

Case Study of Real-time Monitoring of Groundwater Levels and Rainfall Data for a Hillside Terrain Site Formation Works for Public Housing at Pok Fu Lam in Southern District, Hong Kong in Year 2023

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ABSTRACT

A record-breaking extreme rainfall event happened in early September 2023 raised the public concern on the design safety of infrastructural works and geotechnical works to withstand the inclement weather. Real-time monitoring has become an effective tool nowadays to provide accurate and comprehensive information to record both the rainfall data and groundwater level for design review for civil engineering projects. This paper is to picturize the impact of extreme rainfall event on the groundwater table by case study on a hillside site formation project at Pok Fu Lam in Year 2023 via observations from the real-time rolling rainfall depth together with groundwater level. The groundwater levels have risen 3m to 18m from their long-term average level during the extreme rainfall event which the groundwater level rose with unprecedented magnitude especially for those located near existing natural drainage line identified from the aerial photo interpretation study. Superposition effect is also observed from two successive extreme rainfall events in September and October. Recommendations are then suggested to respond to the findings observed from the real-time monitoring information.

1 INTRODUCTION

1.1 Background

In recent decades, global warming turns the weather of the subtropical zone, like Hong Kong, becoming more familiar to the tropical weather than before. Although the code of practices for drainage design recently updated the rainfall increase to 16.0% due to climate change for design life reached the end of 21st Century, the extreme weather becomes more frequent and keeps breaking the extreme weather record which threatens the factor of safety for the infrastructure design. This case study provides valuable insights into geotechnical engineering for site formation works especially for the case with existing nature drainage lines. The analysis of real-time monitoring data offers a comprehensive understanding of the groundwater behavior and its relationship with rainfall events.

2 RAINFALL ANALYSIS

2.1 Rainfall in Hong Kong

Generalized extreme value (GEV) distribution is commonly adopted to estimate magnitude of rainfall extreme events for design purposes which is well defined in Stormwater Drainage Manual which adopted the hourly rainfall data was recorded at Hong Kong Observatory (HKO) headquarter since 1884. It is revealed that the extrapolation of design rainfall intensity for very long return periods, says 200 years, would be based on limited amount of historical data which are clustered at the side with shorter return periods. As such, the uncertainty at high levels would increase drastically (Tang et al. 2011). The tendency of extreme rainfall events continues to increase, as reflected in the HKO data shown in Figure 1. To address this concern, the Drainage Services Department (DSD) Stormwater Drainage Manual (SDM) 2018, with Corrigendum No.



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1/2022 & 1/2024, and the Geotechnical Engineering Office (GEO) technical guidance note TGN-30 (issue no. 3) recommend increasing the mean rainfall intensity given by the IDF curves by 16.0% and 28.1% to incorporate the climate change effects projected up to the end of the 21st century. Overall, the predicted mean rainfall intensity by storm constants by TGN-30 (issue no. 3) is about 1.19 to 1.96 times higher than the one predicted by DSD SDM (Corr. 1/2024) with climate change effect projected up to the end of the 21st century for Intensity-Duration-Frequency (IDF) relationship curves of HKO headquarters, with time of concentration ranged from 1 to 240 minutes and return period from 2 years to 1000 years.

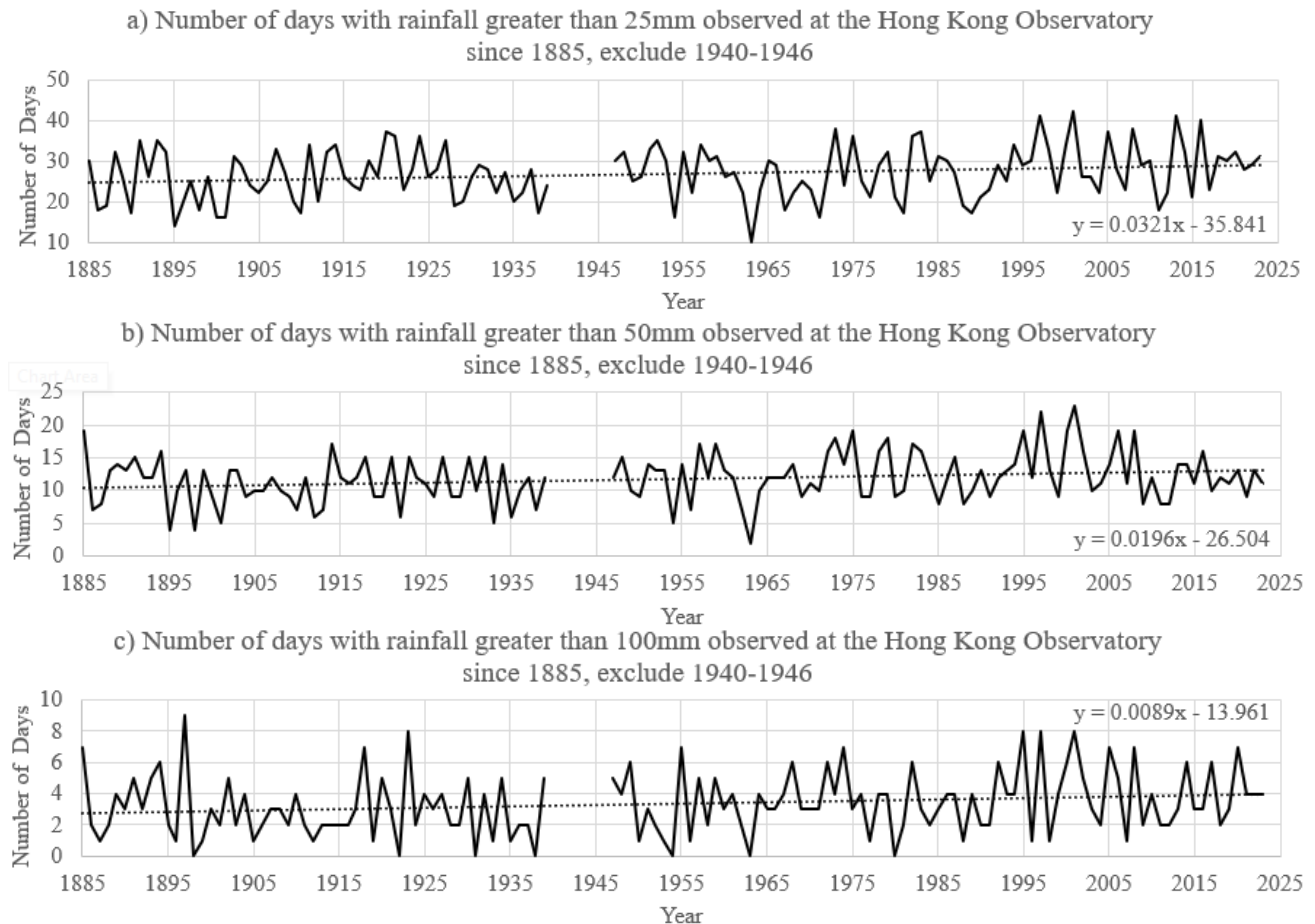


Figure 1: Number of Days with rainfall greater than (a)25mm, (b)50mm and (c)100mm observed at HKO since 1885, exclude 1940-1946 (HKO, 2024)

2.2 Summary of Rainfall in 2023

The year 2023 was identified as the warmest year on record, with an established El Niño event that persisted throughout the year. The annual total rainfall in Hong Kong reached 2774.5mm, representing a 14% increase compared to the 1991-2020 normal of 2431.2mm. There are 47 rainstorm warning signals, consisting of 37 amber, 8 red and 2 black, recorded in 2023. Notably, the rainfall concentrated in wet season in 2023, i.e. 1st April to 31st October, which contributed the annual rainfall depth from 95.4% (Yuen Long) to 98.1% (Islands District) for all districts in Hong Kong such that the discussion of dry season in 2023 would be neglected in following study.

The rainfall pattern in 2023 generally followed the trend of the previous 30 years, with the exception of a record-breaking event in early September. The measured rainfall varied across different districts, with Tai Po and Lantau Island recording the highest rainfall throughout the year. However, the extreme event in early September had a significant impact on the Hong Kong Island, particularly the Southern District and Eastern District. Over 400 mm of rainfall was recorded in many parts of the territory, with the Eastern District and Southern District of Hong Kong Island receiving over 800 mm of rainfall on 7th – 8th September. These two

days contributed an average of 16.5% to the annual rainfall depth, with a range of 8.7% (Tuen Mun) to 22.3% (Eastern District).

Table 1: Summary of Record-breaking Events in Year 2023 (HKO, 2024)

Record-breaking Events (since records began in 1884)	Date / Period	New HKO Record
Highest 1-Hour Total Rainfall (All Months)	7 September 2023 23:00 to 24:00	158.1 mm
Highest 2-Hour Total Rainfall (All Months)	7 September 2023 23:00 to 8 September 2023 01:00	201.0 mm
Highest 12-Hour Total Rainfall (All Months)	7 September 2023 22:00 to 8 September 2023 10:00	605.8 mm

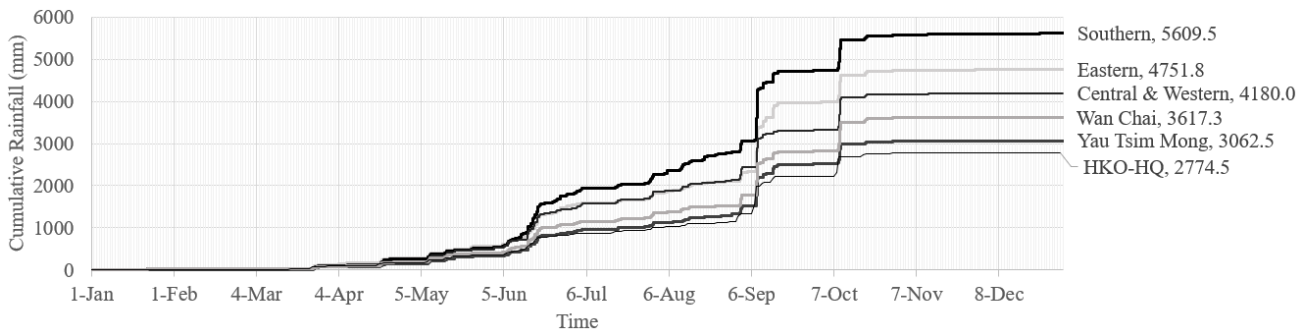


Figure 2: Rainfall Record in Different District in Year 2023 (i-lens, 2024 and HKO, 2024)

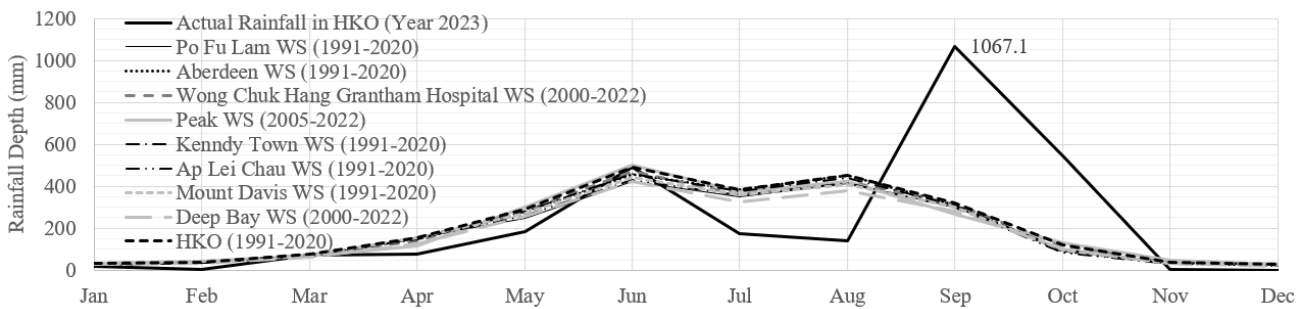


Figure 3: Comparison of Rainfall Record of HKO in 2023 amongst the Average Rainfall Record in Various Weather Stations in Central & Western and Southern District of Hong Kong Island (i-lens, 2024 and HKO, 2024)

To compare with the extreme rainfall depth information from DSD SDM, as illustrated in Figure 4, it is revealed that the rolling rainfall record of the 7th – 8th September event far exceeded the required design return period of 50 years for the urban drainage branch system in the area of concern. This suggests that the surface water may spill over the drainage system, resulting in potential localized flooding issues, especially in areas near the natural drainage line in the territory.

In this study, the real-time respond of the groundwater level is to be illustrated to provide insights how the extreme rainfall affects the groundwater table in hillside territory. Notwithstanding, there is no clear correlation between the return period of rainfall depth and the return period of observed groundwater level.

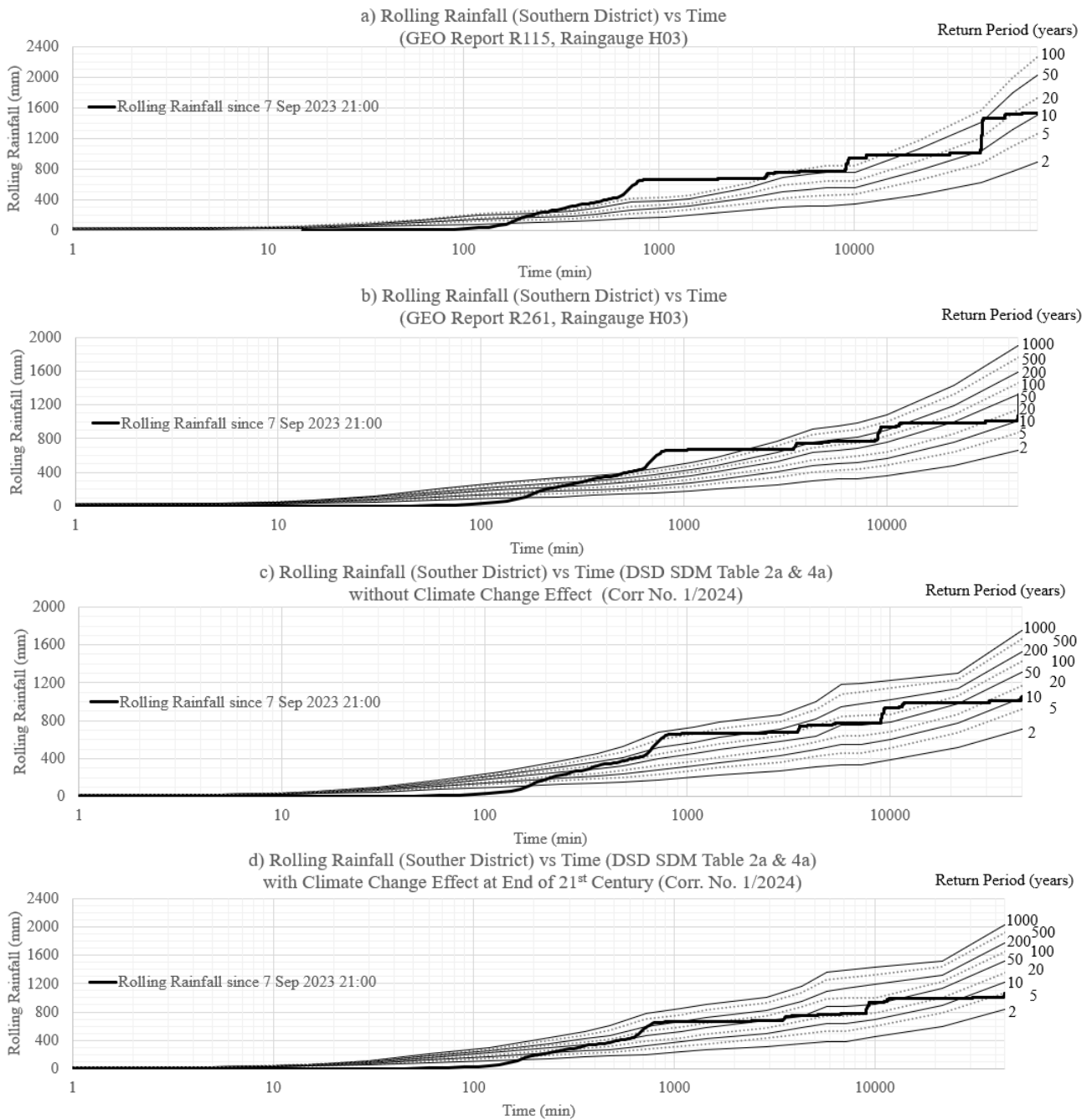


Figure 4: Comparison of Rolling Rainfall Record of Southern District to (a) GEO Report R115 Rain Gauge H03; (b) GEO Report R261; (c) DSD SDM 2018 (Corr. No. 1/2024) and (d) DSD SDM 2018 (Corr. No. 1/2024) with Climate Change Effect at End of 21st Century (Corr. No. 1/2024).

3 CASE STUDY FOR REAL-TIME MONITORING

3.1 Background

The study area is located at the south-west of Hong Kong Island of size 2.6-hectare for hillside site formation works which is up to 67m high rising from approximately +85mPD at the toe on the northern flank up to +152mPD at the crest, with slopes generally dipping at approximately from 10° to up to 30°. The site is underlain by the fine ash vitric tuff and an NNE-SSW orientated band of coarse ash crystal tuff is present to the west of the study area. Both the fine ash vitric tuff and coarse ash crystal tuff are assigned to the Ap Lei Chau Formation of the Repulse Bay Volcanic Group.

The study site is characterized by a south-west facing hillside with predominantly planar slopes between two rounded spurlines. The crest area has a gentle incline ($<15^\circ$), which becomes steeper (20° – 30°) at mid-slope, and the slopes are gentler ($<15^\circ$) towards the toe of the study area. A small depression is present at the lower central part of the study area, containing slightly steeper slopes, up to 30° locally. The depression is the head of a valley up to 45 m long and 45 m wide. The study area is covered with thick vegetation, with trees and bushes on the gentler slopes, and ferns and grasses on the upper slopes.

The majority of rock outcrops and boulders found within the study area are composed of coarse ash crystal tuff with local exposures of fine ash tuff limited to the small depression at the lower central part of the study area. Intermittent rock outcrops of coarse ash crystal tuff, with moderately to closely spaced joints, are exposed along the spurline of the northern side of the study area. The rock is found to be weak to moderately strong, greyish brown, highly to moderately decomposed. Exhumed corestones of very strong, slightly decomposed, coarse ash crystal tuff are located on the southern spurline. The largest is approximately 3m high and 2.4m wide. The corestones are subangular to subrounded and relatively blocky due to the widely spaced joints. The exposed subrounded boulders of coarse ash crystal tuff may also be locally displaced exhumed corestones now part of the general slope colluvium.

Saprolite of extremely weak, moist, orangish brown, completely decomposed coarse ash crystal tuff is exposed at the upper part of the study area and forms a stiff, moist, brown, mottled white, sandy silt/clay soil. Residual soil is exposed at the crest of the study area and in the lower part of the spurline at the northern side of the study area where it is composed of stiff to very stiff, moist, orangish brown, sandy silt/clay.

The upper part of the regional catchment of the study area has been modified by the formation of extensive agricultural terraces. These terraces have been formed by localized cutting and filling activities and associated with the construction of small rubble walls. Stepped terraces range from 1.5m to 4m wide but are typically 2m to 3m wide and 0.5m to 1.5m high. For drainage estimation, the surface characteristics of the catchments involve excavated surfaces, paved surfaces and steep grassland natural slopes where the majority of site area is underlain by an impervious rock layer. The groundwater monitoring system consisted of 36 standpipes or piezometers strategically placed across the site area and these devices were equipped with real-time monitoring sensors to accurately record groundwater fluctuations in 5-minute intervals to match with rain gauge data in 15-minute intervals for Southern District for reference.

3.2 Observations

Except for the extreme events recorded on 7th – 8th Sep & 9th Oct and site-specific local activities in affected areas, all measured groundwater levels remained steady which fluctuated within 2m throughout the year. The groundwater level did not rise significantly despite that several red rainstorm intensity events are encountered from May to July 2023; however, the extreme rainfall events in September and October incurred significant changes in groundwater levels. The groundwater levels rose with range from 3 to 5m for the majority of the monitoring points during this record-breaking event whereas the groundwater level of remaining monitoring points generally rose 5 to 8m from its long-term average especially for those located near existing natural drainage lines.

Apart from the above, the groundwater level raised up to approximately 18m from its long-term average for piezometer BP05P was highlighted as shown in Figure 5. This unprecedented observation is most likely incurred by combination of superposition effect of two successive extreme rainfall events and surface water collected along the drainage line. Overall, once groundwater levels rise, they eventually return to the long-term average level which the rate of decreasing of groundwater levels are generally consistent after rainfall events. Given the consistent decreasing behavior, if another heavy rainfall occurs before full recession to the long-term average, groundwater levels will start from the prior elevation and potentially reach a new maxima measurement point exceeding the previous peak by superposition as illustrated in Figure 5. On the contrary, the groundwater levels would only rise by independent rainfall event if it has returned to its long-term average level as illustrated in Figure 6. It suggests that the recession rate of groundwater level interferes in the degree of superposition for continuous rainfall events which the superposition effect may incur unprecedented rise of groundwater resulting in catastrophic consequence.

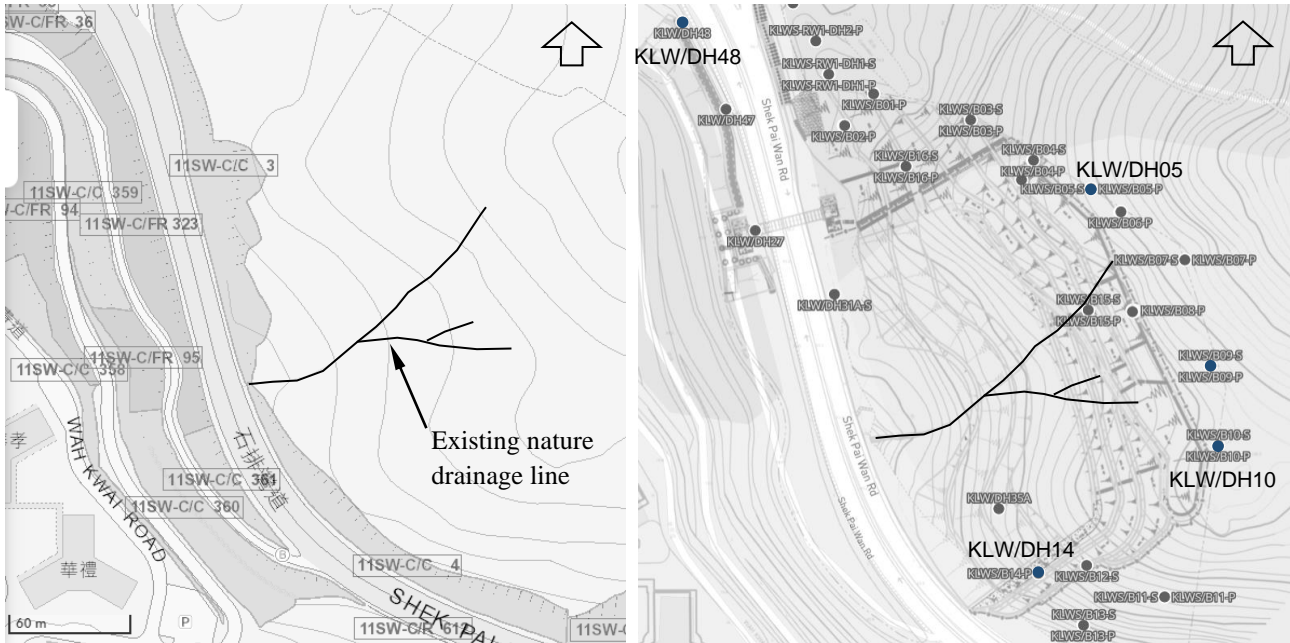


Plate 1: Location Map and Groundwater Monitoring Plan

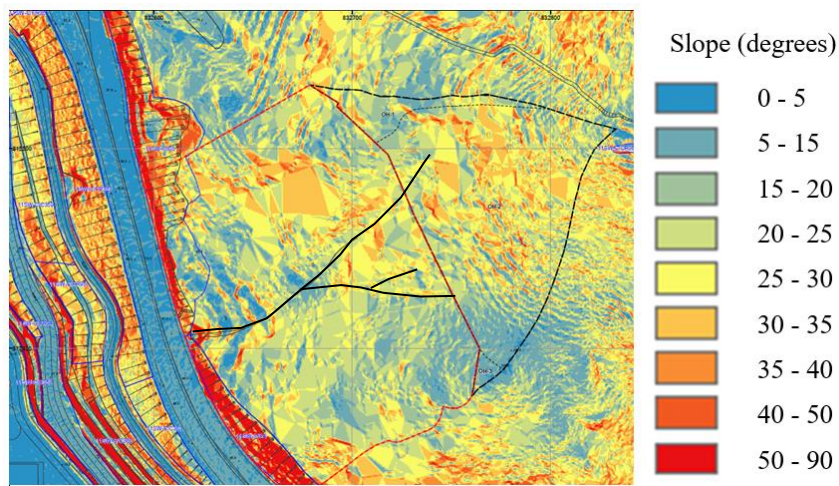


Plate 2: Slope Angle Map

The permeability of the soil layers in the study area ranged from $5.4E-6$ m/s to $1.8E-7$ m/s, as measured by in situ falling head permeability tests. The decreasing rate of groundwater level after extreme events ranged from $7.4E-5$ m/s to $4.9E-6$ m/s, as observed from real-time monitoring. The falling rate of groundwater levels after extreme events was found to be consistent with the permeability of the soil layers in the affected areas.

There is a consistent groundwater flow from the crest to the toe of the hillside study site due to gravity. The measured groundwater level was found to be higher than the measured piezometric head in the same borehole during extreme events, as illustrated in Figures 9 and 10. This indicates the existence of groundwater flow after heavy rainfall and suggests that there are no damping effects or low permeability obstacles in the influenced areas. The rate of groundwater level falling was observed to be similar after two black rainstorm events, despite the dropping pattern being disturbed by another amber rainstorm event and red rainstorm event.

The rises of groundwater levels are influenced by various factors, including site topography, geological profile, site geometry, rainfall intensity and duration, and site activities. For instance, a rise of groundwater level was recorded at BP10P on 3rd Sep due to site activities nearby, which slightly modified the groundwater flow in the affected area. However, only some of the measured groundwater levels were affected by the

rainfall dated 14th Sep, suggesting that the rise of groundwater is more likely to be observed near existing natural drainage lines.

Considering spatial variability in rainfall, autonomous monitoring points are advisable to quantify rainfall-groundwater relationships at specific sites. Attention should be paid to site peripheries and interiors to identify drainage lines, which influence potential for sudden groundwater rises. Notably, groundwater level increases do not proportionally correspond to rainfall intensities, as infiltration effects introduce temporal lags before levels change. Continuous monitoring provides insights into the complex interplay between precipitation inputs and subsurface responses over varying conditions.

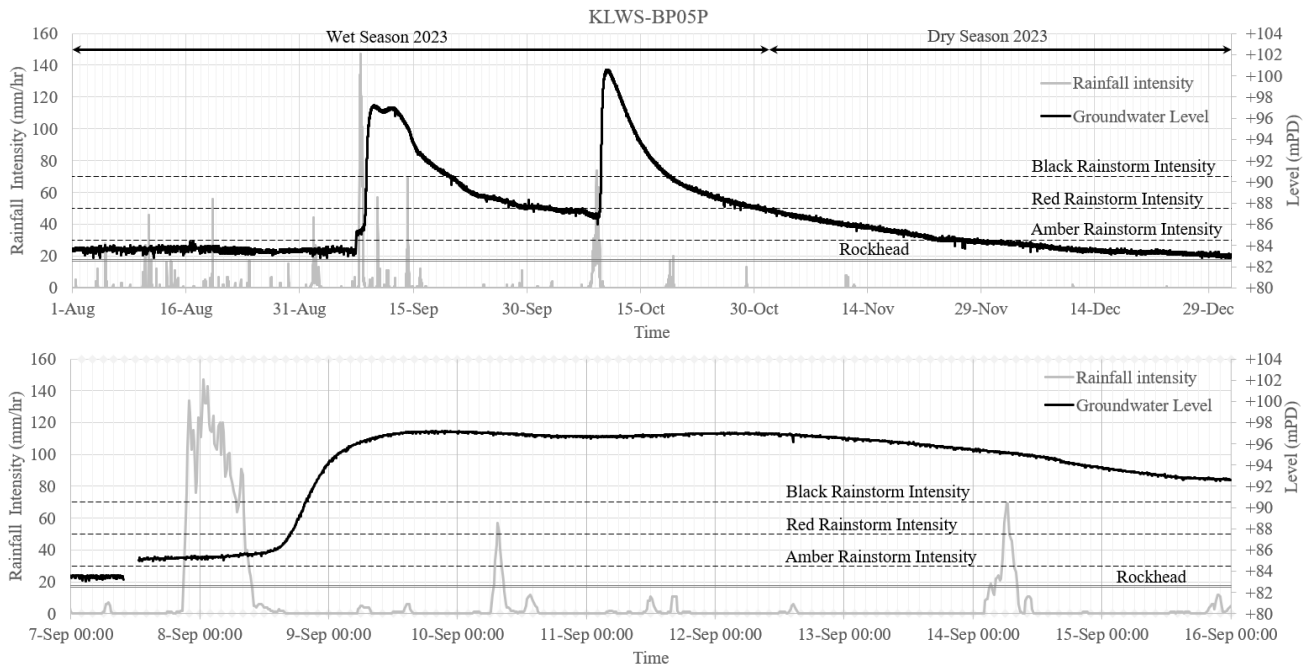


Figure 5: Real time monitoring groundwater level compared with rain gauge information at Southern District at BP05P with ground level at +108.01mPD and piezometer tip level at +82.77mPD

The lead time for the rise of groundwater level from the rainfall varies from 1.6 hours to 28.8 hours in the sloped ground profile in Pok Fu Lam South site with mean of 10.7 hours amongst 15 piezometers or standpipes. Both piezometric head and measured groundwater level rise at the same time at the beginning of extreme rainfall event except the standpipe reading is generally found to be higher than piezometer reading. The piezometric head then will drop to its long-term average together with the measured groundwater level as shown in Figure 9 and Figure 10. In general, the variation of the lead time is believed to be governed by the topography of the site, the permeability of soil profiles, aquifer characteristics, saturation of aquifer and the depth of soil stratum thereat. The soil stratum acted as a de facto water storage tank which the groundwater may rise rapidly provided that the outlet rate (drains) is far less than the inlet rate (infiltrations).

Apart from those piezometers/standpipes located inside the site area, monitoring point DH48 is located on the crest of a fill slope 11SW-C/FR323 on the westbound carriageway of Shek Pai Wan Road. The response of the groundwater is relatively rapid compared with those located on the crest of excavated area of main site which the falling rate of groundwater level after the extreme event is approximately $7.4E-5$ m/s. The monitoring record indicates that the groundwater kept steady unless high rainfall intensity with relatively long duration happened. Notwithstanding, 5m rise of groundwater level was observed for some hours which design review for the design groundwater level of the slope feature may be required for those extreme rainfall event.

This observation of measured groundwater level of DH48 raised the concern for a sudden rise of groundwater level which may impact the accuracy of determination of actual design groundwater level for a hillside slope feature involving nature drainage line nearby if no Halcrow bucket are installed at the monitoring points.

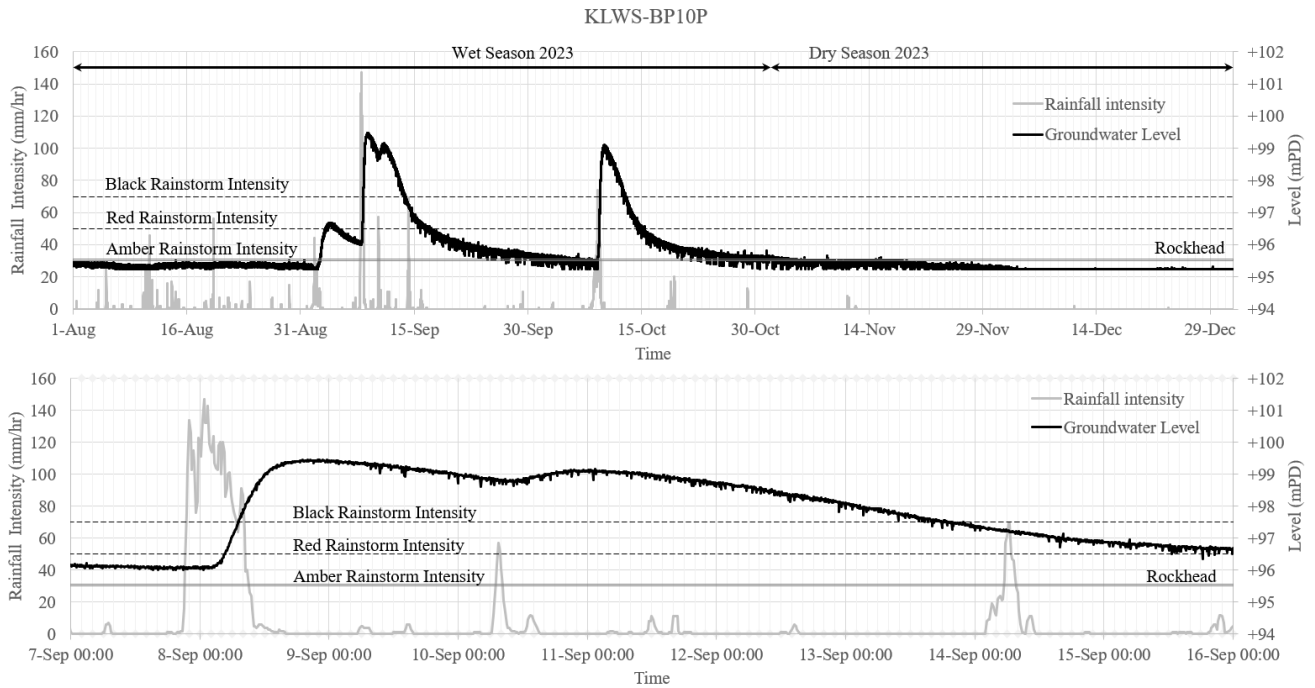


Figure 6: Real time monitoring groundwater level compared with rain gauge information at Southern District at BP10P with ground level at +102.57mPD and piezometer tip level at +95.14mPD

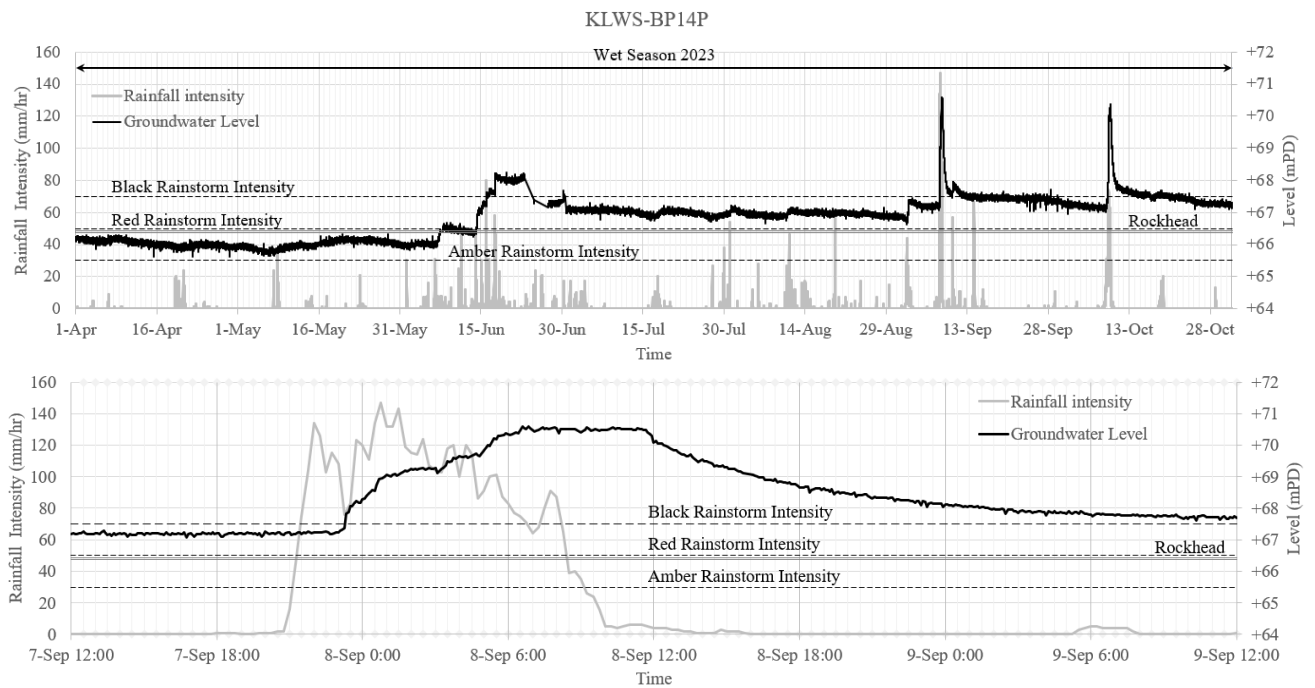


Figure 7: Real time monitoring groundwater level compared with rain gauge information at Southern District at BP14P with ground level at +73.23mPD and piezometer tip level at +65.53mPD

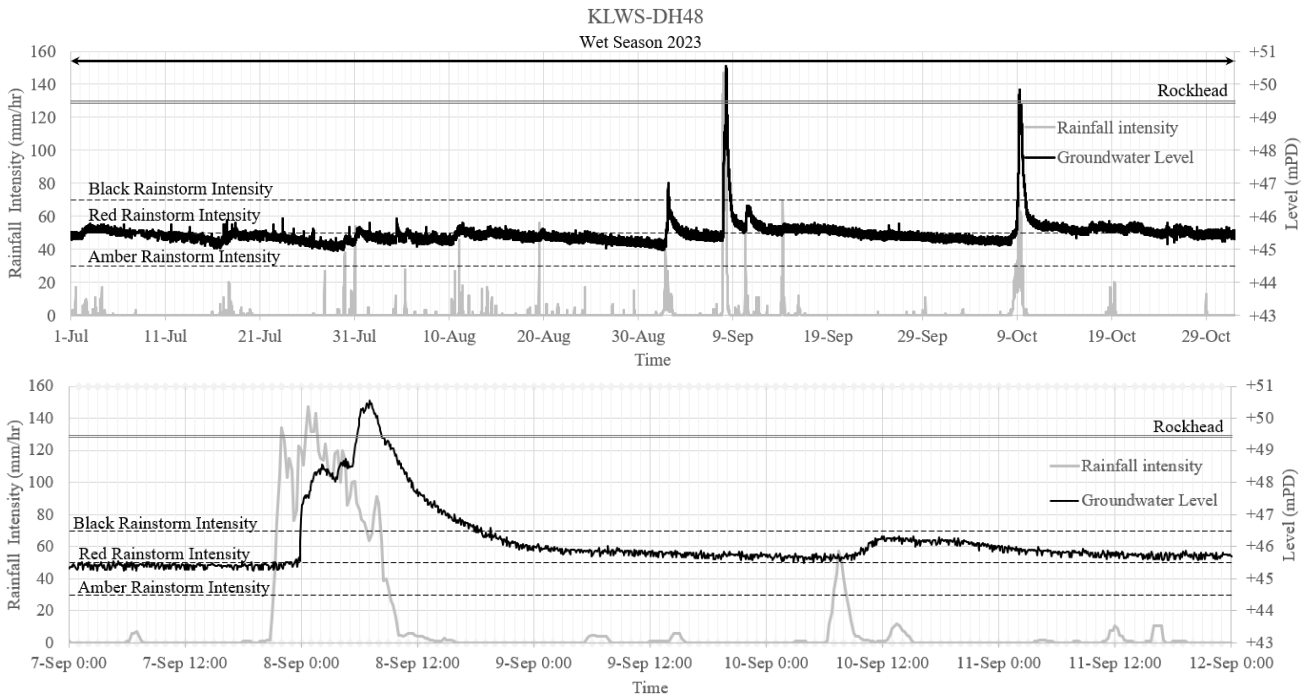


Figure 8: Real time monitoring groundwater level compared with rain gauge information at Southern District at DH48 with ground level at +56.70mPD and piezometer tip level at +43.62mPD

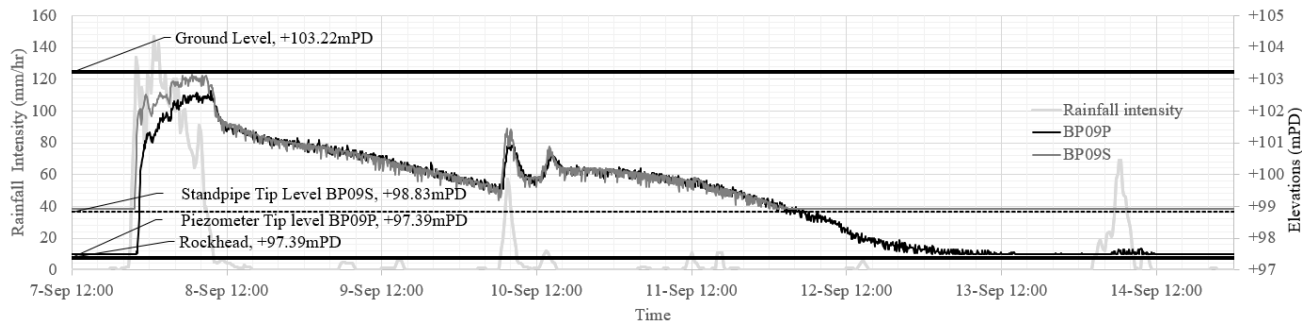


Figure 9: Real time monitoring groundwater level compared with rain gauge information at Southern District at BP09P (Piezometer) and BP09S (Standpipe)

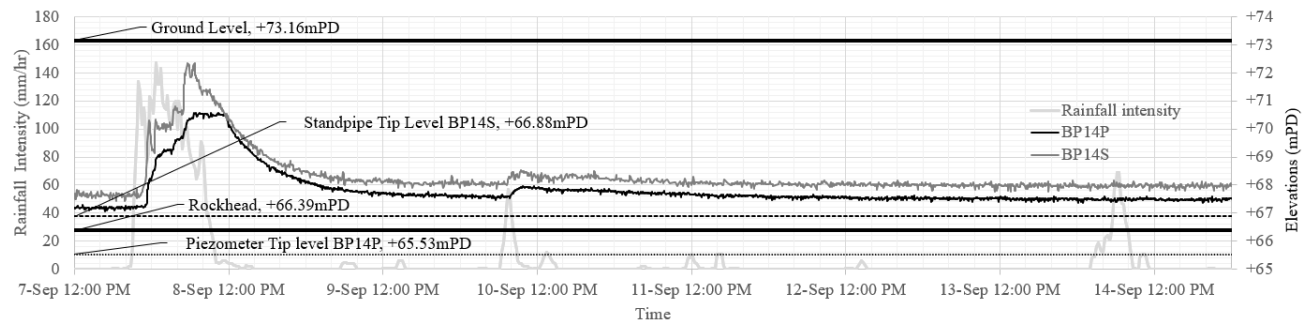


Figure 10: Real time monitoring groundwater level compared with rain gauge information at Southern District at BP14P (Piezometer) and BP14S (Standpipe)

Kaolins was first found in Nov 2023 at the southern portion of the study site during bulk excavation. Further to the following up additional ground investigation fields works for kaolins, it is concluded that kaolins are randomly distributed on the southern corner of the study site. The field works study indicated that up to 7.5m length persistent, shallow dipping, rough undulating rough planar kaolin-rich zone of completely to highly decomposed tuff contains relatively thick (55mm to 70mm) veins or stringers of white, firm sandy clay occurs sub-parallel to the surface of Grade II/III rock.

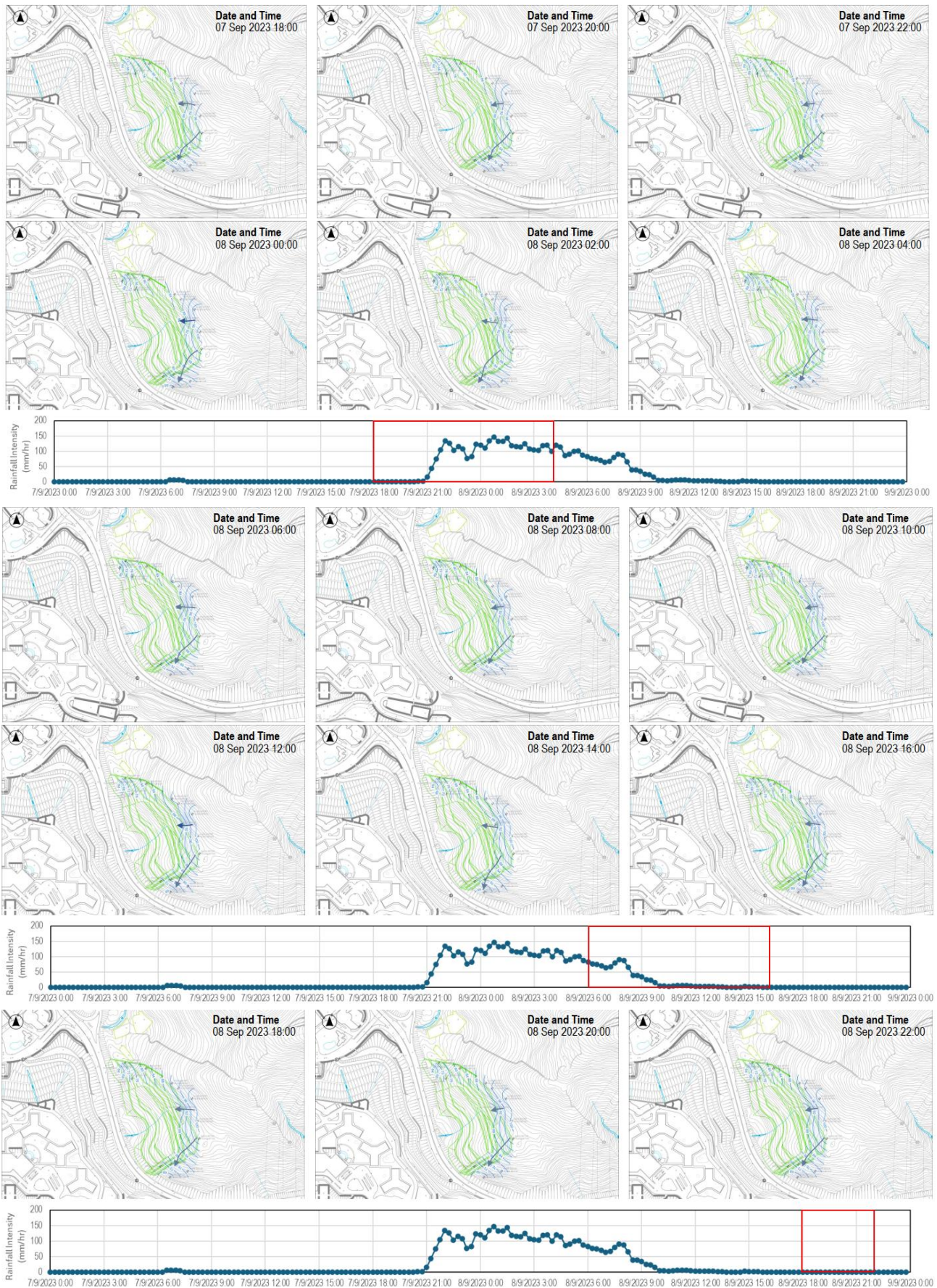


Figure 11: Groundwater contour map and flow direction during the extreme event at 7-8 Sep 2023 with rainfall intensity



Plate 3: Thin veins or stringer of white, firm sandy clay occurs sub-parallel to the surface of grade II/III rock

LiDAR survey was then deployed to identify the existence of potential cavities in the study area to justify the impact to the ground-water hydrology. The LiDAR scanner confirmed that there are three observed voids of size 1.5m wide, 0.5m thick with 4m long identified as natural cavities with same orientation. The field study reveals that the transportation of solutes and fines produced as a by-product of in situ weathering rock masses by intergranular flow of groundwater which may result in formation of those voids. Notwithstanding, the groundwater monitoring record from piezometers and standpipes of BP14 located at southern corner of the site indicated that the damping effect of such cavities are negligible as piezometric head is synchronized with the groundwater level measured by standpipe as shown in Figure 10.

Additionally, the groundwater contour map revealed that the flow directions are quite consistent, as shown in Figure 11. The flow direction changes of groundwater between 18:00 on 7th Sep and 22:00 on 8th Sep were found to be insignificant, even with an observable rapid rise of the groundwater table. These findings suggest that the presence of randomly distributed thin layers of kaolins may not significantly affect ground hydrology in this study area.

3 RECOMMENDATIONS

It is recommended to consider the Factor of Safety (FOS) for slope stability design by introducing the concept of the "Extreme Highest Groundwater," with a defined return period of rainfall, says 1:1000 years, to eliminate the risk under extreme events. The defined return period of rainfall for the "Extreme Highest Groundwater" can be varied up to the satisfaction of geotechnical engineer to suit the needs of different sites especially for those with drainage lines to balance the consideration of economical cost and practicality in civil works design. Meanwhile, the above concept was adopted in the Pok Fu Lam site to demonstrate the stability of retaining structures with FOS at 1.1 for 1000 years rainfall return period to mitigate the risk under the extreme conditions.

Automated monitoring system with intervals of 10 to 15 minutes for measuring rainfall and groundwater changes for geotechnical design is found to be adequate and it provides sufficient information for analysis to verify the design assumption of design groundwater levels and justify the possibility of sudden rise of groundwater level in the subsurface. Nevertheless, it is crucial to thoroughly examine both the periphery and interior of the site to identify the presence of drainage lines including all natural rivers, streams and the former riverbed by aerial photo interpretation study and site survey to mitigate all the potential risks incurred by the sudden rise of groundwater level for sloping terrain. Should real time monitoring be impracticable to be installed, Halcrow buckets may become an alternative solution to record the historical measured highest groundwater level for design concerns. Notwithstanding, technology nowadays such as "Smart Site Safety System" not only record the geotechnical data to the designer for reviewing but also send warning message to frontline staff for if the pre-defined Alert-Action-Alarm values are met.

4 CONCLUSIONS

The extreme event for heavy rainfall becomes more frequent. The average lead time for the rise of groundwater level from the rainfall 10.7 hours in the sloped ground profile in Pok Fu Lam South site. The groundwater levels near natural drainage lines should be handled with care and the superposition effect for extreme rainfall events may lead to catastrophic consequences in design concern. Real time monitoring device or Halcrow bucket is highly recommended to record the historical highest measured groundwater level for those monitoring points located near to the existing natural drainage line for design concern.

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