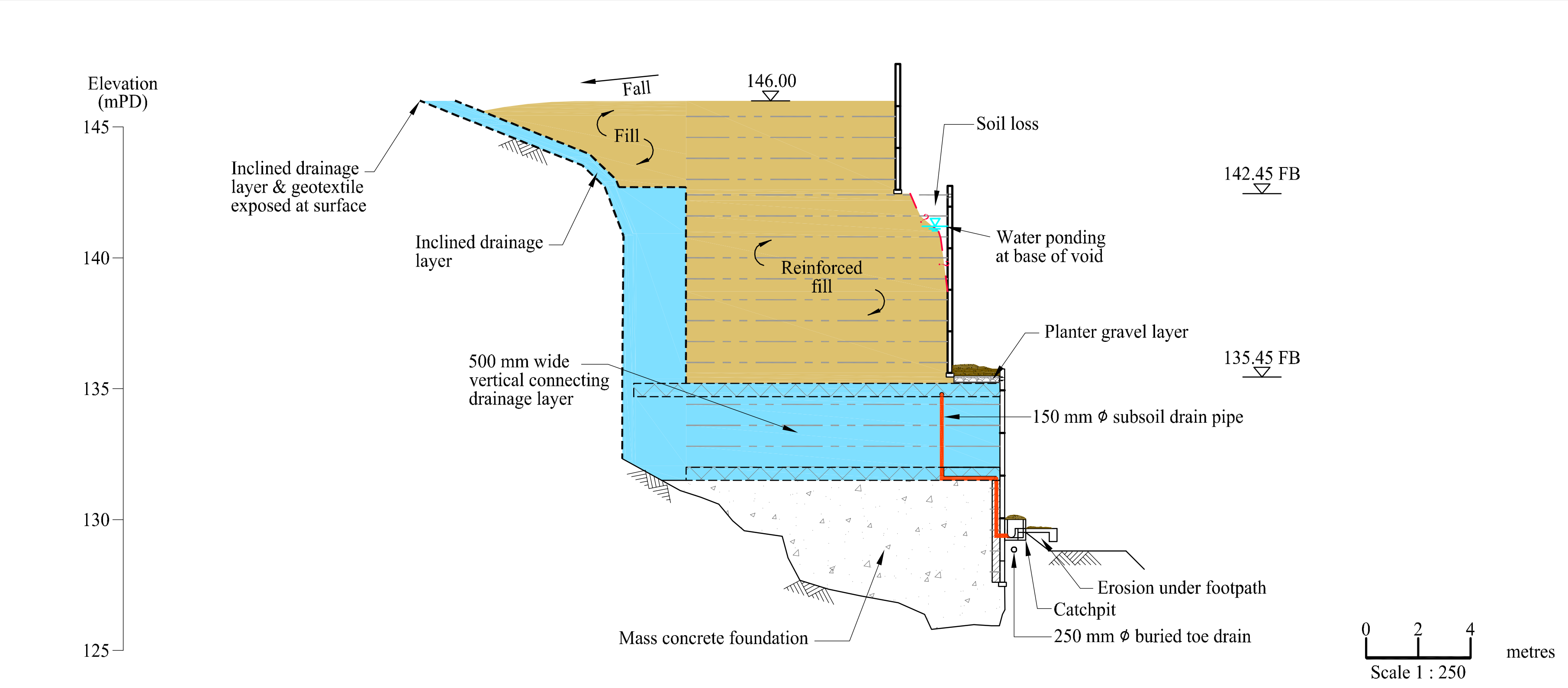
↙ Inferred overall panel displacement

▨ 500 mm thick base drainage layer over mass concrete foundations (connected by 500 mm wide vertical connecting drainage layer)

Notes :

(1) Cross-section based on Drawing Nos. J385/RE/R22/003 and 2RE08054/CD/RE/R22/4001, 4003 to 4030 (Appendix A), as-built drainage filter records (CSCE, 2013) and photographs.
(2) All levels in mPD.
(3) Pre-incident configuration of subsoil drain pipe shown. Upper portion of subsoil drain pipe and surrounding drainage layer lost in the incident.
(4) Top tier under construction at the time of the 22 May 2013 incident.
(5) For location of cross-section, see Figures 3.1 and 3.2.

Figure 3.4 Cross-section B-B of the 22 May 2013 Incident of Wall R22 at the Interface between Bays 6 and 7



Legend :

🟦 Drainage layer

▯ Concrete fill

▨ 500 mm thick base drainage layer over mass concrete foundations (connected by 500 mm wide vertical connecting drainage layer)

🟥 150 mm ϕ subsoil drain pipe wrapped in geotextile

▨ Fill

■ Debris deposit

— ? — Denotes uncertainty

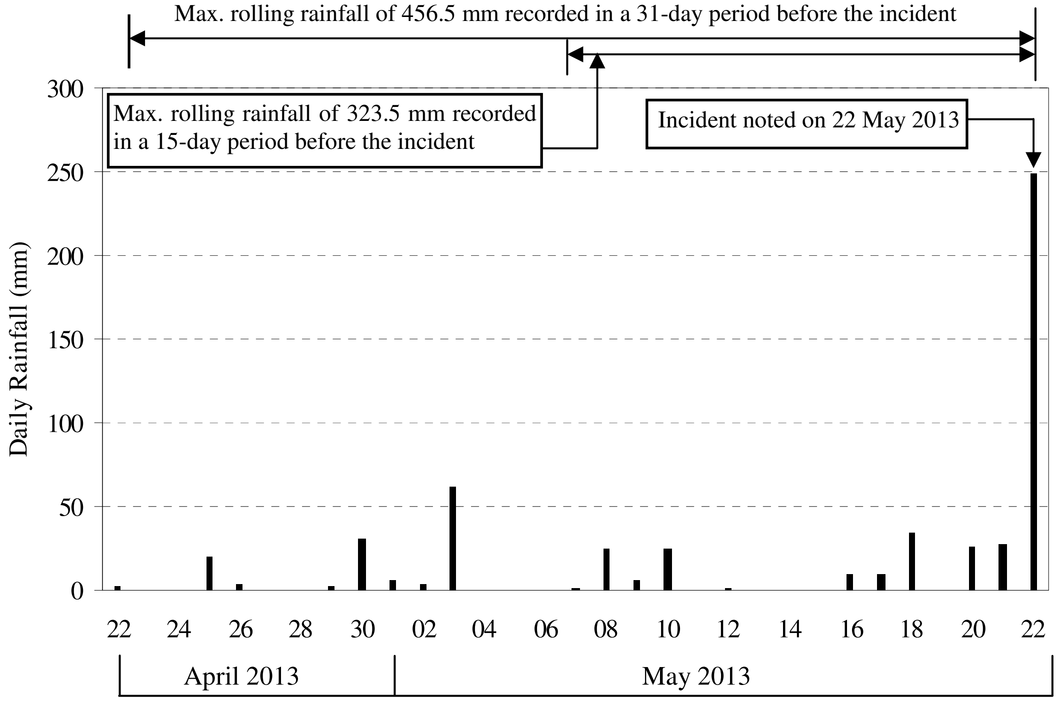
- - - - - - - - - Geotextile

135.45 FB ▽ Base level of peg footing resting on compacted fill

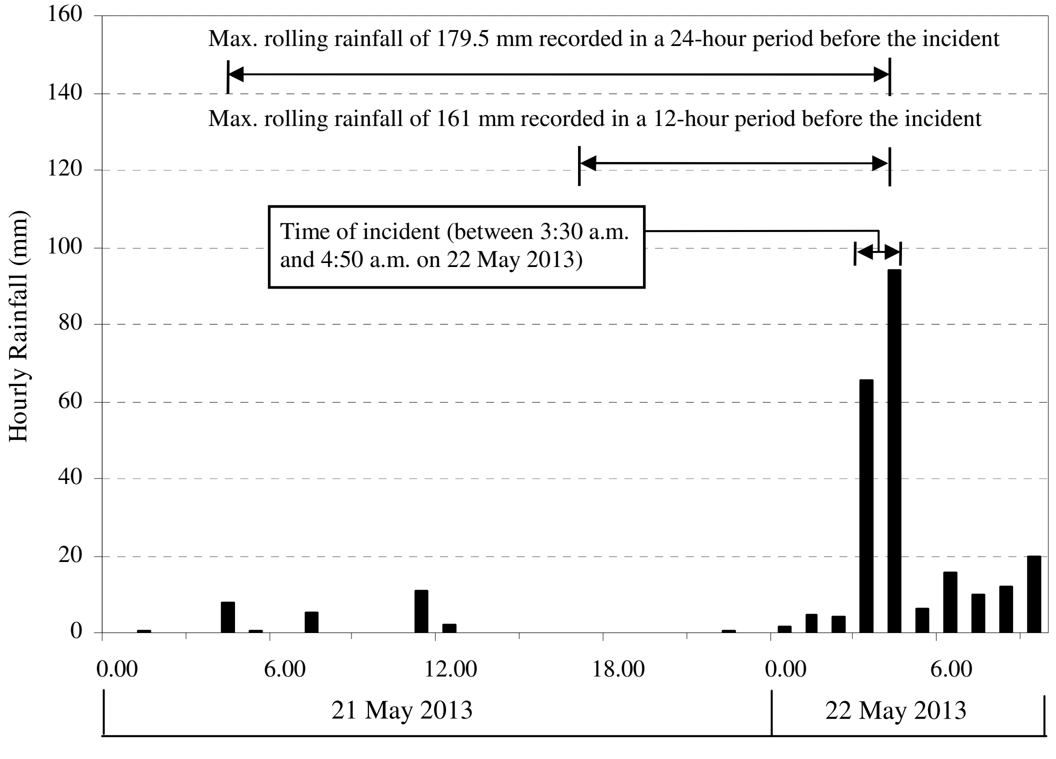
Notes :

(1) Cross-section based on Drawing Nos. J385/RE/R22/003 and 2RE08054/CD/RE/R22/4001, 4003 to 4030 (Appendix A), as-built drainage filter records (CSCE, 2013) and photographs.
(2) All levels in mPD.
(3) Top tier under construction at the time of the 22 May 2013 incident.
(4) For location of cross-section, see Figures 3.1 and 3.2.

Figure 3.5 Cross-section C-C of the 22 May 2013 Incident of Wall R22 at the Interface between Bays 8 and 9

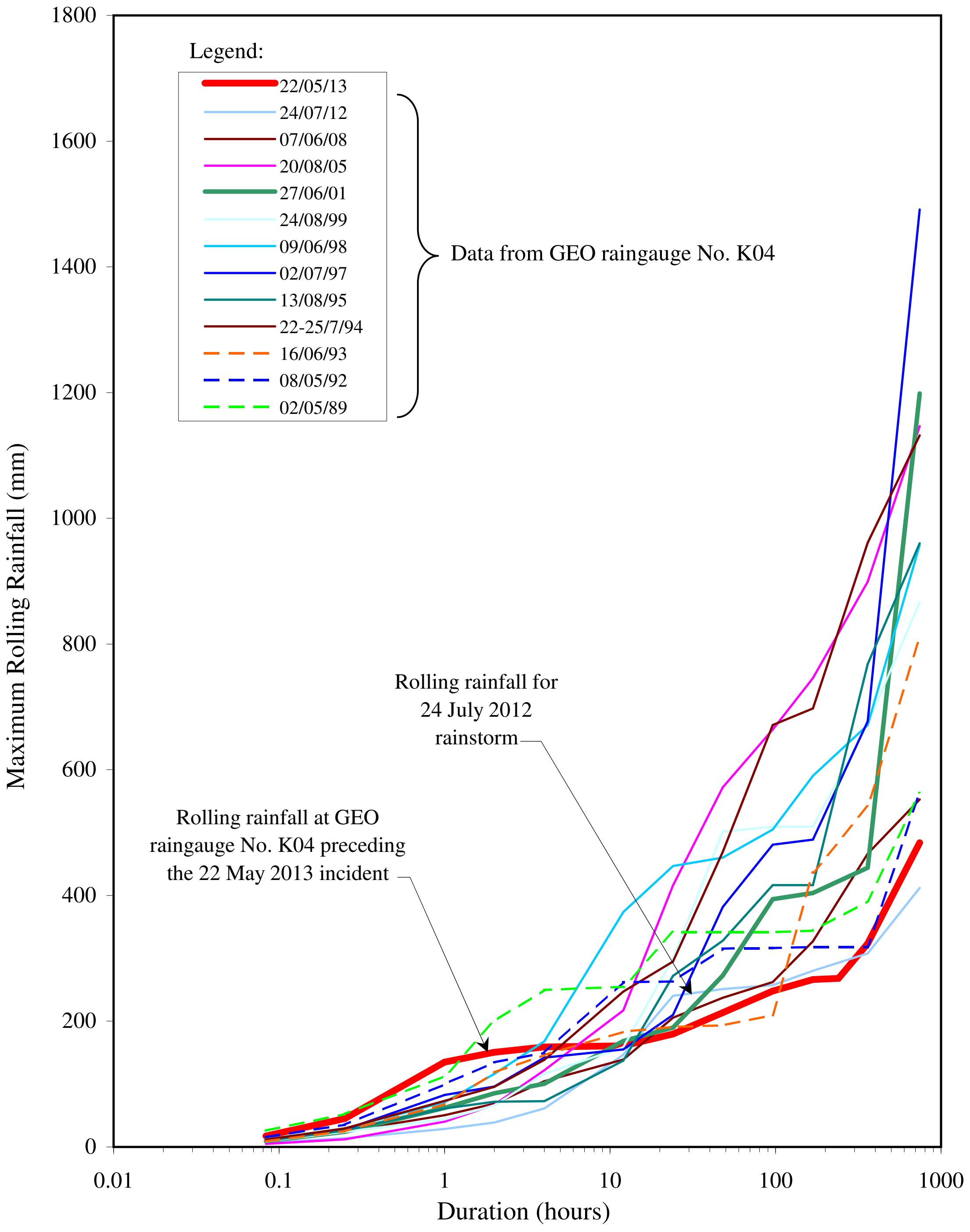


(a) Daily Rainfall Recorded at GEO Raingauge No. K04 between 22 April 2013 and 22 May 2013



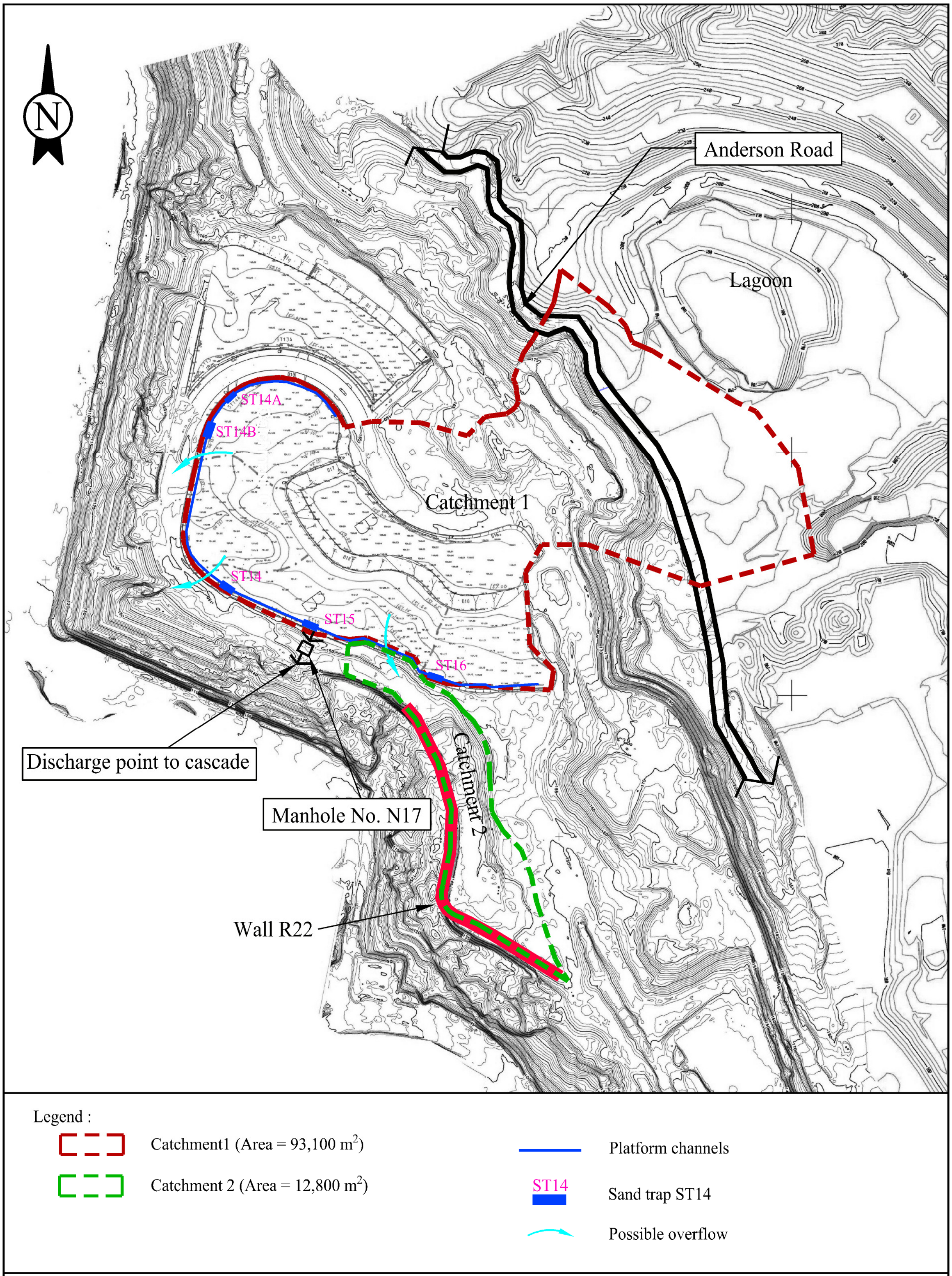
(b) Hourly Rainfall Recorded at GEO Raingauge No. K04 between 21 May 2013 and 22 May 2013

Figure 4.1 Daily and Hourly Rainfall Recorded at GEO Raingauge No. K04 in May 2013



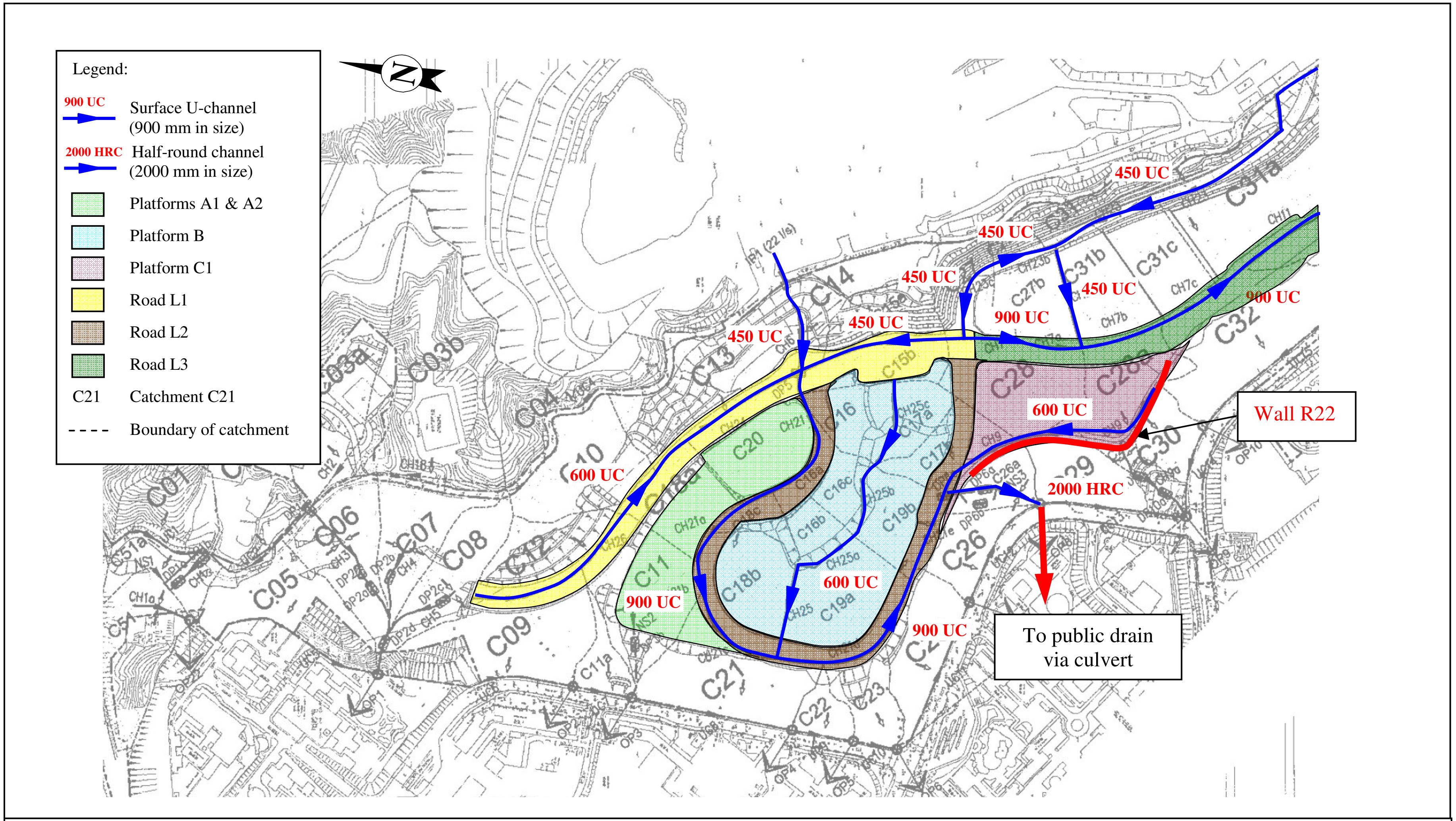
Note: Rainfall data was evaluated from 5-minute readings from GEO raingauge No. K04 (about 930 m to the northwest of Wall R22).

Figure 4.2 Maximum Rolling Rainfall for Previous Major Rainstorms at GEO Raingauge No. K04



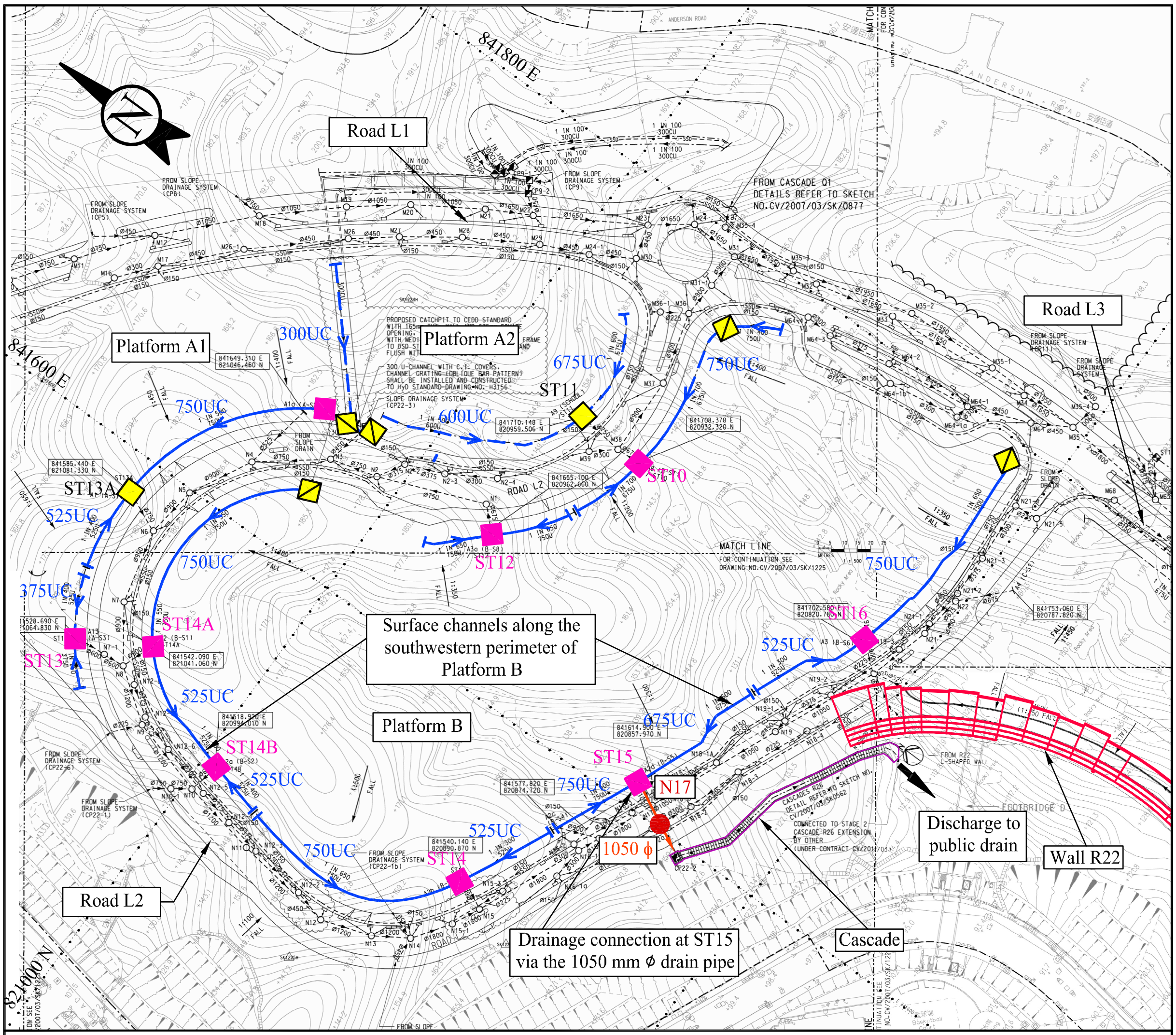
Note : Topographic base plan is compiled from Drawing No. UA130022-SK03 prepared by Survey Division of CEDD in May 2013, Drawing No. KWP/MS195/01 prepared by the Contractor of the Anderson Road Quarry in April 2013 and topographic surveys by OAP on Platform A1 and Platform B on 16 May 2013.

Figure 5.1 Catchment Boundary near Wall R22



Note: The base plan is extracted from Sketch No. SK-TDS-01 (rev. F) of the Temporary Drainage Design Submission (Report ref. R385/02 rev. F) dated 26 April 2013.

Figure 5.2 Schematic Layout Plan of Temporary Site Drainage Design

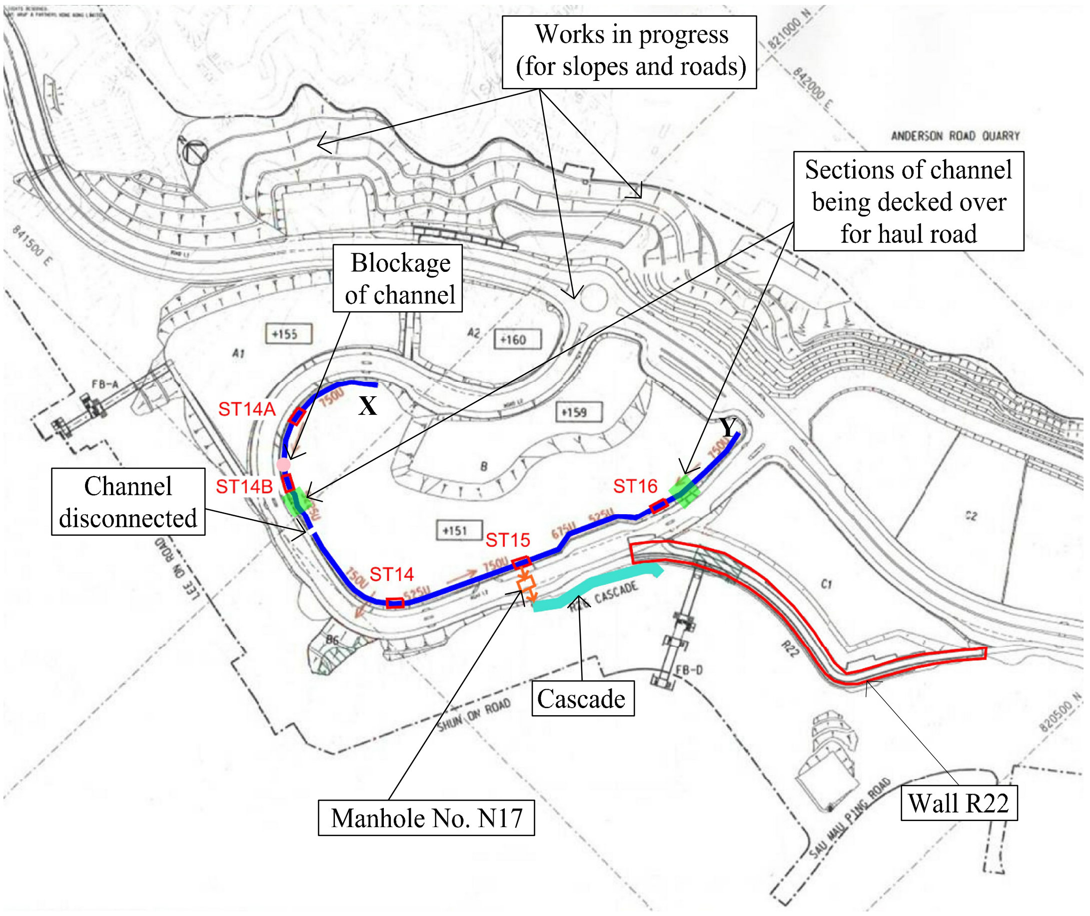


Legend :

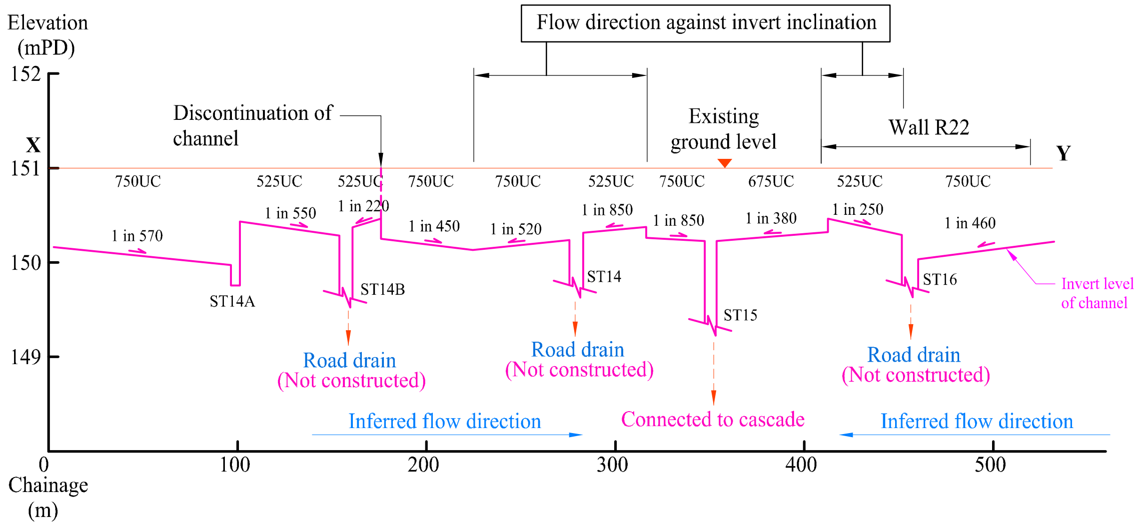
750 UC	As-constructed 750 mm U-channel on platform
ST15 ■	As-constructed sand trap No. ST15
N17 ●	As-constructed manhole No. N17
1050 ϕ	As-constructed 1050 mm dia. underground drain pipe
600 UC	Proposed 600 mm U-channel on platform (not yet constructed at the time of the 22 May 2013 incident)
– –⊣⊢– –	Change in U-channel size and flow direction
⧄	Proposed catchpit (not yet constructed)
ST11 □	Proposed sand trap No. ST11 (not yet constructed)
– – ○ – –	Proposed road drains (not yet constructed)

Note : Base map is extracted from the DAR Drainage Layout Plans Sketch Nos. CV/2007/03/SK/1224 (Rev. H), CV/2007/03/SK/1225 (Rev. H) and CV/2007/03/SK/1226 (Rev. I).

Figure 5.3 Layout Plan of Proposed Permanent Drainage Works



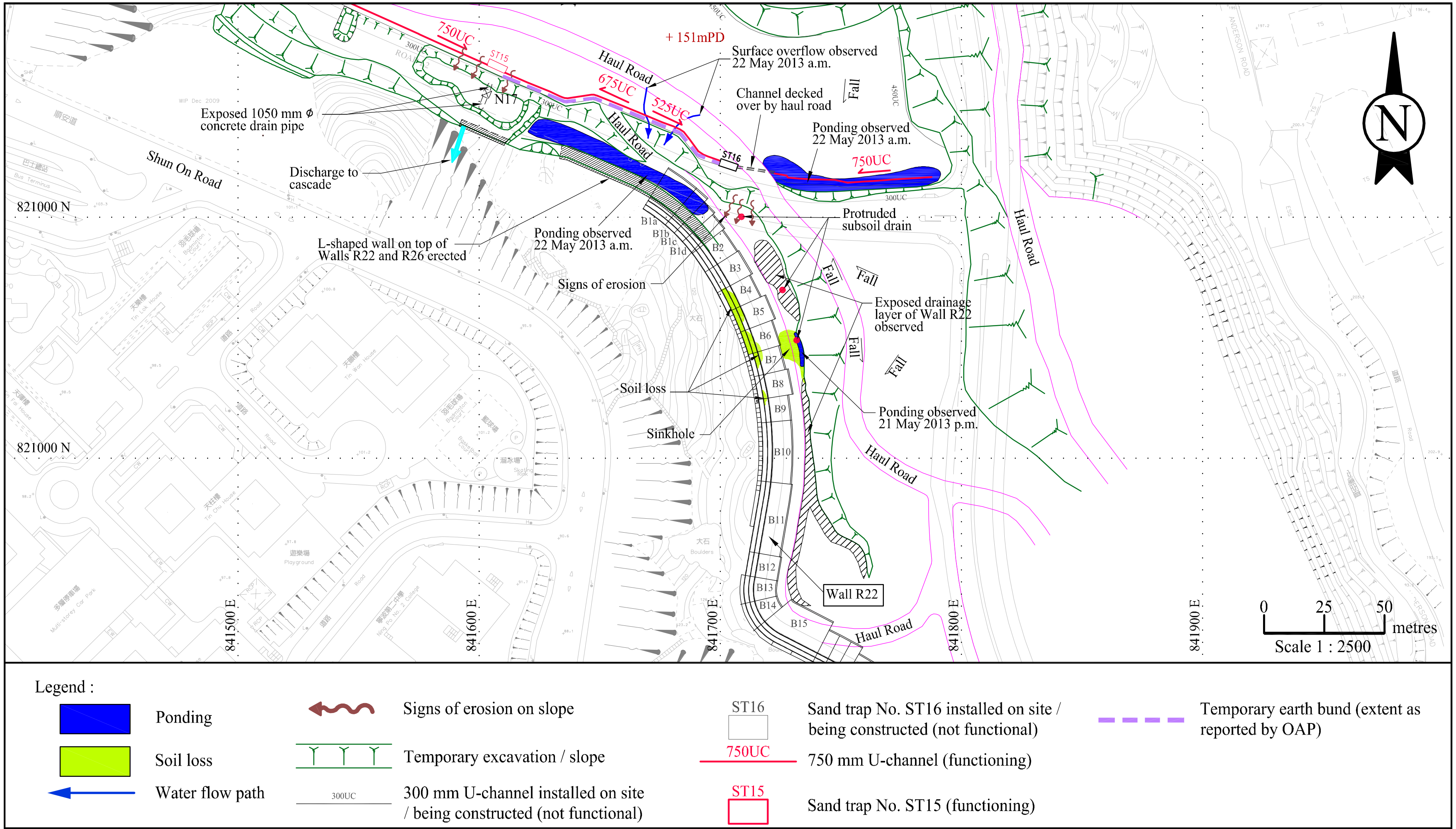
(a) Schematic Layout of the As-constructed Surface Drainage Works as Part of the Permanent Drainage Works



(b) Longitudinal Profile X-Y Along Platform Drain

Note : For Figure (b), vertical scale is exaggerated.

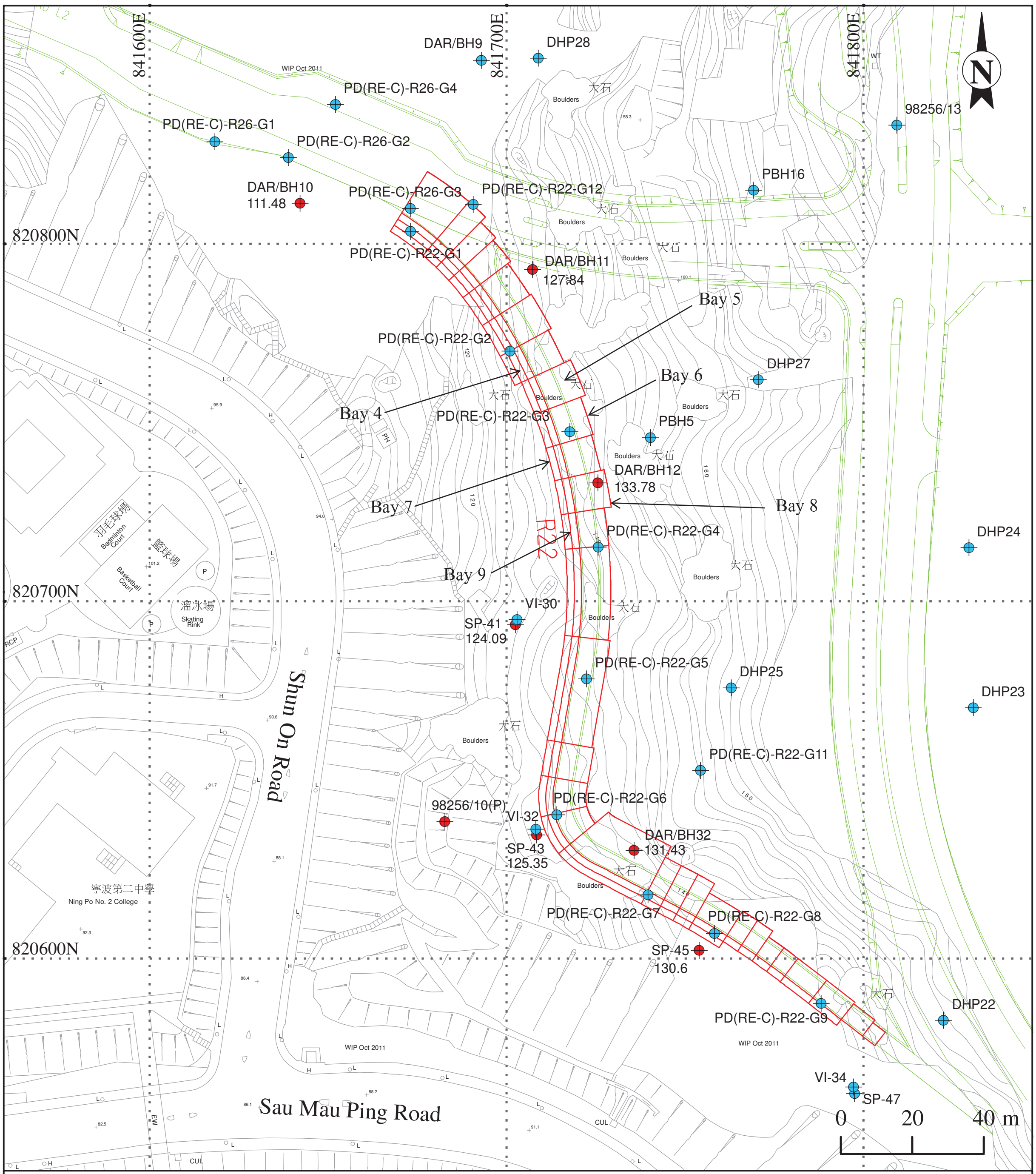
Figure 5.4 Schematic Layout of As-constructed Surface Drainage System at Platform B



Notes : (1) Base map is extracted from Survey Sheet No. 11NE13D.

(2) Observations were made between 22 and 25 May 2013.

Figure 5.5 Field Observations on Surface Drainage Provisions in the Vicinity of Wall R22



Legend:

🔴 Previous borehole with groundwater monitoring with maximum recorded groundwater level in mPD

🔵 Previous borehole

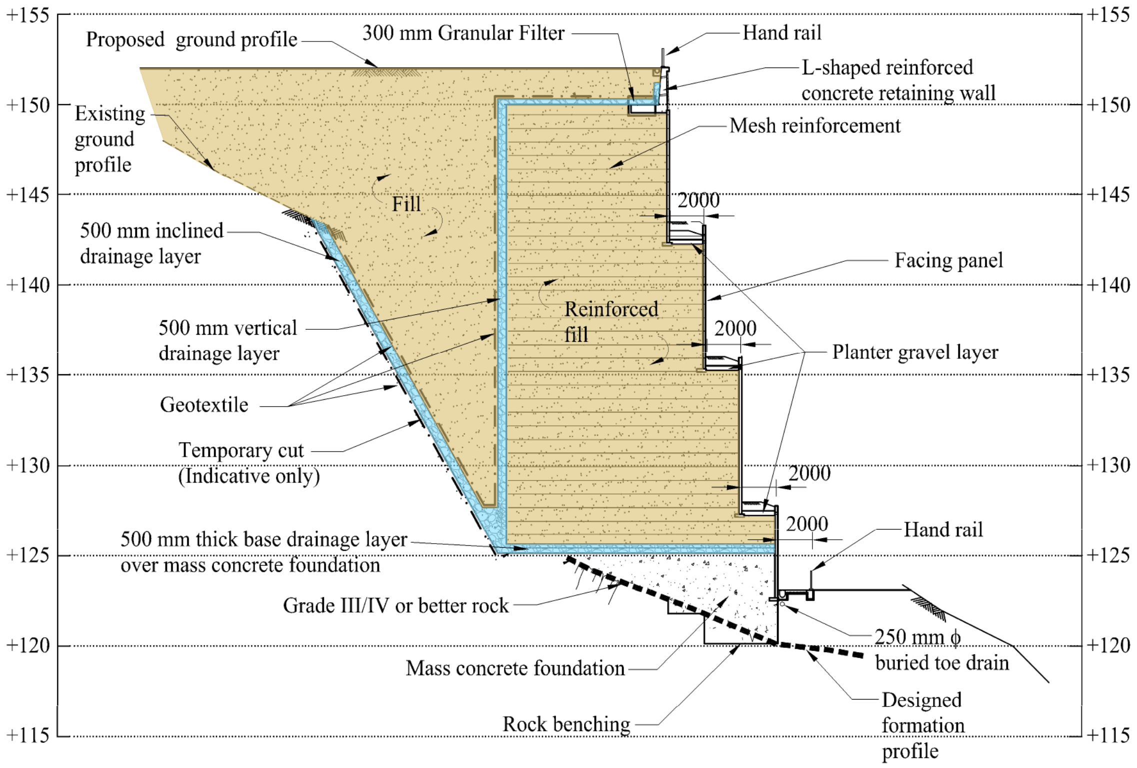
Notes:

(1) Base map is extracted from Survey Sheet Nos. 11NE13B and 11NE13D.

(2) Proposed DAR development layout is extracted from CEDD plan provided by OAP (shown in green).

(3) ⊕ DAR/BHxx series - Fugro Geotechnical Services, 2006a
⊕ PBHxx series - Bachy Soletanche, 1998
⊕ DHPxx series - Fugro Geotechnical Services, 2006b
⊕ PD(RE-C)-R26-Gx series - Gold Ram Engineering & Development, 2008
⊕ PD(RE-C)-R22-Gx series - Gold Ram Engineering & Development, 2008
⊕ 98256/xx series - DrilTech Ground Engineering, 2001
⊕ VI-xx series - Gold Ram Engineering & Development, 2008
⊕ SP-xx series - Gold Ram Engineering & Development, 2008

Figure 6.1 Previous Ground Investigation at Wall R22



N.T.S.

Legend :

🟦 Drainage layer

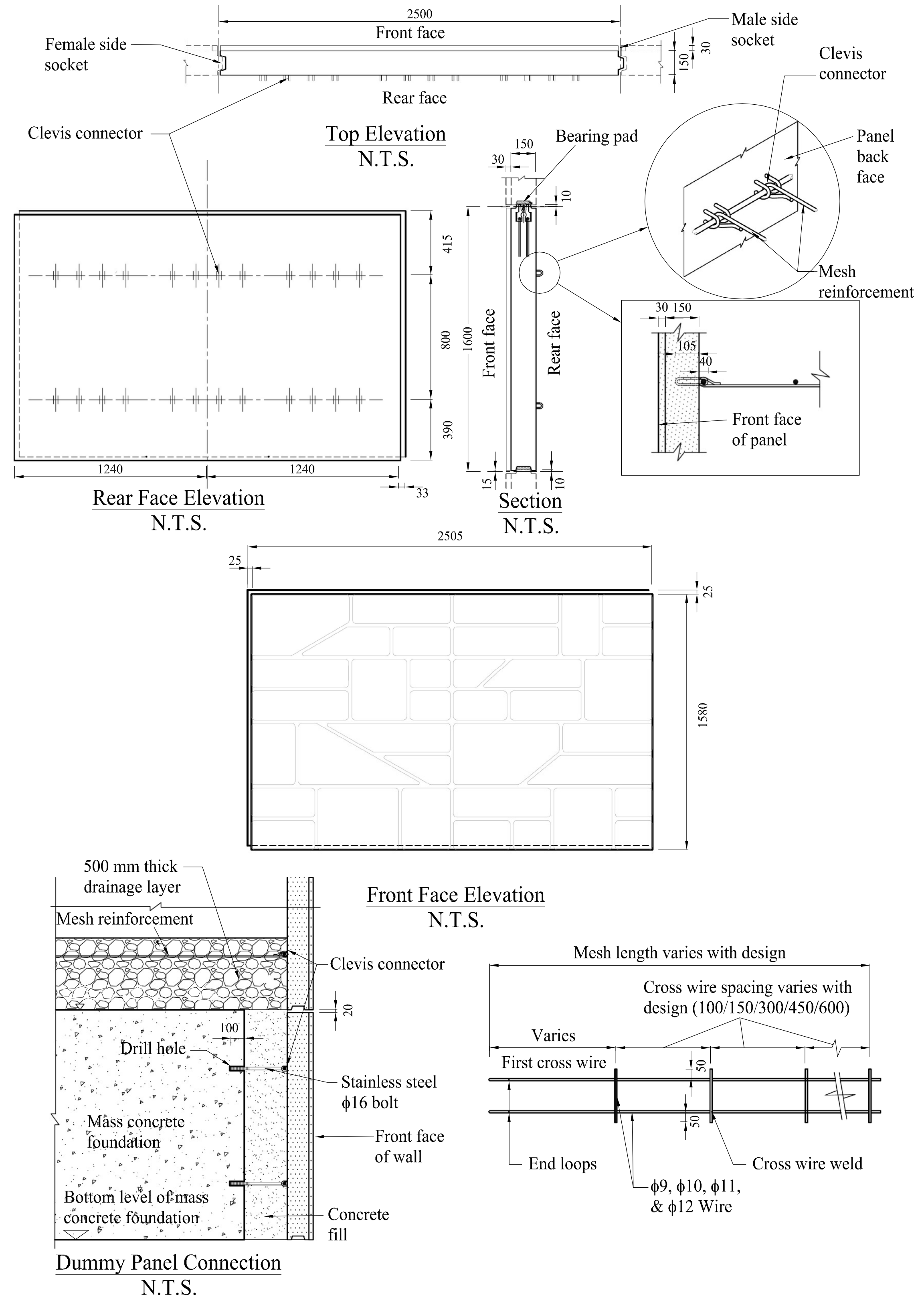
🟨 Fill

Notes :

(1) Cross-section details based on Drawing No. 2RE08054/CD/RE/R22/4017 (Appendix A).

(2) Bay 4 section details shown.

Figure 7.1 Typical Cross-section of Wall R22



Notes : (1) Typical details extracted from Drawing Nos. 2RE08054/CD/RE/D/3002, 2RE08054/CD/RE/R22/4010 and 2RE08054/CD/RE/SK01 (Appendix A).
(2) All dimensions in mm.

Figure 7.2 Typical Details of Wall R22

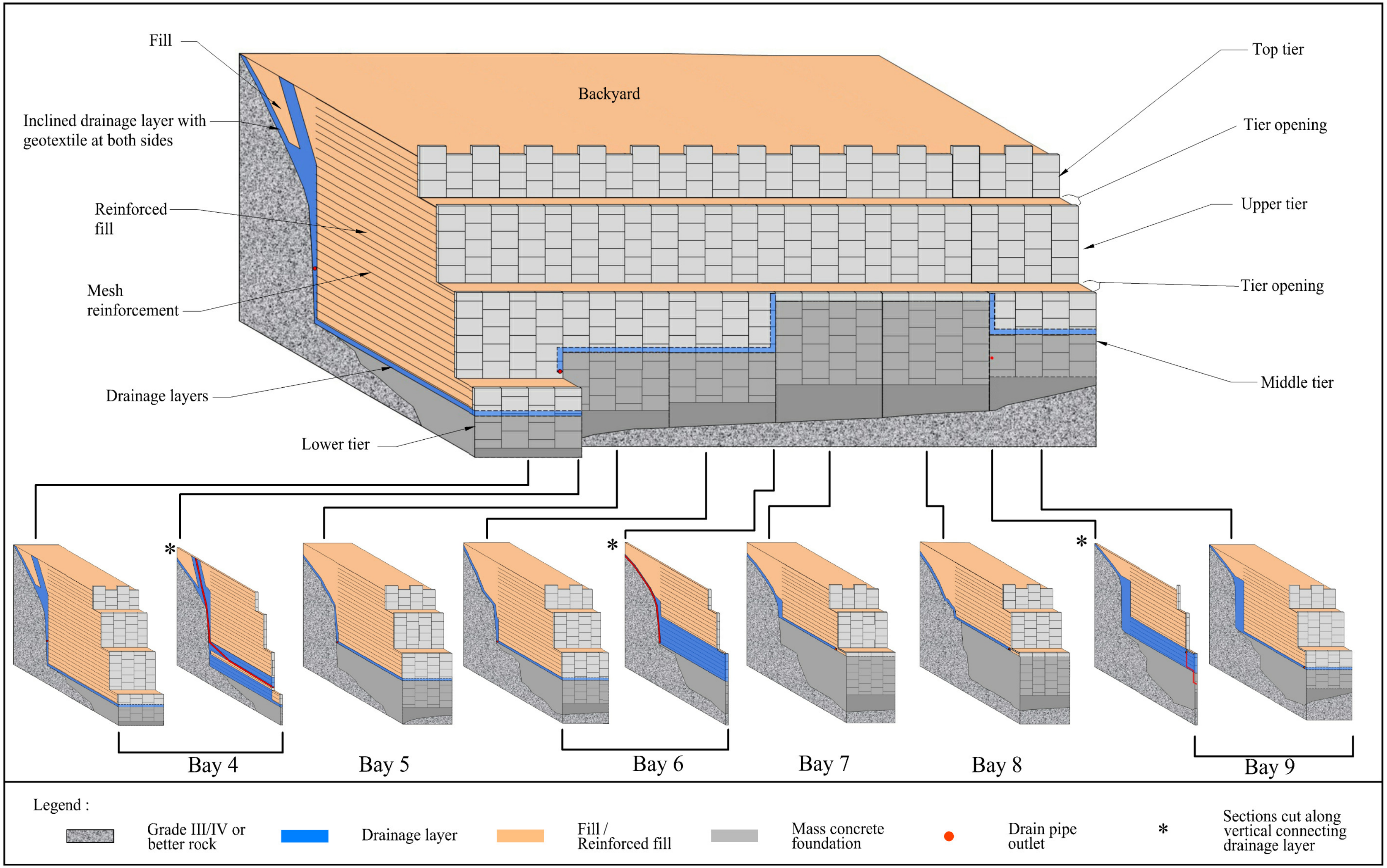
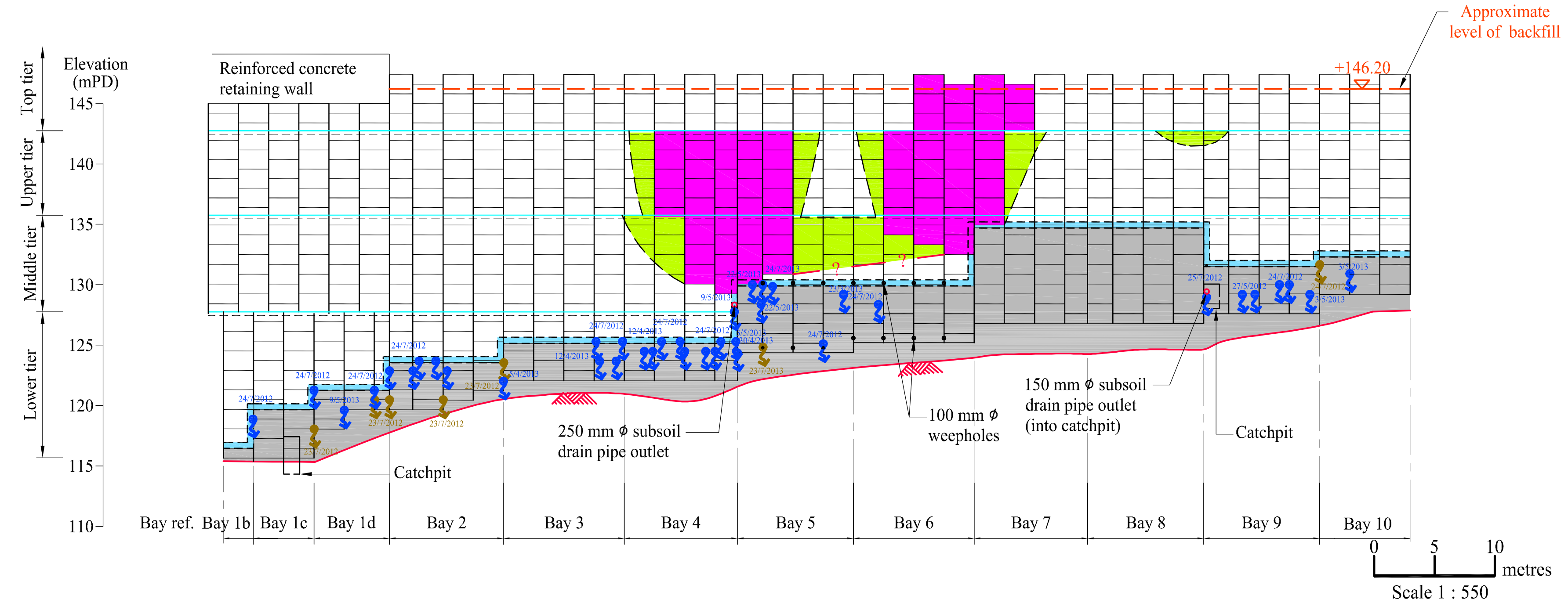


Figure 7.3 3D Spatial Arrangement of the Drainage Layers and Tiers



Legend :

▨ Mass concrete foundation

▭ 500 mm thick drainage layer

🟪 Dislodged panel

🟩 Loss of soil behind retained panels

— Top of tier

- - - - Base level of peg footing resting on compacted fill

Grade III/IV or better rock

? Denotes uncertainty

○ Subsoil drain pipe outlet

24/7/2012 Seepage point observed on 24/7/2012

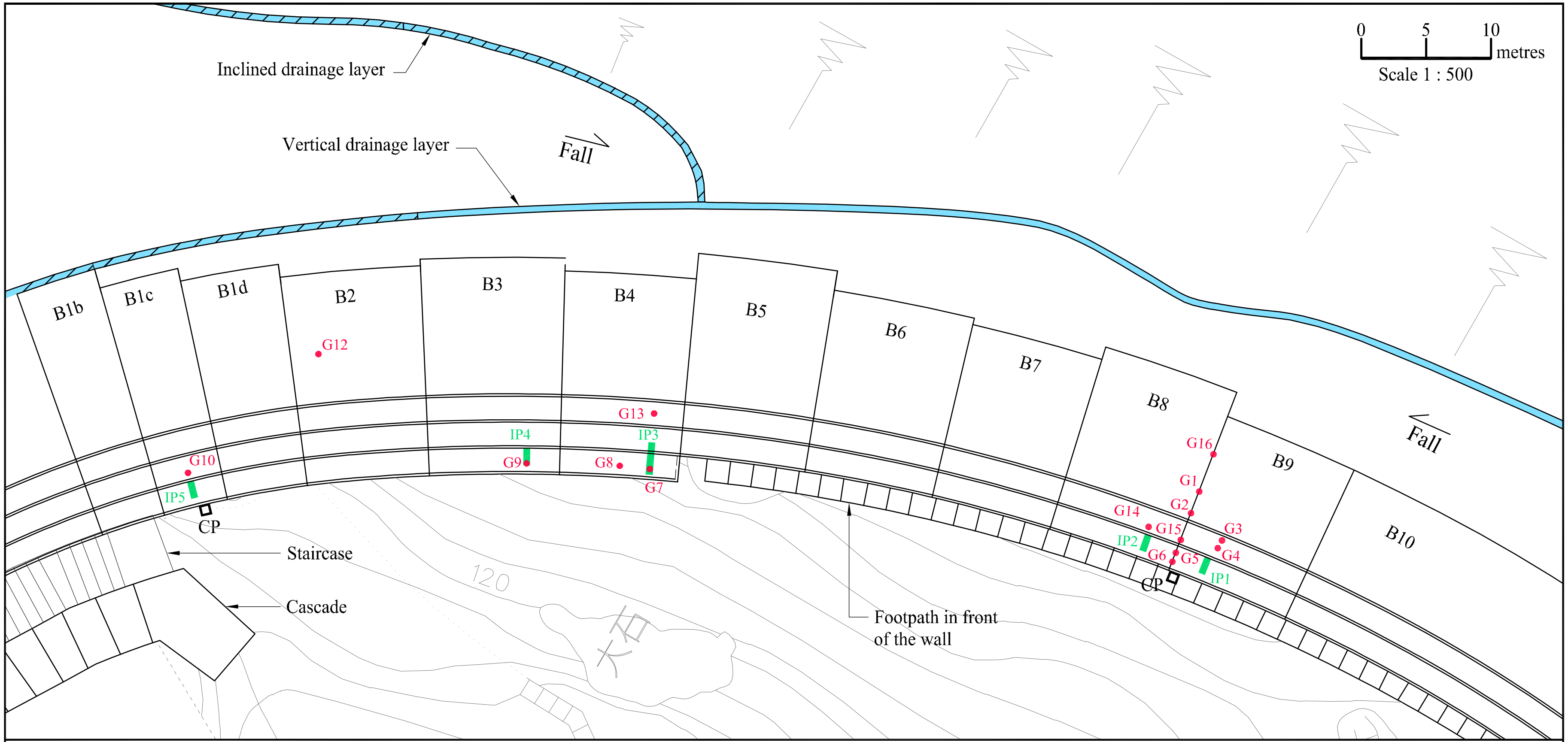
23/7/2012 Seepage point with muddy water or signs of loss of fines observed on 23/7/2012

● 100 mm ϕ weepholes

Notes :

(1) Elevation is based on the merging of Drawing Nos. 2RE08054/CD/RE/R22/4001, 4003 to 4020 (Appendix A).
(2) All levels in mPD.
(3) Peg footings in Bay 7 and Bay 8 resting on mass concrete foundation not shown.
(4) 250 mm ϕ buried toe drain in front of wall not shown.
(5) Grade III/IV or better rock profile is extracted from Drawing No. J385/RE/R22/002 (Appendix A).
(6) Top tier under construction at the time of the 22 May 2013 incident.

Figure 7.4 Seepage Observations at Wall R22



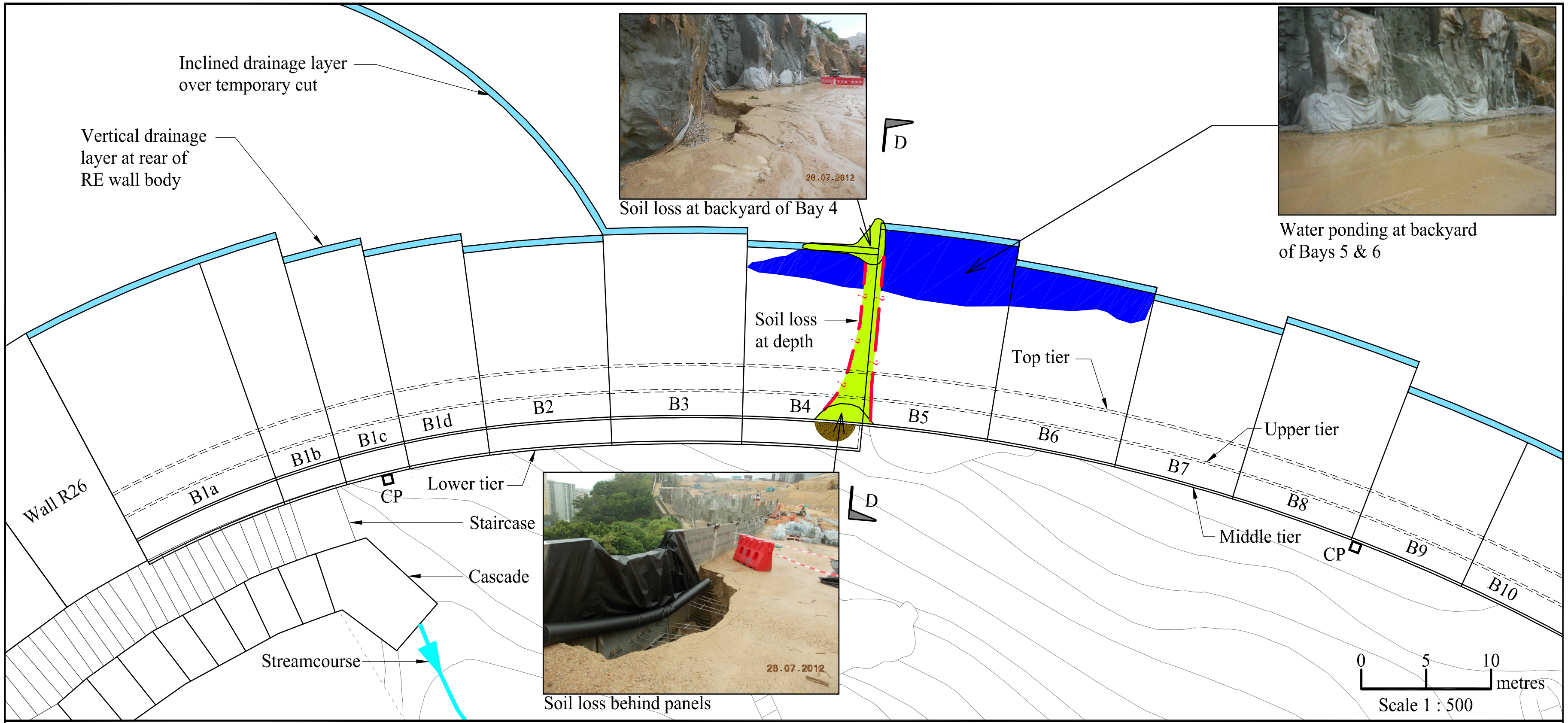
Legend :

G10 ●	GCO probe No. G10
IP5 ▮	Inspection pit No. IP5
🟦	500 mm thick drainage layer
▨	500 mm thick drainage layer (capped by soil backfill)
CP □	Catchpit
B3	Bay 3 for Wall R22

Notes :

(1) Extent and capping of drainage layers based on as-built drainage filter records (CSCE, 2013) and photographs.
(2) Inclined and vertical drainage layers are combined (coincident) at lower portions of Bays 3 and 4 and over the full height of Bays 5 to 11.
(3) Ground investigation works were carried out by DrilTech Ground Engineering Ltd. between August 2013 and September 2013.

Figure 7.5 Ground Investigation at Wall R22 following the 22 May 2013 Incident

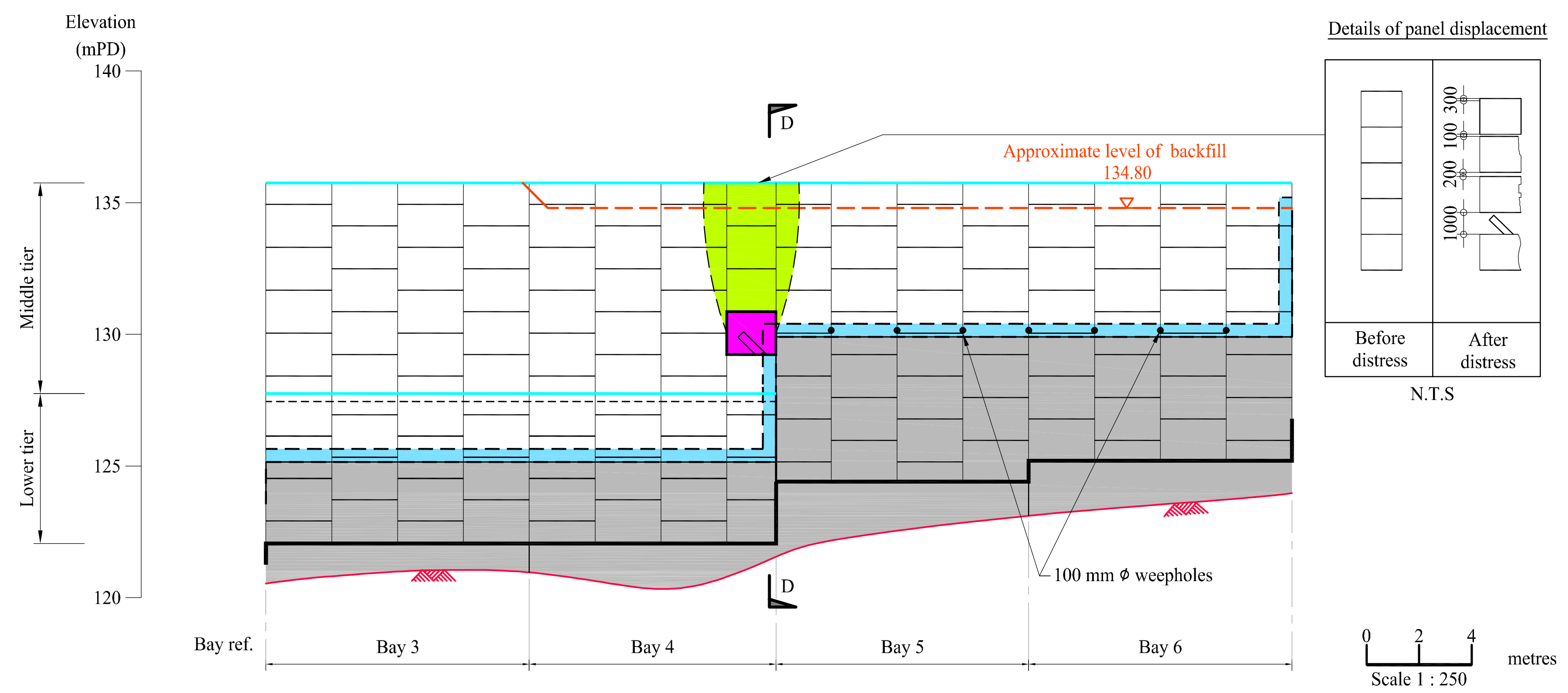


Legend :

●	Soil loss	— ? —	Denotes uncertainty	▭	500 mm thick drainage layer	■	Water ponding observed on 24 July 2012
D D	Cross-section	CP □	Catchpit	▨	Debris deposits	B3	Bay 3 for Wall R22

Notes :
(1) Extent of drainage layers based on as-built filter records (CSCE, 2013) and photographs.
(2) Top and upper tier not yet constructed at the time of the July 2012 incident (in dotted line).
(3) Inclined and vertical drainage layers are combined (coincident) at lower portions of Bays 3 and 4 and over the full height of Bays 5 to 11.
(4) For cross-section, see Figure 8.3.

Figure 8.1 Plan of the July 2012 Incident at Wall R22



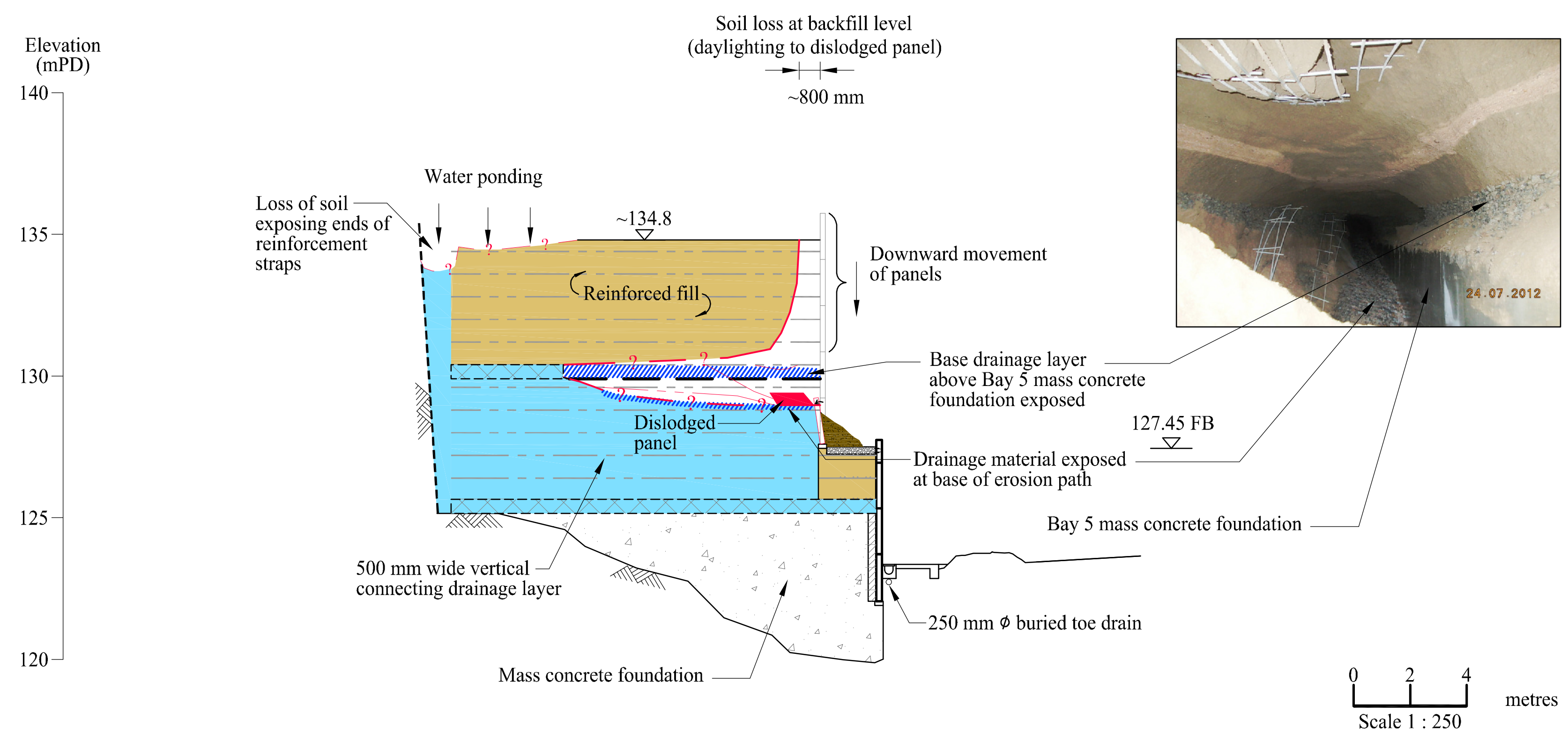
Legend :

▨ Mass concrete foundation
▭ 500 mm thick drainage layer
🟪 Dislodged panel
🟩 Loss of soil behind retained panels
Grade III/IV or better rock
D D Cross-section
- - - - - - - - Base level of peg footing resting on compacted fill
——— Top of tier
● 100 mm ϕ weepholes
——— Base of bottommost panel

Notes :

(1) Elevation is based on merging of Drawing Nos. 2RE08054/CD/RE/R22/4001, 4003 & 4004 (Appendix A).
(2) All levels in mPD.
(3) Grade III/IV or better rock profile is extracted from Drawing No. J385/RE/R22/002, (Appendix A).
(4) Top and upper tier not yet constructed at the time of the July 2012 incident.
(5) For cross-section, see Figure 8.3.

Figure 8.2 Elevation of the July 2012 Incident at Wall R22



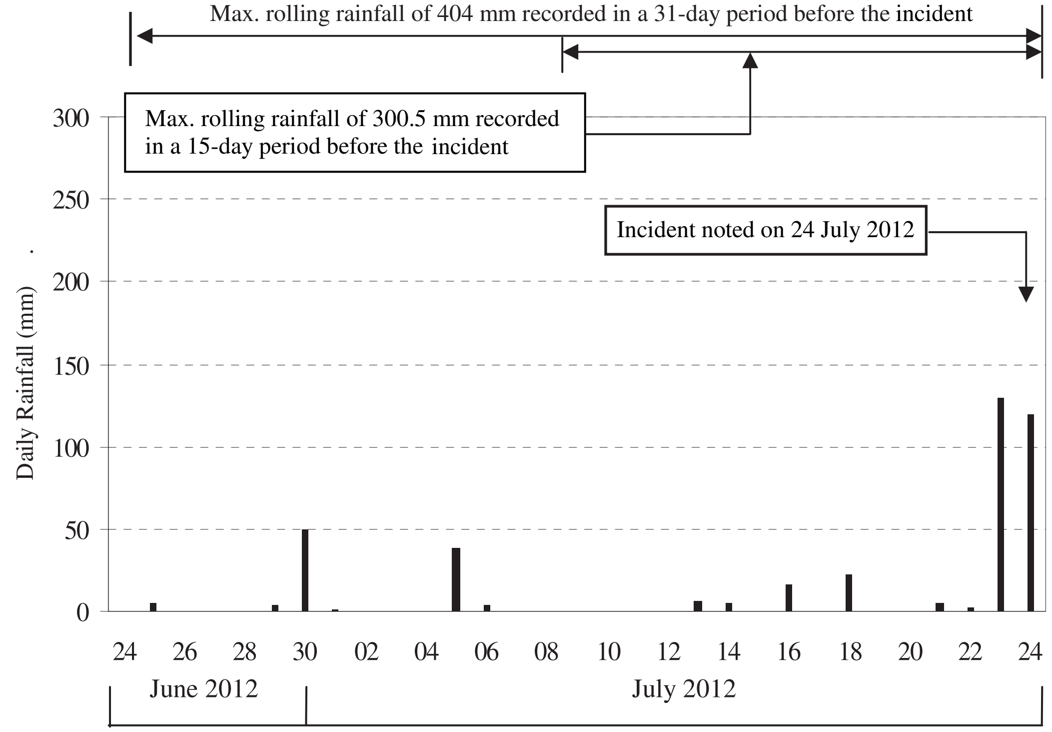
Legend :

🟦	Drainage layer	🟨	Fill	▯	Concrete fill	----------	Geotextile	127.45 FB ▽	Base level of peg footing resting on compacted fill
— —	Exposed top of Bay 5 mass concrete	🟫	Debris deposits	— ? —	Denotes uncertainty				
▨	Exposed drainage layer	▨	500 mm thick base drainage layer over mass concrete foundations (connected by 500 mm wide vertical connecting drainage layer)						

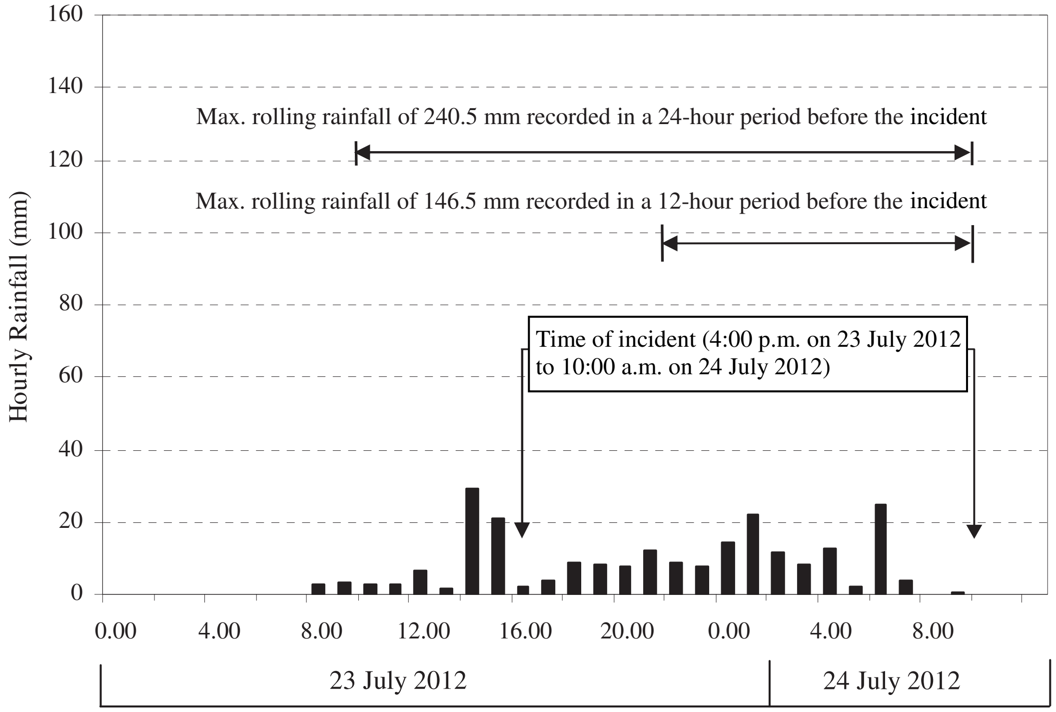
Notes :

(1) Cross-section based on Drawing Nos. J385/RE/R22/003 and 2RE08054/CD/RE/R22/4001, 4003 to 4030 (Appendix A), as-built drainage filter records (CSCE, 2013) and photographs.
(2) All levels in mPD.
(3) Upper and top tiers not yet constructed at the time of the July 2012 incident.
(4) For location of cross-section, see Figures 8.1 and 8.2.

Figure 8.3 Cross-section D-D of the July 2012 Incident at Bay 4 of Wall R22



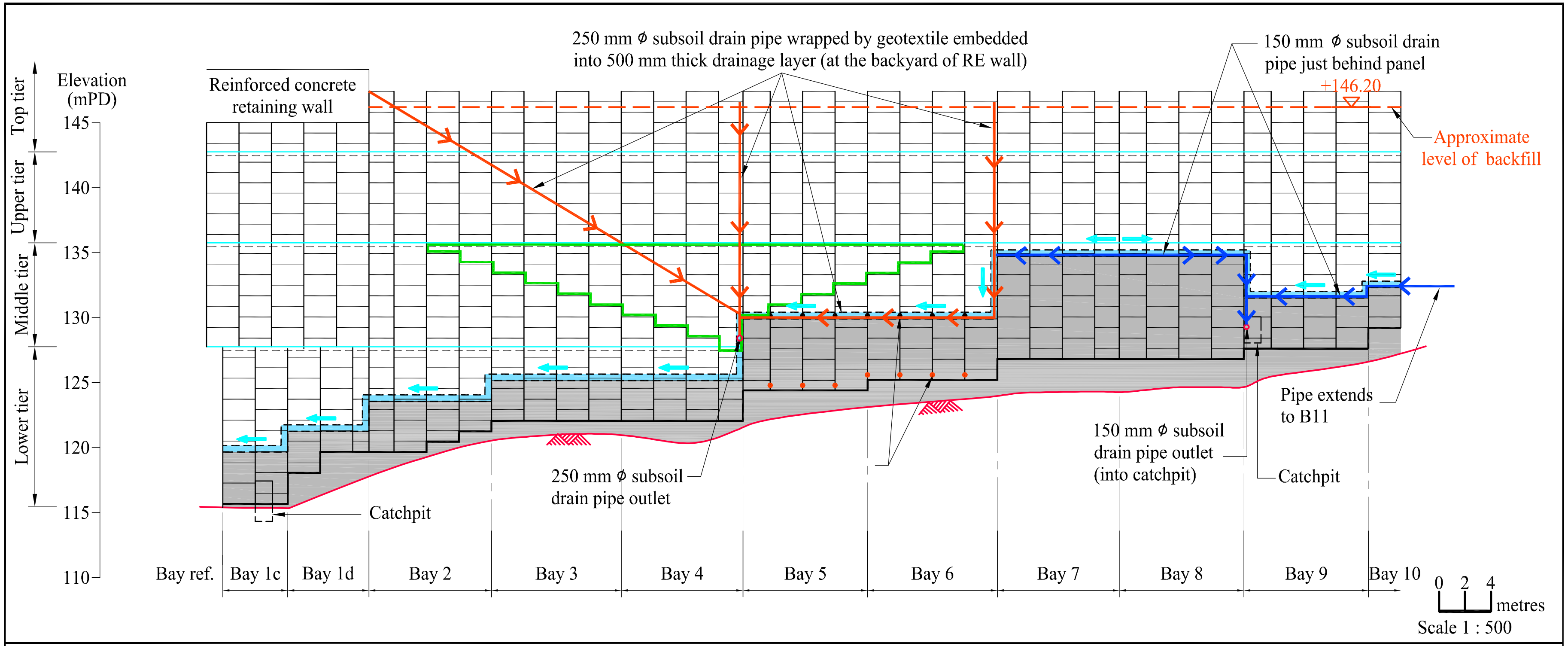
(a) Daily Rainfall Recorded at GEO Raingauge No. K04 between 24 June 2012 and 24 July 2012



(b) Hourly Rainfall Recorded at GEO Raingauge No. K04 between 23 July 2012 and 24 July 2012

Note: Time of incident was between the end of site works activities at 4:00 p.m. on 23 July 2012 and recommencement of site works activities at 10:00 a.m. on 24 July 2012.

Figure 8.4 Daily and Hourly Rainfall Recorded at GEO Raingauge No. K04 in July 2012



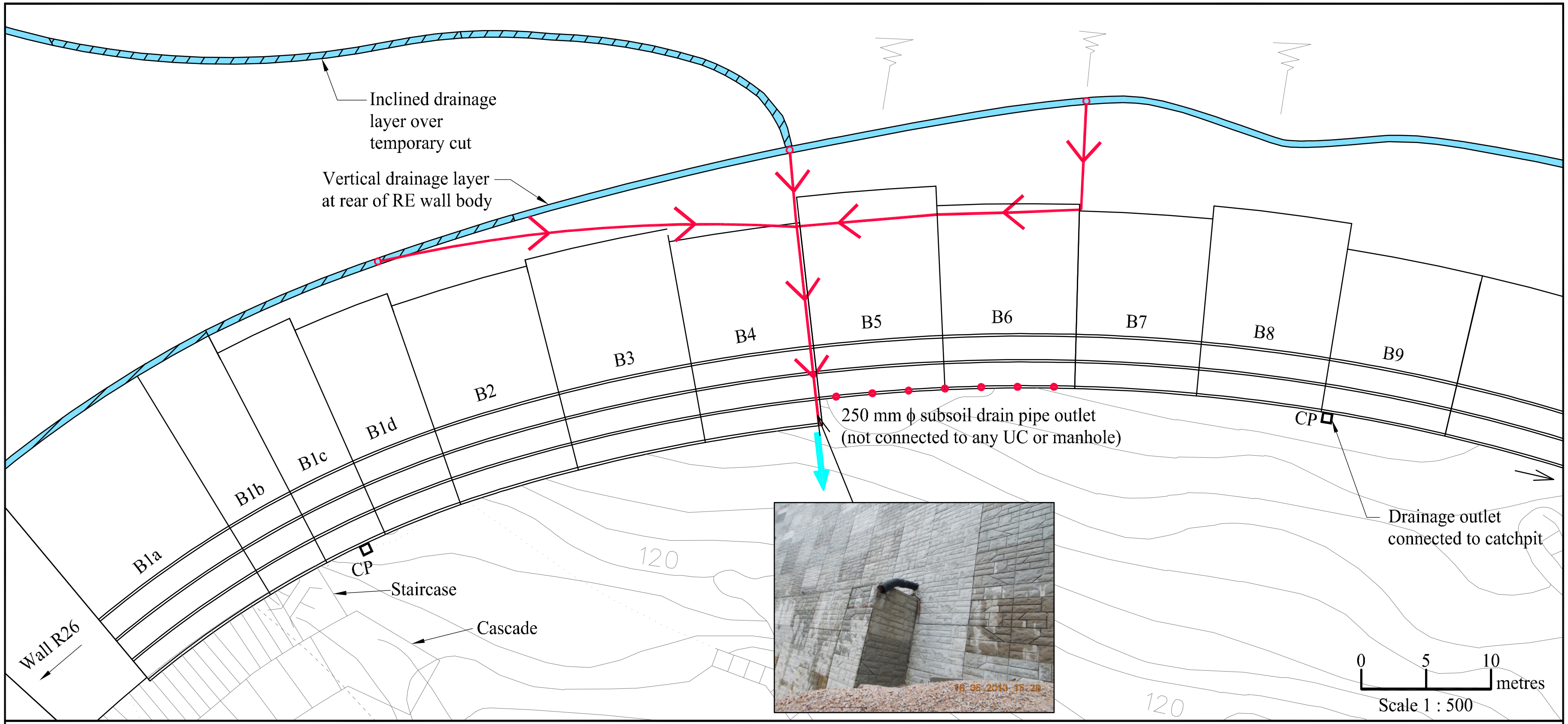
Legend :

▨	Mass concrete foundation	—	Top of tier	←	Design flow direction in drainage layer	○	Subsoil drain pipe outlet
▨	500 mm thick drainage layer	—	Extent of excavation and reconstruction	←	150 mm ϕ subsoil drain pipe (original design)	●	100 mm ϕ weepholes (original design)
▨	Grade III/IV or better rock	- - - -	Base level of peg footing resting on compacted fill	←	250 mm ϕ subsoil drain pipe (July 2012 remedial works)	●	100 mm ϕ weepholes (July 2012 remedial works)

Notes :

(1) Elevation is based on the merging of Drawing Nos. 2RE08054/CD/RE/R22/4001, 4003 to 4020 (Appendix A).
(2) All levels in mPD.
(3) Peg footings in Bay 7 and Bay 8 resting on mass concrete foundation not shown.
(4) 250 mm ϕ buried toe drain in front of the wall not shown.
(5) Grade III/IV or better rock profile is extracted from Drawing No. J385/RE/R22/002 (Appendix A).
(6) Top tier under construction at the time of the 22 May 2013 incident.

Figure 8.5 Elevation of Remedial Works to Wall R22 after July 2012 Incident



Legend :

○	Subsoil drain pipe extends up to backfill level	B3	Bay 3 for Wall R22	🟦	500 mm thick drainage layer	←	250 mm ϕ subsoil drain pipe (July 2012 remedial works)
		CP ☐	Catchpit	▨	500 mm thick drainage layer (capped by soil backfill)	●	100 mm ϕ weepholes at 2.5m horizontal spacing (July 2012 remedial works)

Notes :

(1) Extent and capping of drainage layers based on as-built drainage filter records (CSCE, 2013) and photographs.
(2) Inclined and vertical drainage layers are combined (coincident) at lower portions of Bays 3 and 4 and over the full height of Bays 5 to 11.
(3) Subsoil drain pipes are wrapped in geotextile and laid within the drainage layers.
(4) 250 mm ϕ toe drain in front of the wall toe not shown.

Figure 8.6 Additional Drainage Provisions following the July 2012 Incident

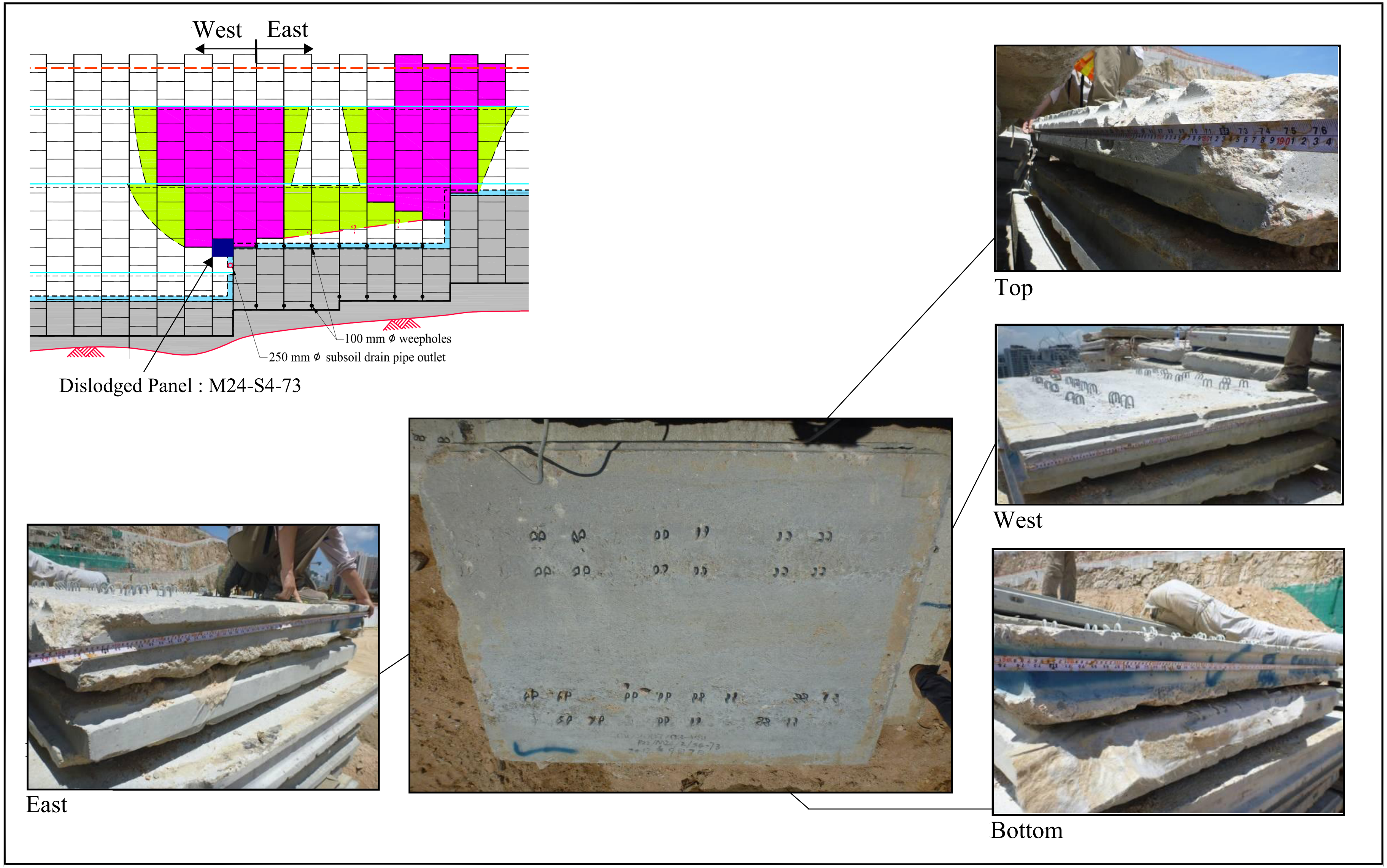


Figure 9.1 Condition of Key Dislodged Panel at Bays 4/5 of Wall R22

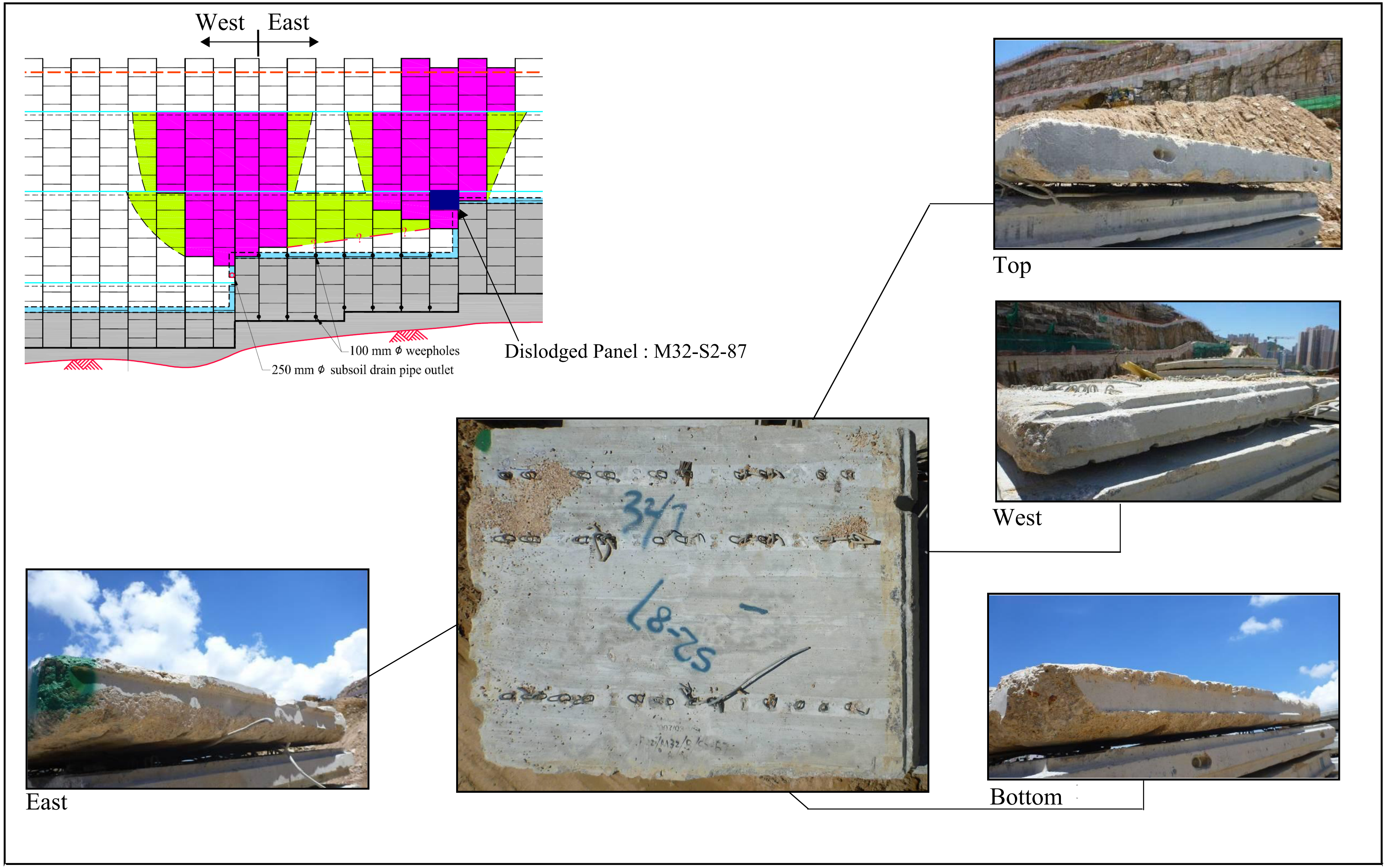
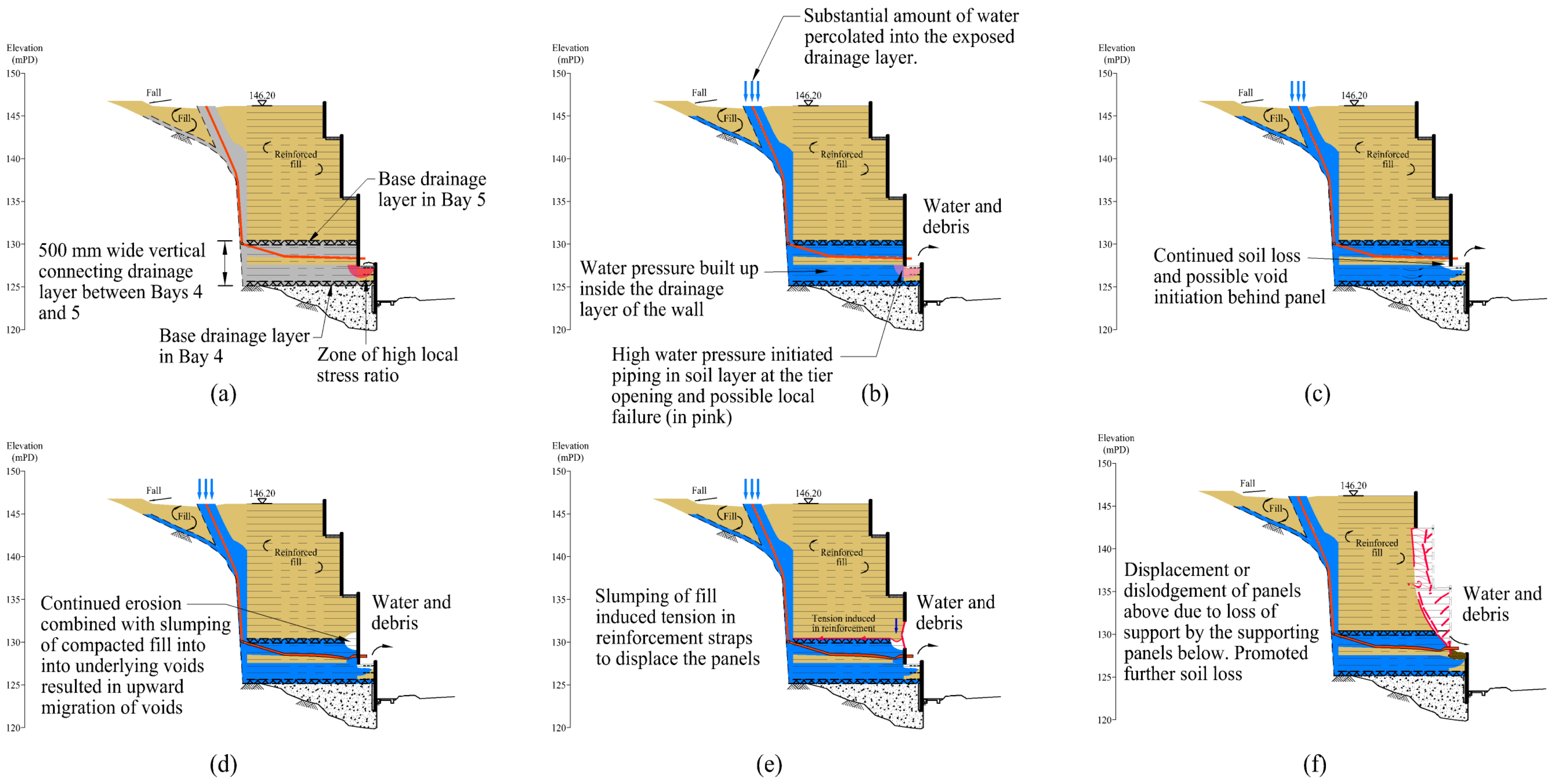


Figure 9.2 Condition of Key Dislodged Panel at Bays 6/7 of Wall R22



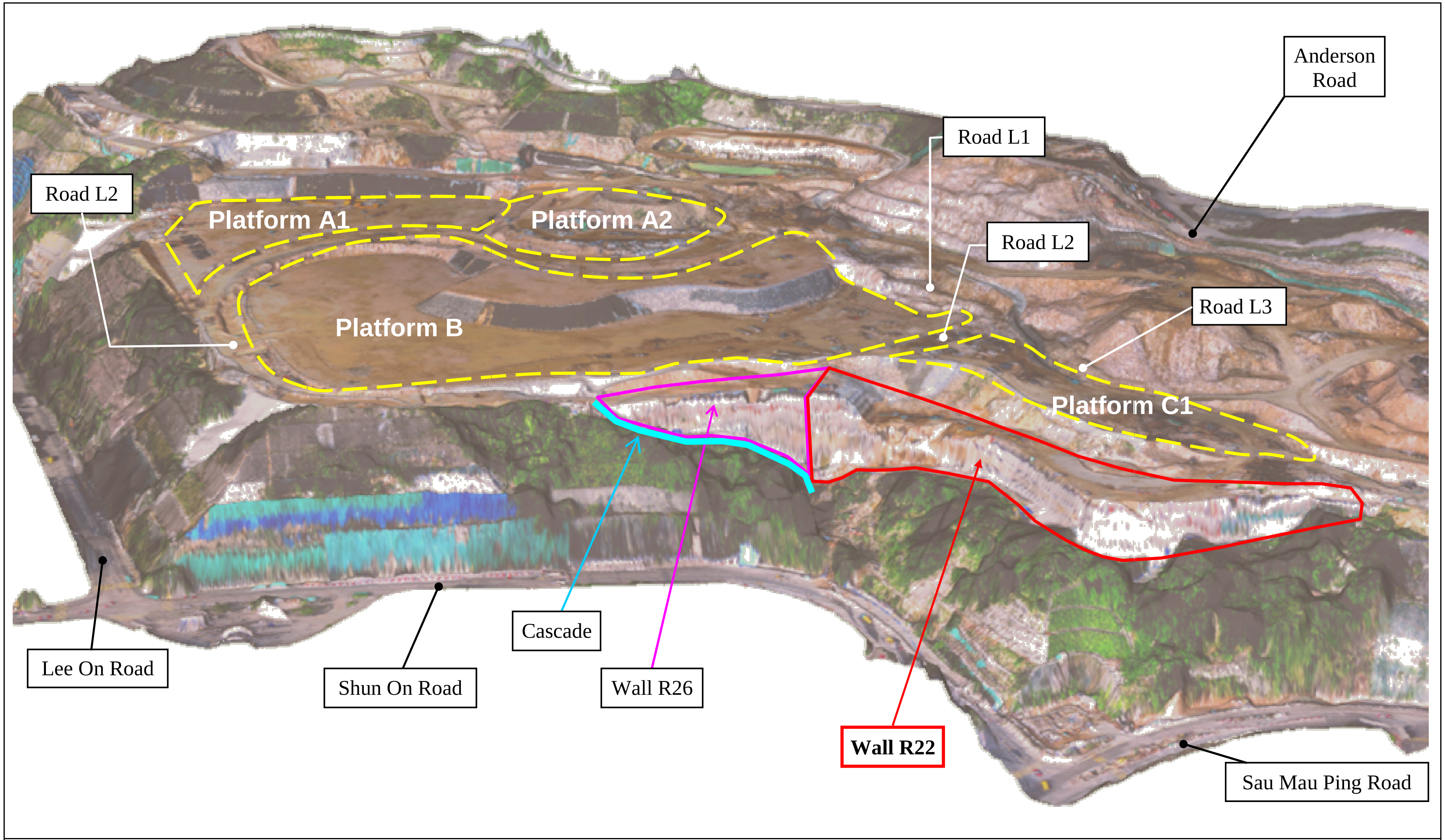
Legend :

▒	Drainage layer	🟨	Fill	- - - - - - - -	Geotextile	▦	500 mm thick base drainage layer (filled with water) over mass concrete foundations
🟦	Drainage layer filled with water	⛶	Mass concrete foundation	—— ? ——	Denotes uncertainly	▩	500 mm thick base drainage layer over mass concrete foundations

Notes : (1) All levels in mPD.
(2) For details of the Bay 4 soil loss profile, see Figure 3.3.

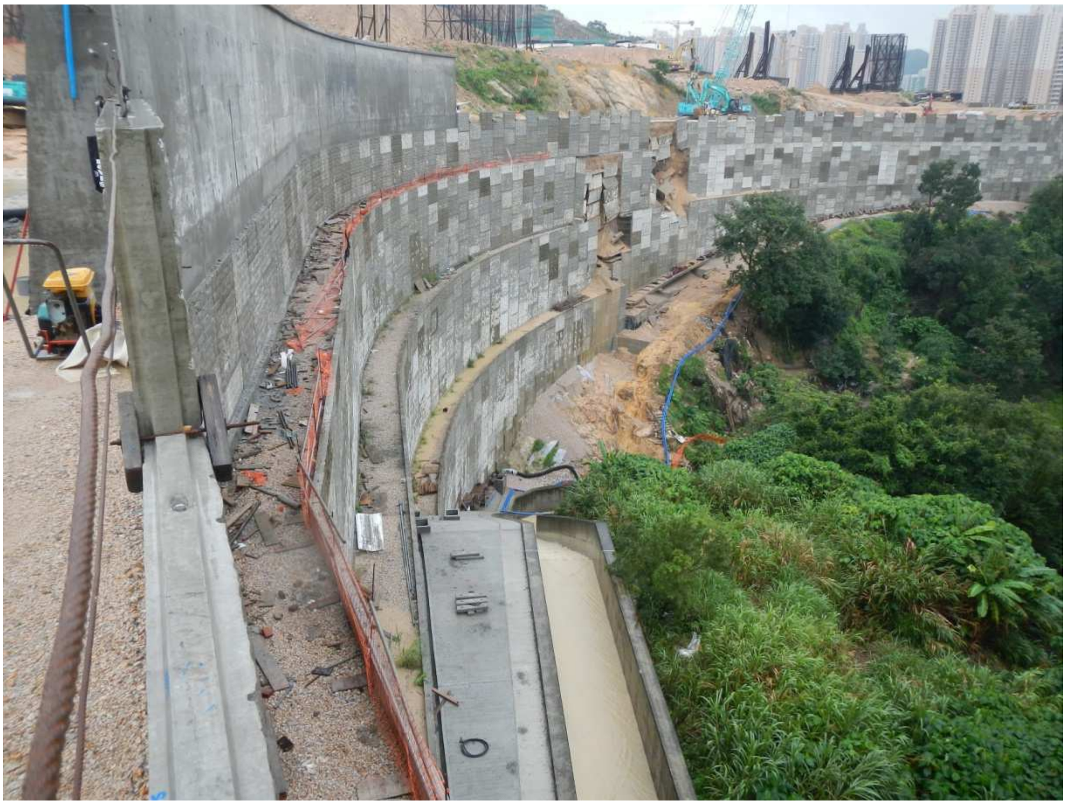
Figure 9.3 Sequence of Distress at Bays 4/5 of Wall R22

List of Plates



Note: The digital terrain model was prepared by Survey Division, CEDD using aerial photographs collected between 23 May 2013 and 29 May 2013.

Plate 1 Digital Terrain Model of the Northwestern Part of the DAR Site



(a) Frontal Elevation of Wall R22

(b) Backyard of Wall R22

Plate 2 Post-incident Conditions of Wall R22 (Photographs taken on 22 May 2013)

(a) Frontal Elevation of Wall R22

(b) Backyard of Wall R22

Plate 3 Pre-incident Conditions of Wall R22 (Photographs taken on 21 May 2013)

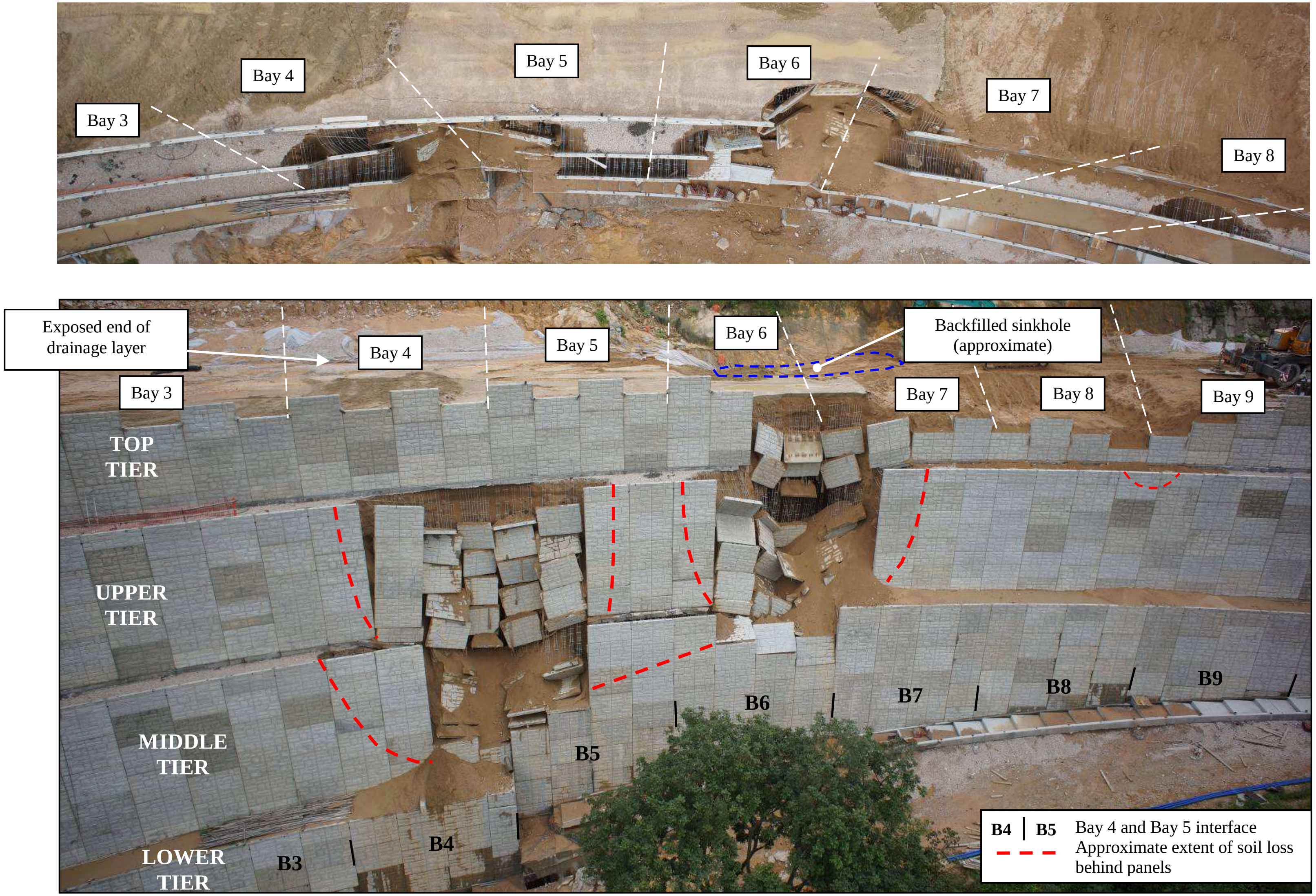


Plate 4 Aerial Views of the 22 May 2013 Incident at Wall R22 (Photographs taken on 23 May 2013)

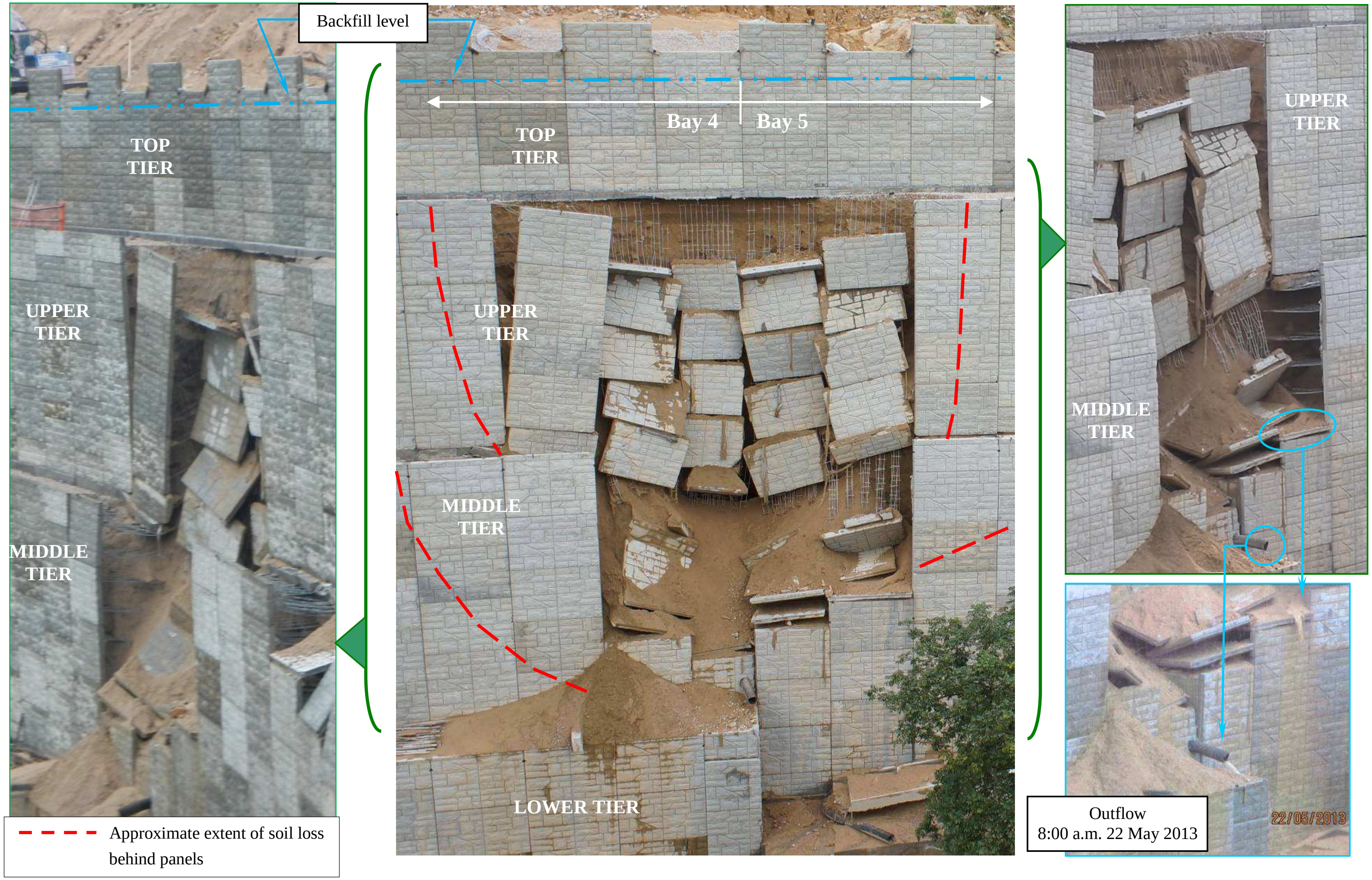
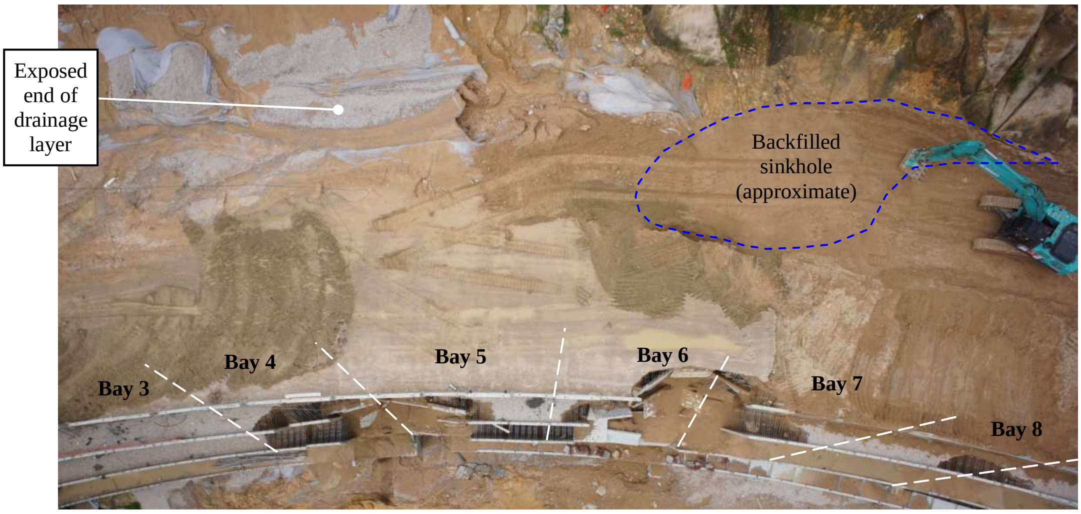


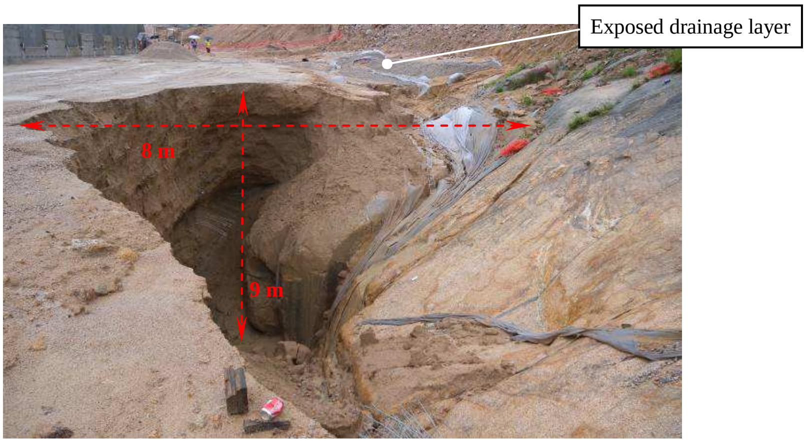
Plate 5 Distressed Zone at Bays 4/5 of Wall R22 (Photographs taken on 22 and 23 May 2013)

Deeper soil loss discernable along the mid-line of the collapse. Postulated point of connection to the erosion pipe observed in sinkhole.

Plate 6 Distressed Zone at Bays 6/7 of Wall R22 (Photographs taken on 22 and 23 May 2013)



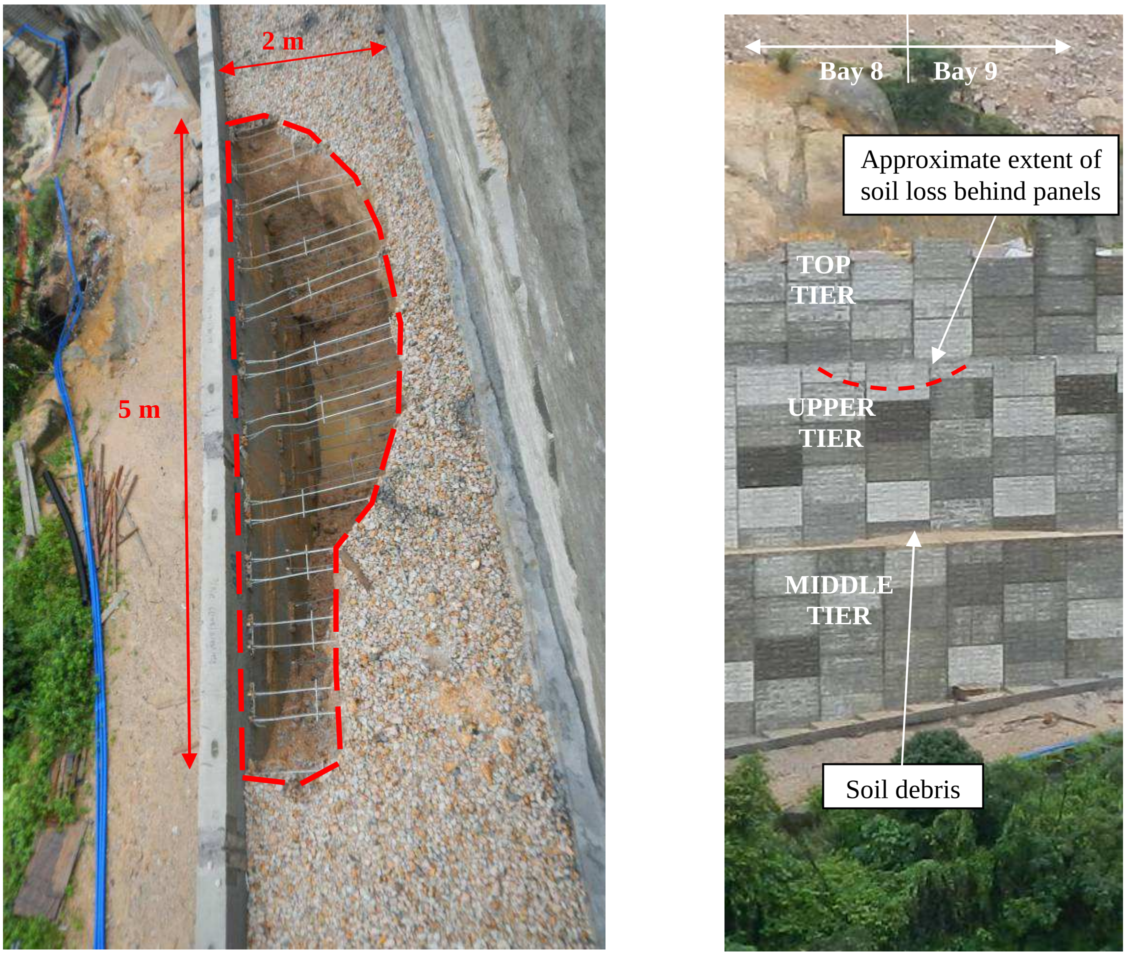
(a) Plan View of Sinkhole Position (Photograph taken on 23 May 2013)



(b) Formation of Sinkhole in Backyard of Bays 6/7 (Photograph taken on 22 May 2013)

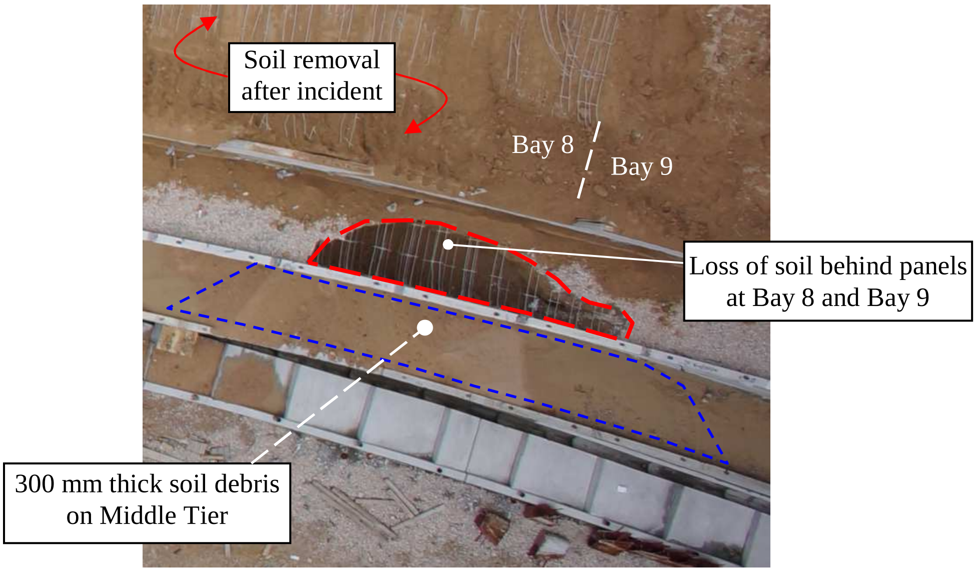
(c) Condition of Sinkhole (Photographs taken on 22 May 2013)

Plate 7 **Sinkhole Formation behind Wall R22 (Photographs taken on 22 and 23 May 2013)**



(a) Soil Loss at Bays 8/9 Upper Tier

(b) Elevation of Affected Bays



(c) Soil Debris on Bays 8/9 Middle Tier

Plate 8 Soil Loss behind the Upper Tier at Bays 8/9 (Photographs taken on 23 May 2013)

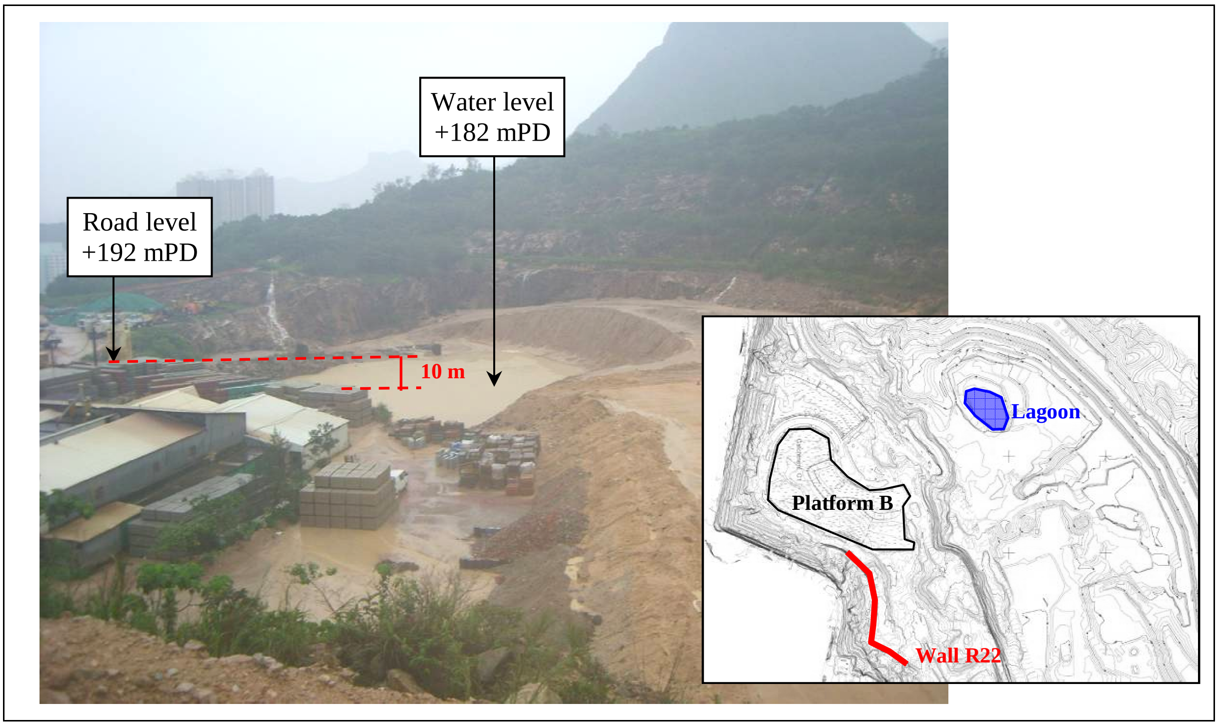


Plate 9 Condition of the Lagoon within the Anderson Road Quarry above the Northwestern Part of the DAR Site (Photograph taken in the morning of 22 May 2013)

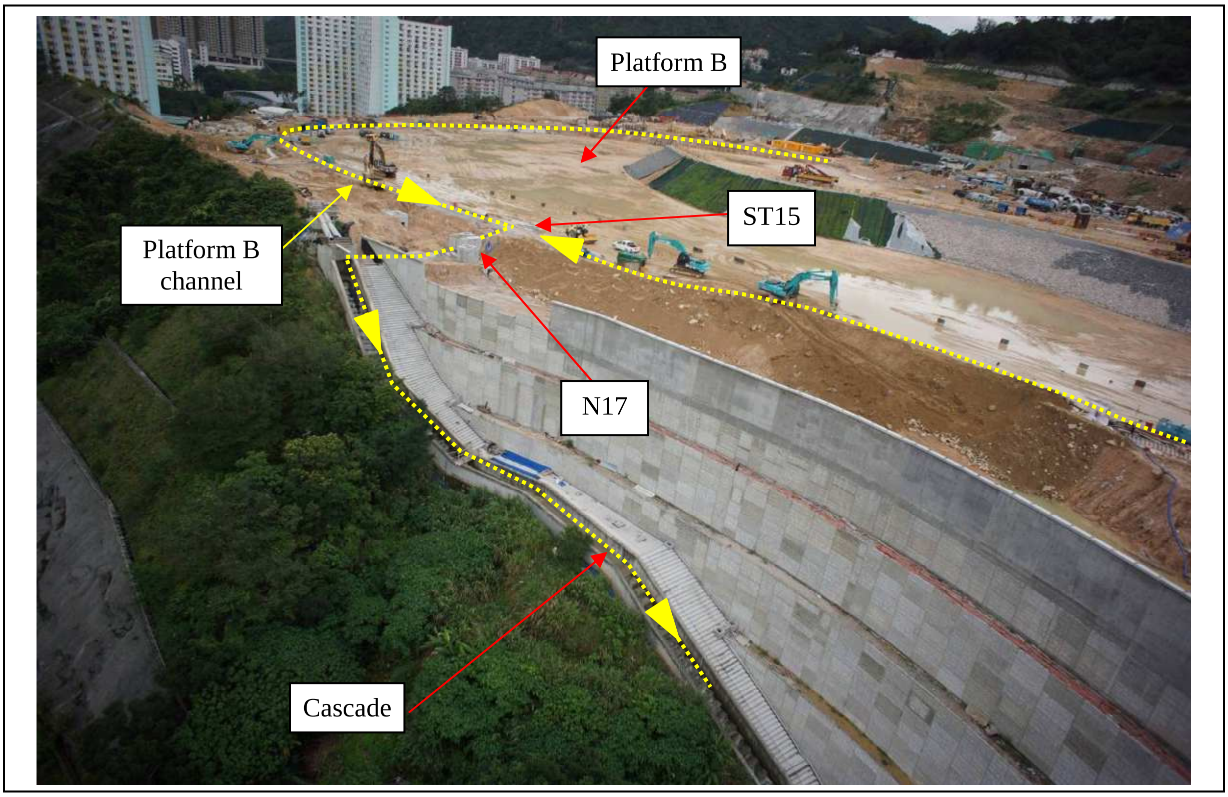


Plate 10 Drainage Outlet at Cascade in front of Wall R26 (Photograph taken on 23 May 2013)

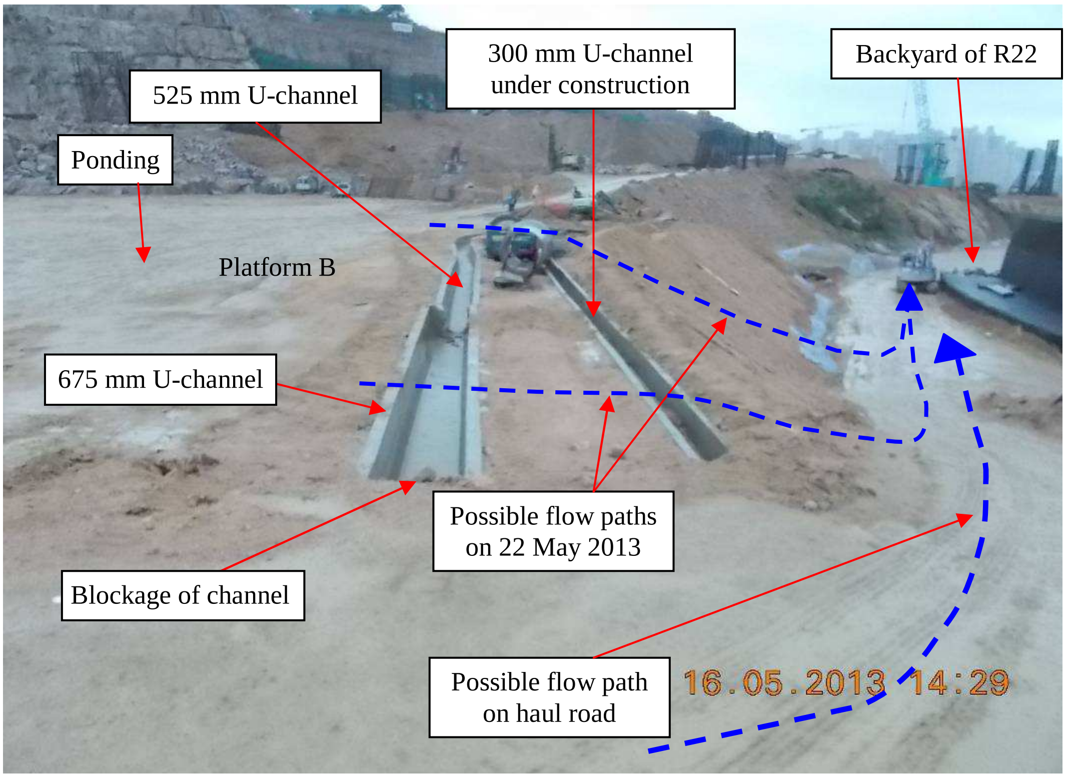
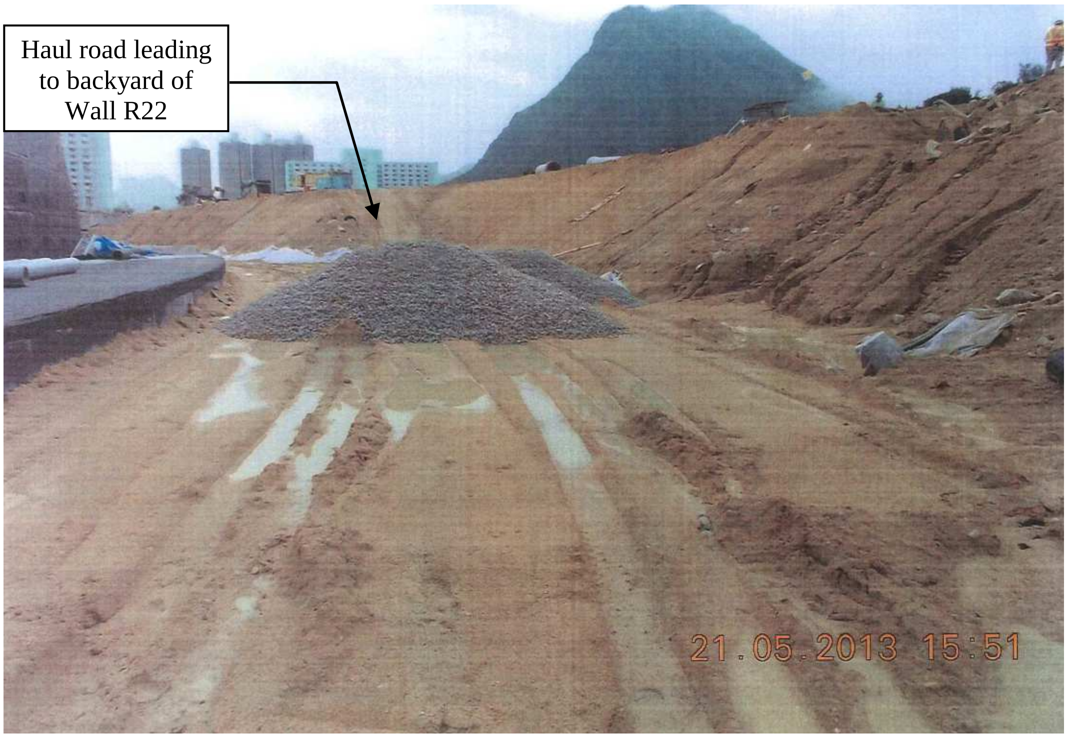
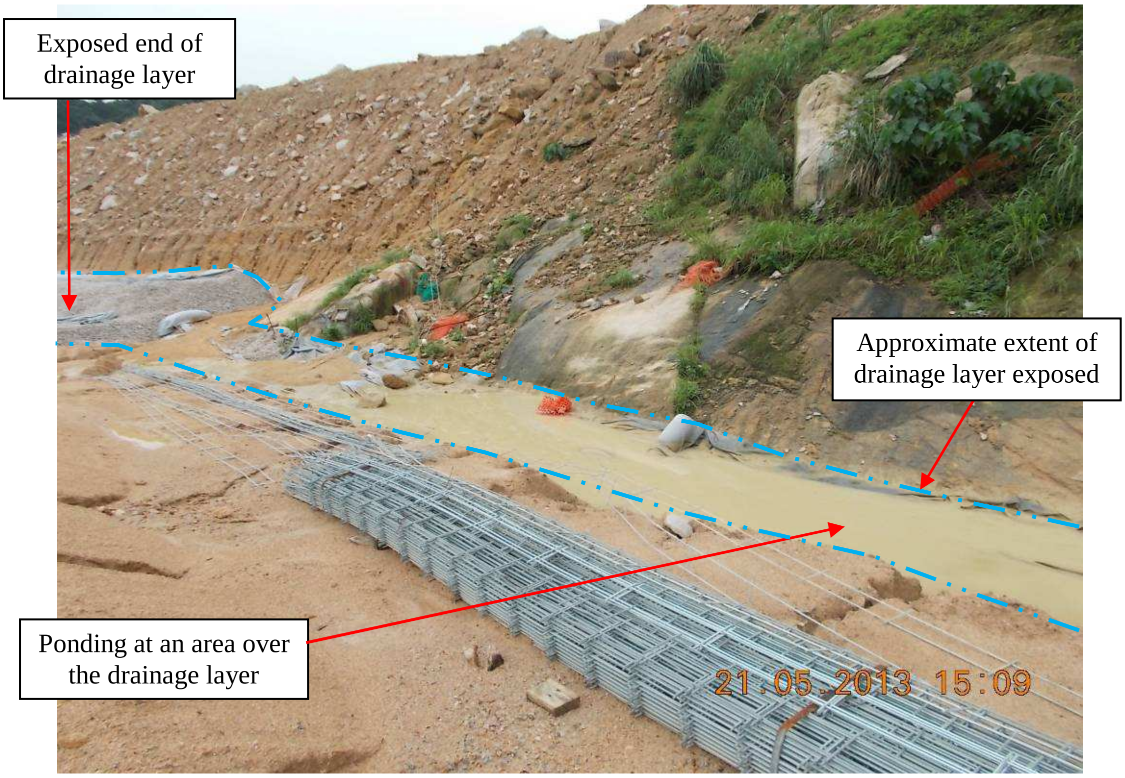


Plate 11 Temporary Haul Road over the 675 mm U-channel between Sand Traps ST15 and ST16 (Photograph taken on 16 May 2013)

Plate 12 Significant Overland Flow from Platform B between Sand Traps ST15 and ST16 towards the Back of Wall R22 (Photographs taken around 9:00 a.m. on 22 May 2013)



(a) Backyard Condition at Bay 2



(b) Backyard Condition at Bay 4 to Bay 7

Plate 13 **Backyard Conditions of Wall R22 Prior to the 22 May 2013 Incident (Photographs taken between 3:00 p.m. and 4:00 p.m. on 21 May 2013)**

(a) Seepage Flow Rate of 0.84 ℓ/s Recorded at Bay 1 in April 2010

(b) Seepage from Weak Seam at Temporary Cut at Bay 3 and Bay 4 (Photograph taken on 1 November 2011)

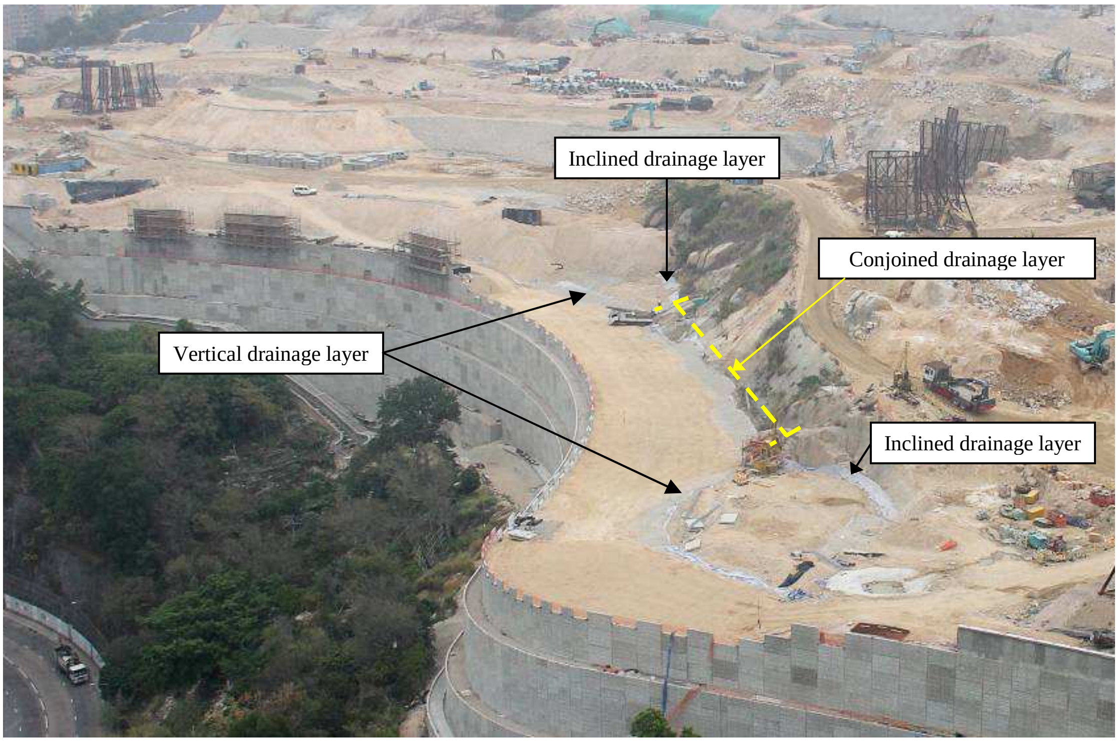
(c) Seepage from Weak Seam at Bay 7 (Photograph taken on 1 December 2011)

Plate 14 Seepage from Temporary Cuts during the Construction of Wall R22

(a) Installation of Subsoil Drain Pipe at Bay 4 (Photograph taken on 13 October 2012)

(b) Placement of Vertical Connecting Drainage Layer above Subsoil Drain Pipe (Photograph taken on 13 October 2012)

Plate 15 Placement of Additional Subsoil Drain Pipe at Bay 4 following the July 2012 Incident



(a) View of Wall R22 in February 2013 (Photograph taken on 25 February 2013)

(b) View of Wall R22 in April 2013 (Photograph taken on 30 April 2013)

Plate 16 Layout of Drainage Layers in Wall R22

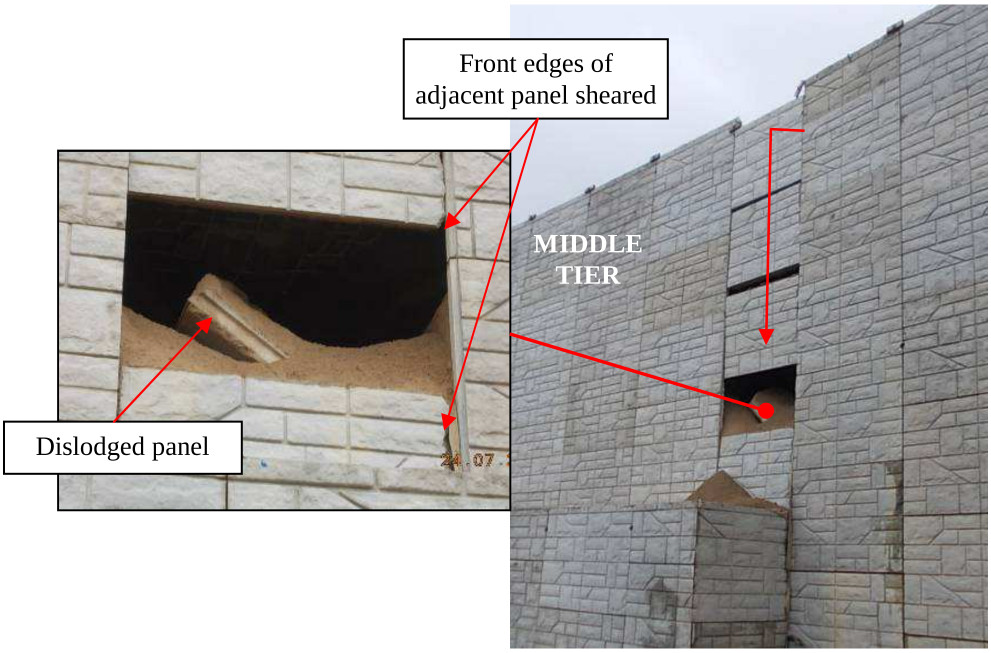
(a) Muddy Seepage at Bottom of Dummy Panels at Bay 3 (Photograph taken on 18 May 2012)

(b) Seepage at Bottom of Dummy Panels at Bay 3 (Photograph taken on 6 May 2013)

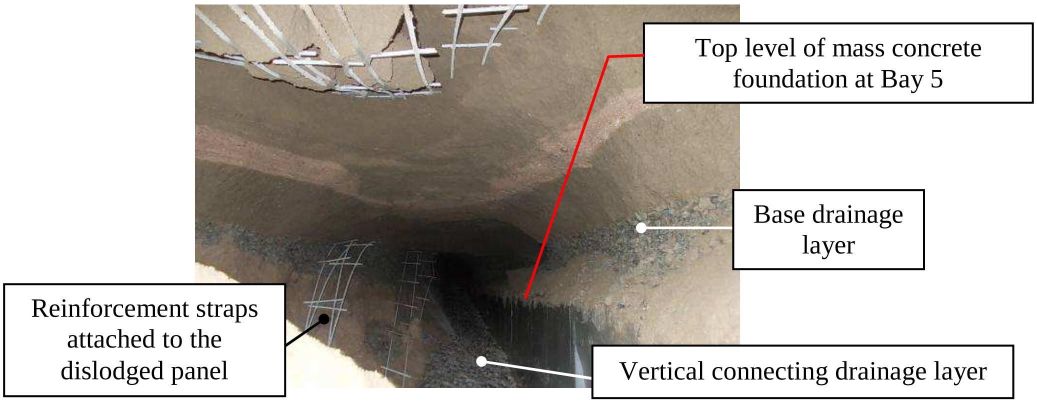
(c) Seepage at Bay 4 prior to July 2012 Incident (Photograph taken on 23 July 2012)

(d) Muddy Outflow from Subsoil Drain Pipe at Bay 9 (Photograph taken on 25 July 2012)

Plate 17 Examples of Observations of Seepage from the Face of Wall R22



(a) Elevation View of July 2012 Incident at Bays 4/5

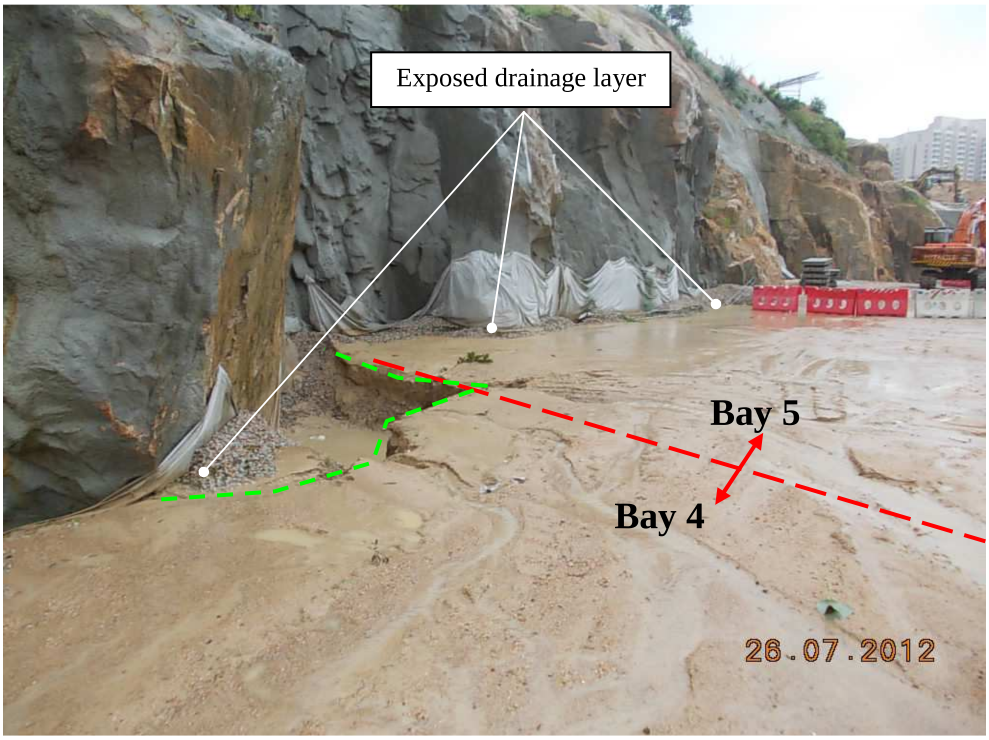


(b) Erosion alongside the Step in Mass Concrete Foundation at Bays 4/5

(c) Soil Loss behind Panels

Plate 18 July 2012 Incident at Bays 4/5 of Wall R22 (Photographs taken on 24 July 2012)

(a) Ponding at Bays 4/5 (Photograph taken on 24 July 2012)



(b) Soil Loss at Backyard of Bays 4/5 (Photograph taken on 26 July 2012)

Plate 19 Backyard of Bays 4/5 after the July 2012 Incident

Appendix A

List of Drawings Referenced

Contents

List of Tables

Table A1   List of Drawings Referenced (Sheet 1 of 3)

Drawing No.	Revision	Date	Title	By (see Note)
J385/RE/GA/R22/001	C	Mar-11	Reinforced Fill Retaining Wall - General Notes for Retaining Wall No. 22	GCG
J385/RE/R22/001	M	May-13	Retaining Wall No. 22 - Site Formation Plan	GAL
J385/RE/R22/002	Q	May-13	Retaining Wall No. 22 - Elevation	GAL
J385/RE/R22/003	H	May-13	Retaining Wall No. 22 - Sections (Sheet 1 of 4)	GAL
J385/RE/R22/004	L	May-13	Retaining Wall No. 22 - Sections (Sheet 2 of 4)	GAL
J385/RE/R22/005	K	Aug-11	Retaining Wall No. 22 - Sections (Sheet 3 of 4)	GAL
J385/RE/R22/006	D	May-13	Retaining Wall No. 22 - Sections (Sheet 4 of 4)	GAL
2RE08054/CD/RE/G/1001	H	19-Jul-11	VSL Retained Earth Wall - Site Formation General Notes (Sheet 1)	VSL
2RE08054/CD/RE/D/S001	D	19-Jul-11	VSL Retained Earth Wall - Preliminary Details (Sheet 1)	VSL
2RE08054/CD/RE/D/S002	F	19-Jul-11	VSL Retained Earth Wall - Preliminary Details (Sheet 2)	VSL
2RE08054/CD/RE/D/S003	D	19-Jul-11	VSL Retained Earth Wall - Preliminary Details (Sheet 3)	VSL
2RE08054/CD/RE/R22/4001	F	26-Jul-11	VSL Retained Earth Wall No. 22 - Elevations (Lower Part) (Sheet 1)	VSL
2RE08054/CD/RE/R22/4003	F	26-Jul-11	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) (Sheet 1)	VSL
2RE08054/CD/RE/R22/4004	E	03-Jul-12	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) (Sheet 2)	VSL
2RE08054/CD/RE/R22/4005	E	04-Jul-12	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) (Sheet 3)	VSL
2RE08054/CD/RE/R22/4006	G	05-Aug-11	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) (Sheet 4)	VSL
2RE08054/CD/RE/R22/4007	E	14-Apr-11	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) (Sheet 5)	VSL

Table A1 List of Drawings Referenced (Sheet 2 of 3)

Drawing No.	Revision	Date	Title	By (see Note)
2RE08054/CD/RE/R22/4008	F	16-May-12	VSL Retained Earth Wall No. 22 - Elevations (Upper Part) (Sheet 1)	VSL
2RE08054/CD/RE/R22/4009	C	05-Aug-11	VSL Retained Earth Wall No. 22 - Elevations (Upper Part) (Sheet 2)	VSL
2RE08054/CD/RE/R22/4010	J	09-Feb-11	VSL Retained Earth Wall No. 22 - Elevations (Upper Part) (Sheet 3)	VSL
2RE08054/CD/RE/R22/4011	F	26-Nov-12	VSL Retained Earth Wall No. 22 - Elevations (Top Part) (Sheet 1)	VSL
2RE08054/CD/RE/R22/4012	C	05-Aug-11	VSL Retained Earth Wall No. 22 - Elevations (Top Part) (Sheet 2)	VSL
2RE08054/CD/RE/R22/4013	F	20-Dec-10	VSL Retained Earth Wall No. 22 - Elevations (Top Part) (Sheet 3)	VSL
2RE08054/CD/RE/R22/4014	H	04-Dec-12	VSL Retained Earth Wall No. 22 - Plan View (Sheet 1)	VSL
2RE08054/CD/RE/R22/4015	N	04-Dec-12	VSL Retained Earth Wall No. 22 - Plan View (Sheet 2)	VSL
2RE08054/CD/RE/R22/4016	K	16-May-12	VSL Retained Earth Wall No. 22 - Typical Mesh Type Table (Sheet 1)	VSL
2RE08054/CD/RE/R22/4017	C	22-Aug-11	VSL Retained Earth Wall No. 22 - Section (Sheet 1)	VSL
2RE08054/CD/RE/R22/4018	E	04-Dec-12	VSL Retained Earth Wall No. 22 - Section (Sheet 2)	VSL
2RE08054/CD/RE/R22/4019	A	05-Aug-11	VSL Retained Earth Wall No. 22 - Typical Mesh Type Table (Sheet 2)	VSL
2RE08054/CD/RE/R22/4020	B	22-Aug-11	VSL Retained Earth Wall No. 22 - Section (Sheet 3)	VSL
2RE08054/CD/RE/R22/4021	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Lower Part) Drainage Layout (Sheet 1)	VSL
2RE08054/CD/RE/R22/4022	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Lower & Middle Part) Drainage Layout (Sheet 2)	VSL

Table A1 List of Drawings Referenced (Sheet 3 of 3)

Drawing No.	Revision	Date	Title	By (see Note)
2RE08054/CD/RE/R22/4023	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Upper & Middle Part) Drainage Layout (Sheet 3)	VSL
2RE08054/CD/RE/R22/4024	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) Drainage Layout (Sheet 4)	VSL
2RE08054/CD/RE/R22/4025	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Middle Part) Drainage Layout (Sheet 5)	VSL
2RE08054/CD/RE/R22/4026	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Elevations (Upper Part) Drainage Layout (Sheet 6)	VSL
2RE08054/CD/RE/R22/4027	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Plan View (Drainage Layout) (Sheet 1)	VSL
2RE08054/CD/RE/R22/4028	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Plan View (Drainage Layout) (Sheet 2)	VSL
2RE08054/CD/RE/R22/4029	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Plan View (Drainage Layout) (Sheet 3)	VSL
2RE08054/CD/RE/R22/4030	-	25-Sep-12	VSL Retained Earth Wall No. 22 - Plan View (Drainage Layout) (Sheet 4)	VSL
CV/2007/03/SK/1224	H	02-May-13	Drainage Layout Plans (Sheet 4 of 13)	OAP
CV/2007/03/SK/1225	H	06-May-13	Drainage Layout Plans (Sheet 5 of 13)	OAP
CV/2007/03/SK/1226	I	20-Feb-13	Drainage Layout Plans (Sheet 6 of 13)	OAP

Notes:
GAL – Golder Associates Limited
GCG – Geotechnical Consulting Group
OAP – Ove Arup & Partners Limited
VSL – VSL Hong Kong Limited

Appendix B

Drainage Assessment

Contents

B.1 Catchment Characteristics

The catchment that could contribute surface runoff to the backyard of Wall R22 is shown in Figure B1. Runoff in Catchment 1 was intended to be discharged at the cascade via a system of U-channels around the western and southern periphery of Platform B. Runoff in Catchment 2 directly flowed towards and accumulated at the low-point at the backyard of Bays 4 to 7 of Wall R22. However, any overflow from the U-channels of Catchment 1 would flow towards two low points: one at the crest of a fill slope on the western end of Platform B and the other at the backyard of Bays 4 to 7 of Wall R22.

The majority of the ground surface in Catchments 1 and 2 was bare soil (either compacted soil fill or saprolite). The runoff coefficient of the catchment is dependent on the permeability, gradient and retention capability characteristics of the ground surface (DSD, 2013), rainfall intensity and the antecedent rainfall. Given the high intensity of the rainfall in the early morning of 22 May 2013 (see Section 4 of the main text) and the shallow bedrock in the area, the runoff coefficient could be relatively high. Runoff coefficients ranging from 0.4 to 0.9 have been adopted in the assessment of surface runoff.

B.2 Assessment of Surface Runoff and Flow Capacity of Drains

The surface runoff of the catchment has been calculated as follows:

$$Q = \frac{K\,i\,A}{3600}$$

where Q = surface runoff (ℓ /s),
i = actual rainfall intensity (mm/hr),
A = area of catchment (m^2), and
K = runoff coefficient.

The actual rainfall intensity given has been determined from the 5-minute rainfall data collected from GEO raingauge no. K04 located approximately 0.93 km from the distressed portion of Wall R22. The surface runoff has been calculated with various runoff coefficients as summarized in Table B1.

Surface runoff from Catchment 1 was discharged offsite via the U-channels on Platform B and the cascade in front of Walls R22 and R26. The flow capacity of the U-channels has been determined in accordance with the Geotechnical Manual for Slopes (GEO, 1984) and is summarized in Table B2.

The actual flow in the 750 mm U-channel and 675 mm U-channel is likely to be less than that given in Table B2 because the adjoining U-channels that discharge into these two channels are smaller in size and the invert gradient of some of them dipped away from these two channels.

Comparing the surface runoff in Table B1 and the flow capacity of the surface drainage measures in Table B2, it can be seen that the total flow capacity (1.034 m^3/s) is below the surface runoff generated from Catchment 1 (1.40 to 3.14 m^3/s) for the range of runoff coefficients considered.

It indicates that the drainage provisions on the northwestern portion of the DAR site were inadequate to cope with the surface runoff arising from the intense rainfall in the early morning of 22 May 2013.

The flow capacity of the subsoil drain pipes at Bays 4 and 9 of Wall R22 has been determined from design curves for corrugated polythene pipes given in Figure B2 (CPPA, 2000) and is summarized in Table B3. The flow capacities are estimated assuming that the geotextile and perforations in the subsoil drain pipes permit full flow capacity of the pipe to be attained.

Comparing the surface runoff in Catchment 2 in Table B1 and the flow capacity of the subsoil drain pipes in Bays 4 and 9 in Table B3, it can be seen that the total flow capacity (0.168 m^3/s) is below the surface runoff (0.19 to 0.43 m^3/s) for the range of runoff coefficients considered. It indicates that water pressures would then develop in the drainage layers of Wall R22. As shown above, the site drainage provisions in Platform B could not cope with the runoff arising from the intense rainfall on 22 May 2013 and overflowing of surface water from Platform B onto the backyard of Wall R22 would further increase the surface runoff in Catchment 2.

B.3 References

Corrugated Polyethylene Pipe Association (2000). *Hydraulic Considerations for Corrugated Polyethylene Pipe*. Corrugated Polyethylene Pipe Association.

Drainage Services Department (2013). *Stormwater Drainage Manual (with Eurocodes incorporated) – Planning, Design and Management (Fourth Edition).* Drainage Services Department, Hong Kong, 172 p.

Geotechnical Engineering Office (1984). *Geotechnical Manual for Slopes (Second Edition).* Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong, 302 p.

List of Tables

Table B1 Surface Runoff for Selected Runoff Coefficients

Runoff Coefficient	Catchment 1 Surface Runoff (m^3/s)	Catchment 2 Surface Runoff (m^3/s)	Total Surface Runoff (m^3/s)
0.9	3.14	0.43	3.57
0.4	1.40	0.19	1.59

Note: Surface runoff has been calculated using a rainfall intensity of 135 mm/hr (3:30 a.m. to 4:30 a.m.) recorded at GEO raingauge no. K04.

Table B2 Flow Capacity of Surface Drains in the Northwestern Portion of the DAR Site

Surface Drainage Measure	Flow Capacity (m^3/s)	Assumptions
750 mm U-channel to ST15	0.467	invert gradient 1 in 850
675 mm U-channel to ST15	0.567	invert gradient 1 in 380
(Total)	1.034	-

Note: Refer to Figure 5.4 of the main text for location of discharge points

Table B3 Flow Capacity of Drainage Outlets at Bay 4 and Bay 9 of Wall R22

Surface Drainage Measure	Flow Capacity (m^3/s)	Assumptions
250 mm dia. subsoil drain outlet	0.155	invert gradient 1 in 10
150 mm dia. subsoil drain outlet	0.013	invert gradient 1 in 100
(Total)	0.168	-

Note: Refer to Figure 2.2 of the main text for location of subsoil drain pipe outlets in Wall R22.

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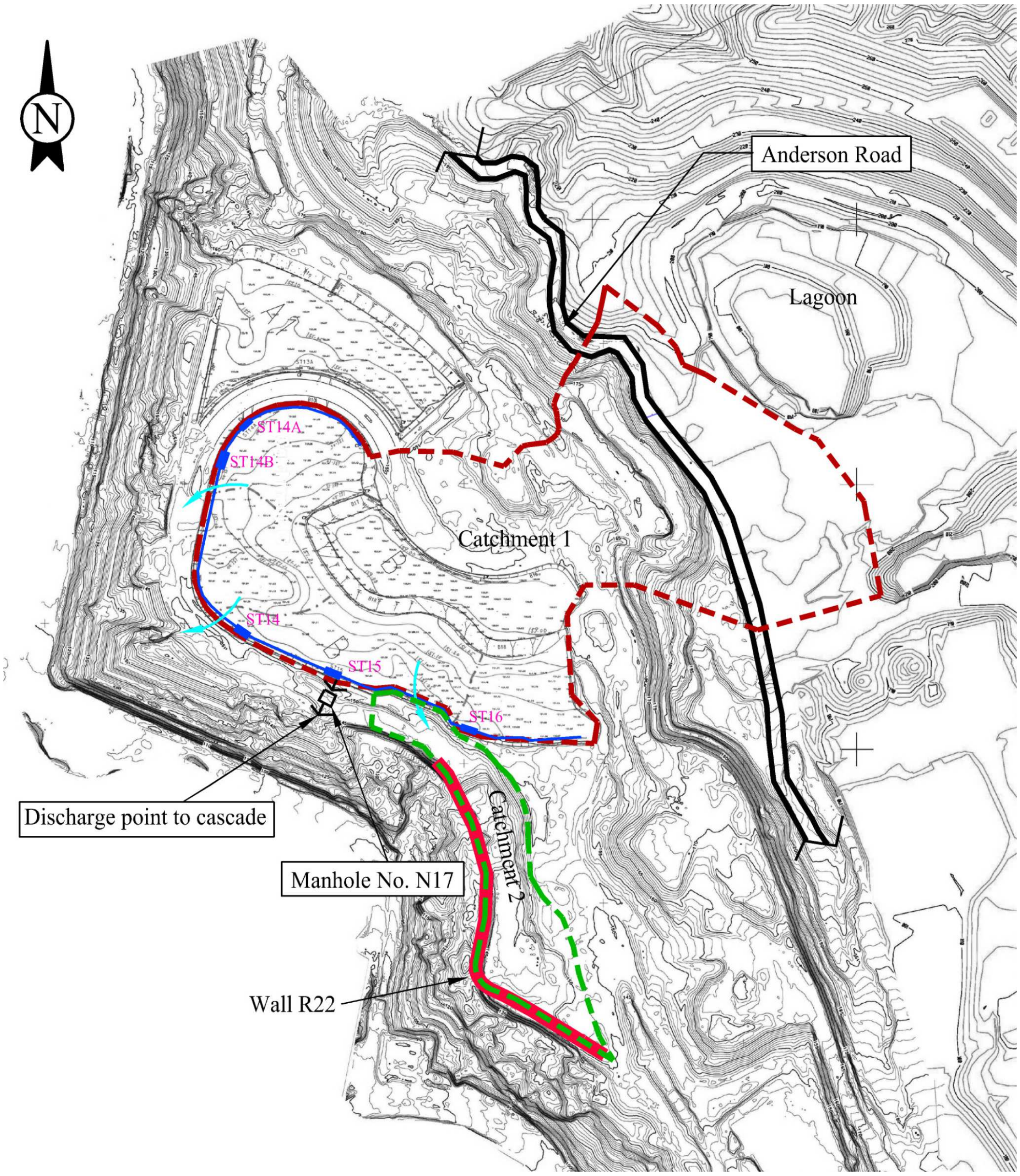

Legend:

🟥	Catchment1 (Area = 93,100 m^2)	—	Platform channels
🟩	Catchment 2 (Area = 12,800 m^2)	ST14 ▬	Sand trap ST14
		⤻	Possible overflow

Note: Topographic base plan is compiled from Drawing No. UA130022-SK03 prepared by the Survey Division of CEDD in May 2013, Drawing No. KWP/MS195/01 prepared by the Contractor of the Anderson Road Quarry in April 2013 and topographic surveys by OAP on Platform A1 and Platform B on 16 May 2013.

Figure B1 Catchment Characteristics

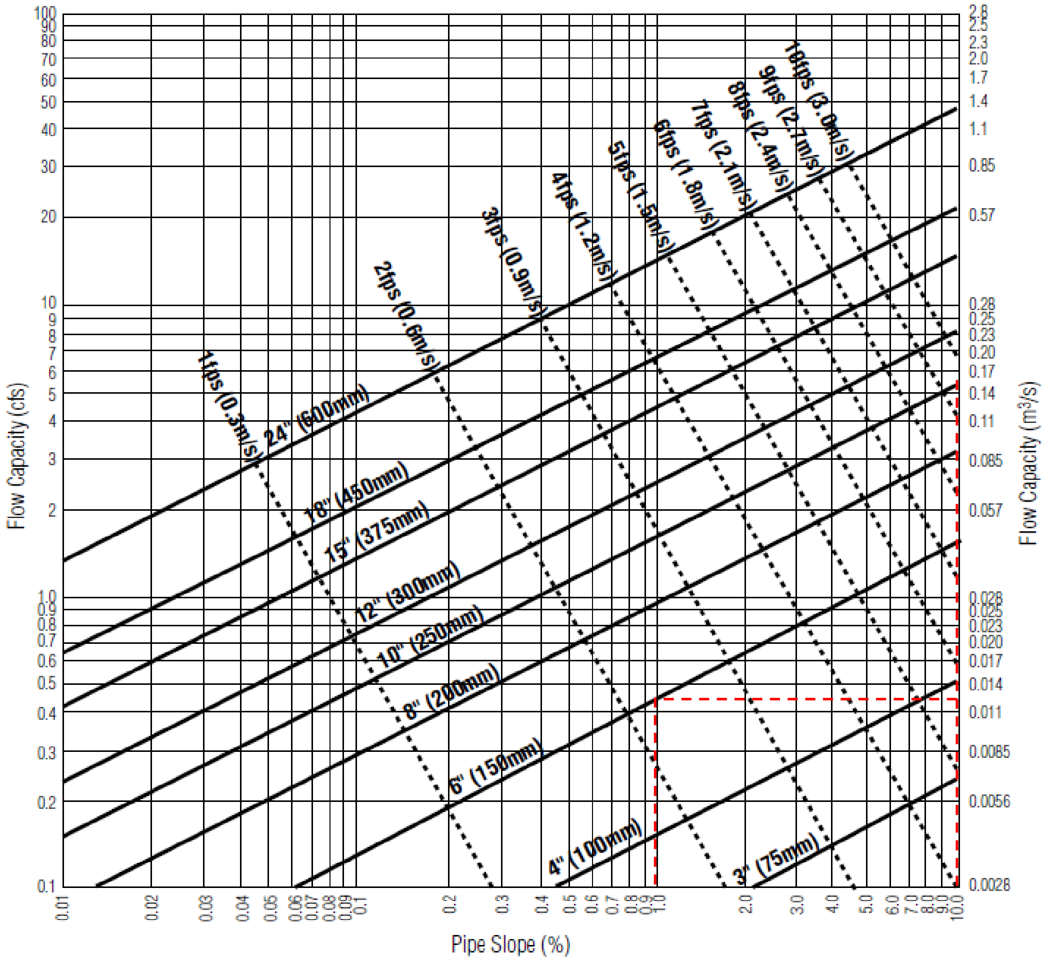

Figure B2 Flow Capacities for Corrugated Polythene Pipes with Corrugated Interior (CPPA, 2000)