Innovative Approach for Landslide Prevention – A Tunnel and Sub-vertical Drain System

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ABSTRACT

The Po Shan Tunnel Landslide Preventive Works consist of two 3m diameter tunnels in deep rock and 172 nos. of sub-vertical drains drilled and installed upward from inside the tunnels and extended into the overlying soil layer. It is the first of its kind in Hong Kong and even in the world to utilize tunnels and a network of sub-vertical drains to form a robust subsurface drainage system to regulate the groundwater table for enhancing the long-term stability of the hillsides. The performance of the system has proven to be satisfactory. The success of the project demonstrates a feasible and effective solution for future landslide prevention and risk mitigation on steep and hilly terrain in Hong Kong.

In this paper, the design philosophy of this innovative landslide prevention approach is briefly discussed, the construction issues are also described, and the performance of the system for landslide prevention purposes are highlighted.

1 INTRODUCTION

In 1972, a catastrophic landslide occurred on the hillside of the Po Shan area in Hong Kong, which took the lives of 67 people. Among other major landslides in Hong Kong, this incident formed the historical background for the slope safety efforts made by the Hong Kong Government. A number of detailed investigations and research studies were carried out and the results indicated that the natural hillside of the Po Shan area was affected by high groundwater level and unfavorable geology. Sub-surface drainage measures by means of sub-horizontal drains were installed in 1984-85. These measures have been successful in lowering the main groundwater table, thus improving the stability of the slopes such that large-scale failures have not occurred over the last two decades. After some twenty years, the monitoring data however showed signs that the groundwater levels in the drained area could be high during periods of heavy rainfall. The hillside was susceptible to small-scale shallow movements, which could damage the existing horizontal drains and render them ineffective in drawing down the main groundwater level.

In 2005, AECOM was appointed by the Geotechnical Engineering Office (GEO), Civil Engineering and Development Department of the Hong Kong SAR Government to design a robust landslide preventive system to protect the residents at the Po Shan Area. With this clear ultimate goal, AECOM came up with a creative and yet practical design. Many design options had been considered, and eventually a tunnel and sub-vertical drain system was adopted.

This paper presents the process leading up to the innovation being developed, the design philosophy of this innovative approach, the construction issues, and the performance of the tunnel and sub-vertical drain system for landslide prevention purposes.

2 SITE DESCRIPTION

The site is located at NW flank of Victoria Peak and south of Po Shan Road. The project area can be broadly defined as encompassing the mostly undeveloped hillsides above No. 4 Po Shan Road in the west to No. 20 Po Shan Road in the east, beyond the man-made cut slope, 11SW-A/CR175, at the site of the catastrophic 1972 Po Shan Road failure.

The project area falls largely within the Pok Fu Lam Country Park and is mainly covered by dense vegetation comprising grasses, shrubs and trees. The hillside is about 210 m high, with crest and toe levels at around +390 mPD and +180 mPD respectively. The maximum span of the site is approximately 730 m in length. Generally, the site is mainly natural terrain with an average gradient of 25^0. Lugard Road is located at the crest whilst residential buildings are located along the toe of the project area. Figure 1 shows the perspective view of the project area and Figure 2 shows the as-built plan for the tunnels and the sub-vertical drains.

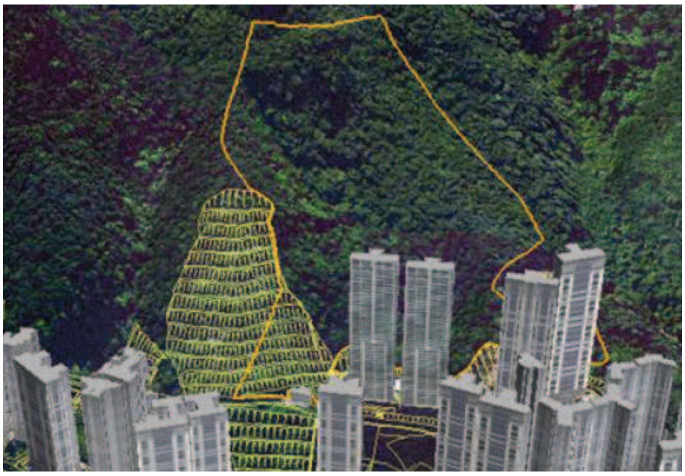
Figure 1: Perspective View of the Project Area

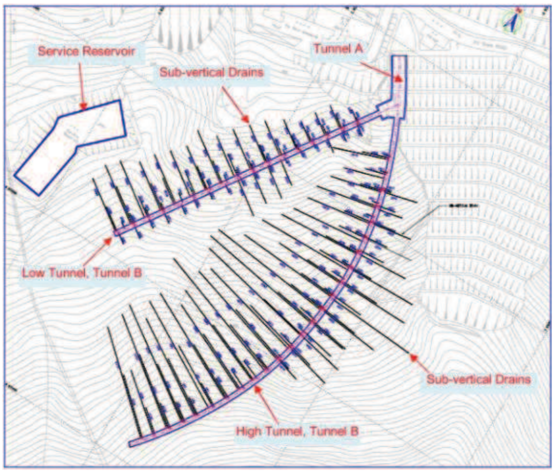

Figure 2: As-built Plan of the Tunnels and Sub-vertical Drains

3 HISTORICAL LANDSLIDES

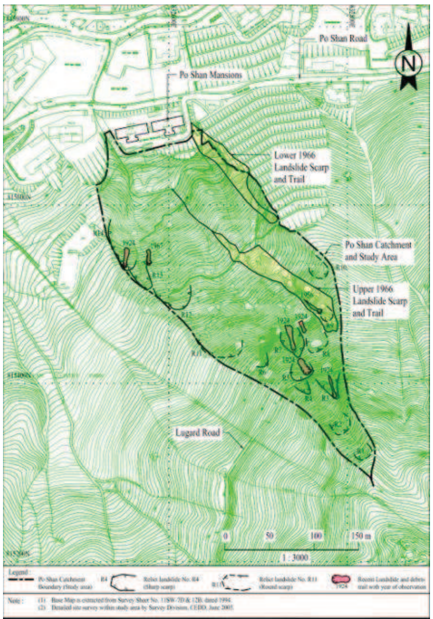

Figure 3: Natural Terrain Landslide within Po Shan Catchment

Figure 4: 1972 Po Shan Road and Hamilton Court Landslides

The Po Shan catchment and adjacent hillsides have been affected by significant historical instabilities. FSW (2005) summarized those natural terrain landslides, which are illustrated in Figure 3 and Figure 4. The key landslide events in the Po Shan area include: a) Fourteen relict landslides identified on 1949 aerial photographs; b) Seven small (<50 m^3) recent landslides identified on 1924, 1956 and 1967 aerial photographs; c) Two large (500 m^3 and 1500 m^3) recent landslides identified on the 1967 aerial photographs (both occurred in June 1966); d) 1972 Po Shan Road landslide; and e) 1972 Hamilton Court landslide.

4 GEOLOGICAL CONDITIONS, LANDSLIDE HAZARDS AND MITIGATION WORKS

Very extensive desk study and ground investigations including two horizontal directional coring (HDC) holes (Lam et al. 2008) were carried out within and in the close vicinity of the proposed tunnels and associated sub-vertical drains before construction to confirm the geological stratification. The site investigation data revealed that the geology of the site comprises three major geological strata, namely Colluvium, Completely and Highly Decomposed Tuff, and Moderately Decomposed Tuff or better rock. However, special geological features such as rock intrusions, granitic vein, quartz vein, pegmatite vein, aplite vein and rhyloite vein, were encountered in both tunnels during construction.

Previous (GCO 1987) and more recent subsurface investigations (FSW 2005) indicated that the majority of the Po Shan catchment is covered with Colluvium, which is often considerably thick (>20m). Saprolite is also found and is generally covered with a thin layer of Colluvium. Four main groups of landslide hazards were also identified from previous studies and are summarized as follows:

(1) Landslide Hazard 1 – Retrogressive / retreating failures of the residual Colluvium on the eastern and western spurs of the site area within the locally steeper portion of slope. These failures probably include debris avalanche (open hillside failures) becoming debris flow landslides if sufficient channelization occurs and if sufficient water is present. Development of perched water conditions within the Colluvium and at the Colluviums-Saprolite boundary are considered to be significant factors for landslide initiation.

(2) Landslide Hazard 2 – Debris avalanche and debris flow type failures sourcing from the upper rock dominated part of the site area, between the cliffs. Development of perched water conditions at the Colluviums-Saprolite-bedrock boundaries are considered to be significant factors for landslide initiation.

(3) Landslide Hazard 3 – Rock slide (wedge and planar) and rock fall failures on the rock cliffs in the middle to upper portions of the catchment, which have produced significant talus deposits overlying Colluviums on the middle portion of the catchment, particularly below the lower cliff.

(4) Landslide Hazard 4 – Deep-seated failures may have occurred in the past within the residual Colluvium and possibly within the buried Saprolite below the Colluvium. This was suggested from the disturbed nature of the CDT recovered from some Mazier samples above the upper 1996 landslide scar. Development of high main groundwater conditions within the Colluvium / Saprolite could have been significant factors for possible deep-seated relict landslide initiation.

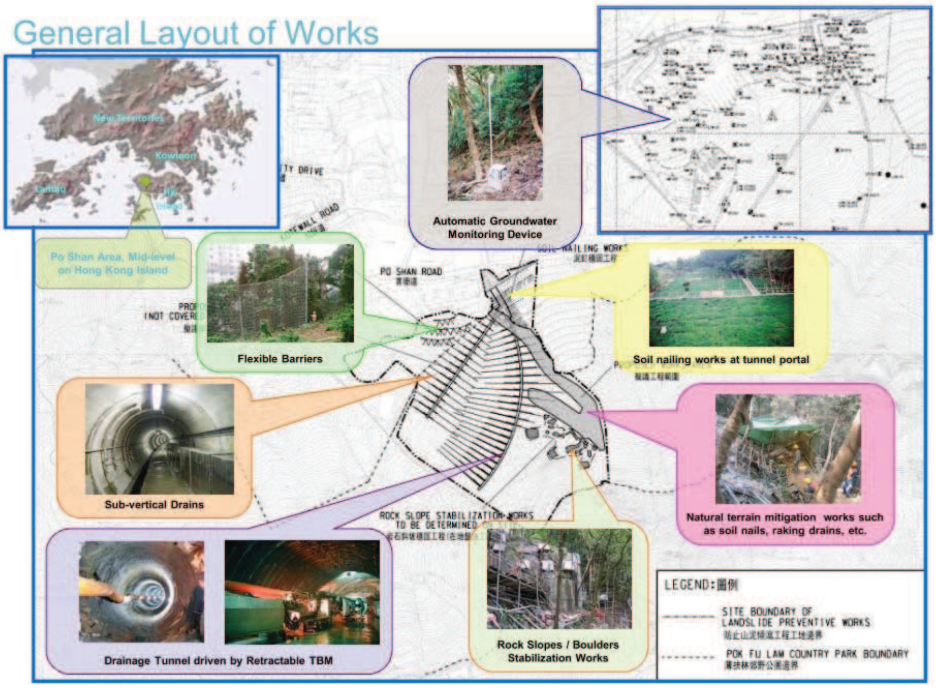

Figure 5: General Layout of Works

Based on quantitative risk assessment (FSW 2005), the natural terrain landslide risk mitigation works including protective measures (e.g. debris barriers, surface drainage improvement, bio-engineering measures, etc.) and preventive measures (e.g. soil nailing, rock slope stabilization and raking drains) were schematically proposed. The detailed landslide preventive works in all identified hazard areas were designed by AECOM in 2005 and the construction works were successfully completed in December 2009. The scope of works include the innovative tunnel and sub-vertical drain system, natural terrain risk mitigation works comprising soil nails, rock slope treatment works, bio-engineering works, and flexible barriers. These works are shown in Figure 5. This paper mainly describes the tunnel and sub-vertical drain system in following sections.

5 INNOVATIVE DESIGN OF THE TUNNEL AND SUB-VERTICAL DRAIN SYSTEM

There are two 3m inner diameter (ID) TBM tunnels, namely High Tunnel and Low Tunnel, extended from the portal chamber and run underneath the natural hillside behind No. 16 Po Shan Road. The High Tunnel is 259 m long and is located at elevations between +184.24 mPD and +197.19 mPD. The Low Tunnel is 188 m long and is located at elevations between +184.06 mPD and +185.95 mPD. The sub-vertical drain system consists of 172 nos. of drains with a total length of approximately 10 km and a maximum individual length of 102 m. The drains were constructed from the two TBM driven tunnels at different orientations and angles from 30^{o} to 125^{o} to the horizontal. The plan and cross-sectional views of the tunnel and sub-vertical drain system are shown in Figure 2 and Figure 6 respectively.

The prime objective of the tunnel and sub-vertical drain system is to reduce the risk of deep-seated landslide. The drains were designed to cover the area of the entire concerned drainage zone of the catchment. From Figure 6, it is clear that the drains take care of the drainage zones of the upper hillside and lower hillside. Each drain consists of an outer 114 mm diameter Stainless Steel (S.S.) or High-density Polyethylene (HDPE) perforated casing, and a geotextile-wrap protected, 50mm diameter, slotted well-screen inner tube. Inside the tunnel, a connection pipe connects every sub-vertical drain and extends to a half round channel. A valve is installed on the connection pipe to control the flow of groundwater from the sub-vertical drain. The arrangement is shown in Figure 7. The tunnel and sub-vertical drain system provides a controllable mechanism through opening and closing of the sub-vertical drains to regulate the groundwater level and ensure that the variation of groundwater level is in line with the design purposes.

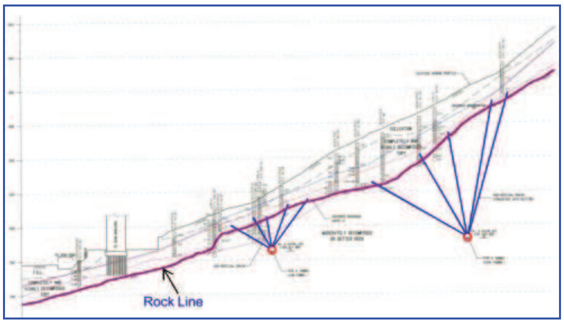

Figure 6: Cross-sectional view of the tunnel and sub-vertical drain system

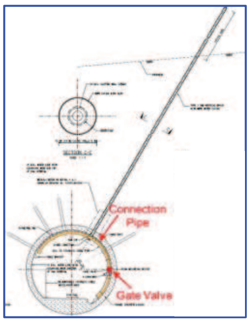

Figure 7: Sub-vertical drain and connection pipe arrangement

6 CONSTRUCTION OF THE SUB-VERTICAL DRAINS

In consideration of the drilling method for the sub-vertical drains, percussive upward drilling from the drainage tunnel was selected as it would give a much higher penetration rate. Water hammer, instead of air hammer, was also adopted to reduce the chance of jamming. The maximum average drilling rate was approximately 32 m/day/rig.

The experience gained in the early stage of the construction suggested that rapid drawdown in groundwater levels usually occurred during drilling or just after completion of drilling. Therefore, the newly constructed drains were temporarily plugged to avoid uncontrolled and excessive drawdown of the main groundwater table. For most of the sub-vertical drains, the actual construction sequence is briefly described as follows:

a) a hole was drilled by using the sub-vertical drilling rig with the high water pressure system;
b) a perforated outer casing was inserted by using the same drilling rig;

c) an inner drain was inserted manually or using the same drilling rig;
d) a locking device was installed onto the tunnel crown and sealed with water sealant and water-proof materials; and
e) an end cap was installed to temporarily cease water drainage from the sub-vertical drain.

Chau et al. (2011) summarized the experience of the sub-vertical drain construction and described the detailed drilling and installation processes of sub-vertical drains, the problems encountered and the corresponding solutions adopted during construction, as well as the valuable experiences gained from the project.

7 PERFORMANCE OF THE TUNNEL AND SUB-VERTICAL DRAIN SYSTEM

Based on the observations obtained during construction, Lo et al. (2011) postulated a simple hydrological conceptual model to depict the variation in groundwater level during and after construction of the entire drainage system. The simple conceptual model is shown in Figure 8 and is briefly described as follows:

Stage 1: Tunnel Construction – Rock storage drainage with limited groundwater drawdown
Stage 2: Drains Construction – Effective groundwater drawdown
Stage 3: Drains Plugged – Groundwater drawdown stops (pressure starts to build up)
Stage 4: Construction Completed – Groundwater rise and back to original

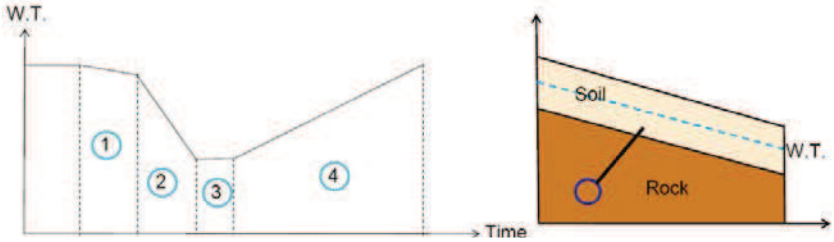

Figure 8: Hydrological Conceptual Model

The hydrological conceptual model has been verified by actual piezometer records. A total of 52 piezometers, some of which were double (upper and lower) tip installation, have been in operation and the readings have been recorded automatically on a real-time basis since the beginning of the construction. Lo et al. (2011) summarized the groundwater monitoring data from November 2006 to September 2010. This paper further updates the monitoring data to December 2010 and a peak groundwater level in 2011 can be shown.

In general, the groundwater levels at most of the piezometers vary with seasonal fluctuations throughout the monitoring period, although some construction activities have affected the groundwater flow regime; the groundwater variation in piezometer SP/022 shown in Figure 9 is a typical example. The groundwater variations at piezometers SP/026U and LPW12/UPZ are also shown in Figure 9.

During tunnel excavation (Stage 1), the variation of groundwater levels was not sensitive, although some of the piezometers exhibited minor groundwater drawdown (0.1 m to 0.2 m). The minor drawdown in piezometers during tunnel excavation was in agreement with the minor inflows measured inside the tunnel (Lo et al, 2010). This is due to the limited local water storage in rock layer and therefore high inflow rates only occurred at the onset of HDC drilling. Once the initial water storage had been dissipated, the amount of water seeping into the tunnel reduced significantly.

During drilling of the sub-vertical drains (Stage 2), the groundwater level in some piezometers exhibited sudden and dramatic drawdown ranging from 1 m to 20 m. The drilling of the sub-vertical drains connected the tunnel to the main groundwater table in the soil layer and/or local water storage in rock layer. The direct drainage paths increased the overall hydraulic conductivity of the rock mass; this resulted in rapid and significant groundwater drawdown in some piezometers in the sensitive areas.

After effectively plugging the drilled sub-vertical drain holes in the High Tunnel and the Low Tunnel (Stage 3 to 4), recovery of groundwater table was observed and the groundwater level varied in accordance with the anticipated seasonal fluctuation in most piezometers. The period for groundwater pressure building up (Stage 3) and recovery of groundwater level (Stage 4) depended on the intensity of rainfall, the duration of the wet season and local material conductivity. For piezometer SP/026U, the groundwater level exhibited two obvious drops in relation to drilling of sub-vertical drains Nos. U100 and U106 on 24 April 2008 and 10 May 2008 respectively, however, the groundwater level immediately recovered after the heavy rain in late May and

June 2008 and thereafter experienced seasonal fluctuation. For piezometer LPW12/UPZ, the groundwater level was affected by drilling of sub-vertical drains Nos. D70, D72, D78 and D80 on 30 July, 31 July, 7 August and 8 August 2008 respectively, remained at a low level, and finally recovered in the wet season of 2009.

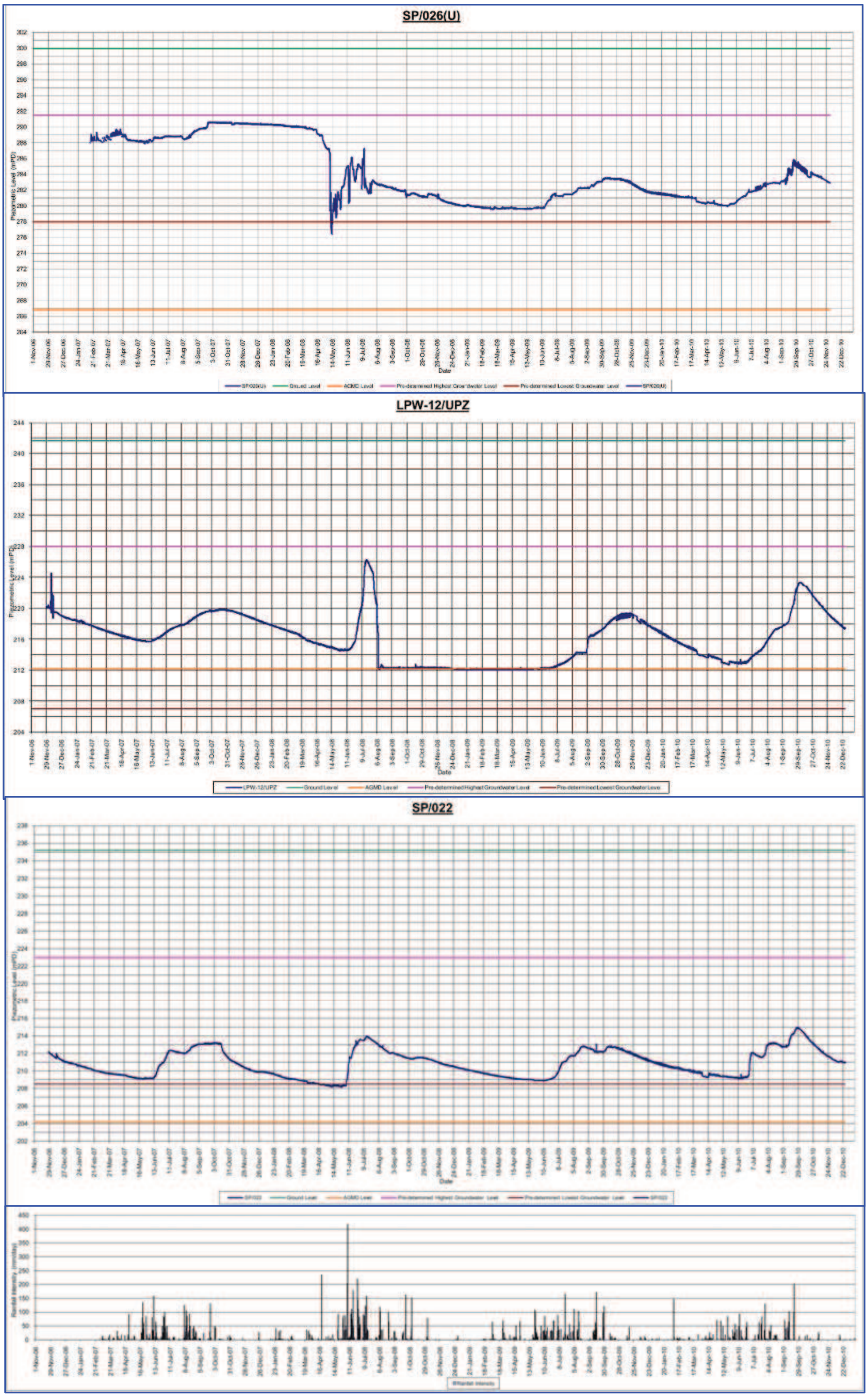

Figure 9: Groundwater Monitoring Results for Piezometers No SP/026U, LPW12/UPZ and SP/022

From the groundwater monitoring results, it is evident that the level of groundwater drawdown due to the presence of sub-vertical drains (when opened) is in line with the design function of the drainage system and the low groundwater levels could recover to the original levels through natural replenishment when drainage from the sub-vertical drains is stopped.

During operation of the drainage system, the valves of the sub-vertical drains can be opened during the wet season when groundwater levels exceed the alarm levels, and be closed when the groundwater table drops to a safe level. The highest and lowest safe levels are the groundwater levels fulfilling minimum factor of safety for overall slope stability and the historical lowest groundwater levels respectively; however, the alarm levels would be within the highest and lowest safety levels. These operational procedures to regulate the groundwater table are in effect replicating Stage 2 to Stage 4 during construction.

8 CONCLUSIONS

The Po Shan Tunnel Project is an innovative solution for slope stabilization, where tunneling has seldom been exploited. The Project is part of the efforts made by the Hong Kong SAR Government to improve slope safety under the Landslip Preventive Measures Programme since the 1970's. The performance of the system has proven to be satisfactory. The success of this project demonstrates a feasible and effective solution for future landslide prevention and risk mitigation on steep and hilly terrain areas.

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