香港岩土及岩土環境工程專業協會

ASSOCIATION OF GEOTECHNICAL & GEOENVIRONMENTAL SPECIALISTS (HONG KONG)

GROUND INVESTIGATION GUIDELINES

08.0 GROUNDWATER PRESSURE MONITORING DEVICES IN HONG KONG

1.INTRODUCTION

Groundwater pressure influences the design, construction and maintenance of all civil engineering works; it is therefore vital that this is recorded as far as is practical during all stages of a construction project. There are many difficulties in obtaining accurate and reliable data, which can lead to the use of erroneous interpretation if not assessed properly. Influences include:

- Ground variability: occurring over relatively small distances; such as permeability variation associated with grain size and / or fracture intensity changes;
- Groundwater level fluctuations: occurring over relatively small time periods; influenced by tidal levels, intense rainstorms, leaking utilities and surface water run-off;
- Workmanship: installation of monitoring devices requires a thorough understanding of the ground conditions and care in material and monitoring device placement to ensure the instrumentation functions adequately.

These determine the type, number, location, installation method, monitoring frequency and design life of the groundwater monitoring devices.

This guideline describes the use of groundwater pressure devices, termed "piezometers", for different engineering works and ground conditions in Hong Kong. Attention is given to the suitability and type of installation and hydrogeological and contractual considerations; the aim is to ensure best practice for the groundwater pressure monitoring.

2.PURPOSE

Groundwater pressure assessment is needed for all civil engineering works ranging from sub-surface excavation, reclamation, slope stability, site formation, foundations and deep excavation. As Hong Kong is a highly urbanized environment disruption to adjacent Existing Building and Structures (EBS) from groundwater drawdown can be hazardous. Ascertaining the groundwater level variation prior to work commencement is therefore needed to assess fluctuation limits and contingencies upon exceedance.

Due to the seasonal fluctuation between wet and dry seasons in Hong Kong the baselines are usually determined following at least one year of monitoring, covering both seasons, with an increased frequency during intense rainfall to determine the maximum groundwater rise.

3.MONITORING INFLUENCES

3.1 Response time

The response time is the period needed for the measuring device to indicate the true groundwater pressure (GEO, 2000). This depends on:

- *Water quantity: needed to operate the device;*
- *Piezometer shape factor: Brand et al, 1980*
- *Piezometer "porous element" permeability and*
- *Ground permeability*

To determine the groundwater pressure a measurement device needs to reach equilibrium with the surrounding groundwater pressure as soon as practical. The accuracy of the data obtained depends upon the device adopted and influences on the response time.

3.2 Monitoring device

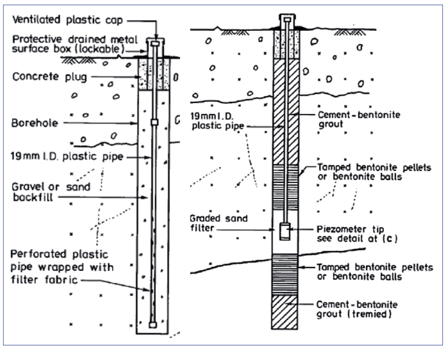
The selection of the monitoring device depends on the monitoring period required, data accuracy, reading frequency and cost limitation. The devices can either be a standpipe, a measuring device connected to a standpipe, or a Diaphragm, which is a porous element placed within the ground connected to flexible tubes to allow groundwater pressure to be measured from the surface. Common measuring devices include:

Standpipe:

This is typically a 19mm diameter PVC tube slotted towards the base, covered by a geotextile membrane with sand / gravel pack surround and a plug seal to prevent water inflow from the surface, see Figure 1.

Standpipe piezometer (Open Hydraulic Piezometer)

Comprises a tube with a porous element, sealed into the ground at the level required. Due to its simplicity this is the most commonly used device in Hong Kong, typically termed the "Casagrande" piezometer, see Figure 1.



The porous element of the standpipe piezometer can be:

- *Low air entry: protected by a rigid sheath (Figure 2) which suits finer grained, lower permeability ground;*
- *High air entry: more rapid response time installed in more permeable ground.*

Figure 1 – Standpipe and standpipe piezometer
(Extracted from Geoguide 2, Figure 19)

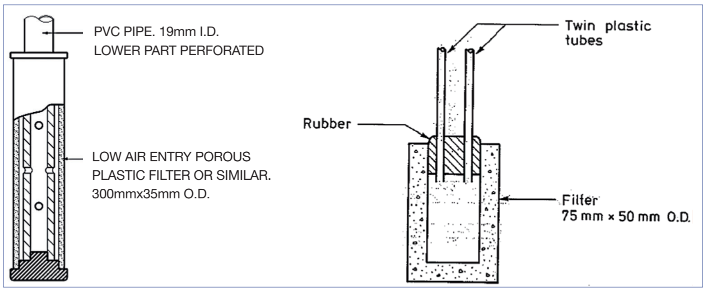


Figure 2 – low air-entry piezometer tip (Casagrande) and Hydraulic piezometer
(Extracted from Geoguide 2, Figures 19 and 20)

Due to the space required for a piezometer installation a relatively high volume of ground water inflow is needed for the groundwater pressure to reach equilibrium. With a response zone of minimum dimensions of 150mm diameter and 0.4m length, in ground with a permeability approaching 10-7m/sec, equilibrium would take a few hours (GEO, 2000).

Hydraulic (Diaphragm) Piezometer (Closed hydraulic)

The groundwater is detected within a monitoring piezometer with porous walls and measured through a relatively small diameter plastic tube connected to a monitoring device, see Figure 2. To avoid reading errors from trapped air the tube is filled with water. Twin tubes are commonly used to allow de-airing of the tubes and porous tip. The disadvantage is potential cavitation of the tip, limiting the groundwater monitoring level to a maximum of 7m above the tip and maintenance ensuring that the tubes remain de-aired.

Electric (Diaphragm) Piezometer

The groundwater is monitored using a pressure transducer located close to the porous element. Electric piezometers include the "vibrating wire (VW)" type, typically used in Hong Kong, and the "electrical resistance" type, which is not typically used.

A vibrating wire piezometer (VW) comprises a vibrating wire that is connected to a sensitive diaphragm in contact with the water through the porous element. A change in water pressure causes a deflection of the diaphragm that in turn alters the tension in the wire. Electromagnetic coils generate vibration in the wire, from which the tension in the wire is determined. Due to its rapid response time, a VW piezometer can provide frequent readings.

Pneumatic (Diaphragm) Piezometers

Comprises two tubes attached to a porous tip. Groundwater pressure is determined by air pressure application through one of the tubes. When the pressure opens the gate into the porous element there is equilibrium between the groundwater and air pressure.

The advantages and disadvantages for reliability and response time are summarised in Table 1 (GEO, 2000).

(Special thanks to Ms Ada Chan and Mr Sandy Mackay for preparation of this guideline)

Piezometer Type	Response Time	Real time application
Closed-hydraulic (high-low air entry pressure)	Moderate	Needs an Automatic Groundwater Monitoring Device (AGMD)
Open-hydraulic (Casagrande)	Slow	Needs an AGMD
Pneumatic	Rapid	N/A
Electric vibrating wire (VW) type	Rapid	Yes

Table 1: Evaluation of Piezometer Types

The open-hydraulic piezometer is considered to be relatively simple and robust and as a result has greater long term reliability (GEO, 2000). Improvements in the reliability of the pneumatic and vibrating wire and resistance electric piezometers over the last decade however have increased long term reliability.

Fully Grouted Piezometer
Given the number and variation in materials needed for a standard piezometer installation fully grouted standpipe or diaphragm piezometers are a practical alternative. The advantages are increased robustness, greater reliability and, as the backfill material is consistent, improved quality control (Vaughan, 1969 & 1973, Contreras et al, 2008 and Mackay et al, 2008). The disadvantages are greater understanding of the grout properties needed to ensure performance. The grout needs to have a compatible strength and permeability with the surrounding ground (Mikkelsen et al, 2003). Lower bentonite volume in the mix increases permeability with ranges varying from 10-6 to 10-8m/sec (Mikkelsen et al, 2003). To ensure a consistent mix the cement and water is added first to ensure a suitable strength. Should multiple piezometer installations be required the separation between piezometer tips can be reduced.

4.INSTALLATION, MEASUREMENT AND INTERPRETATION

The ground conditions surrounding an installation need to be understood to ensure reliable readings are obtained. Prior to installation saturation and de-airing of the monitoring device is required and this saturation needs to be maintained during installation of the device into the response zone. Careful cleaning and successive removal of the borehole casing is needed to ensure a secure installation.
To ensure the piezometers function adequately a response test is required following installation. This follows the procedures for in-situ permeability testing (GEO, 2000) and can be a falling or rising head test depending upon the permeability of the surrounding ground. If the permeability determined from the test is similar to that inferred from the logging the installation is considered to be successful.

4.1 Standard installation

The piezometer is usually placed into a "sand filter" response zone, sealed within bentonite plugs with the remaining borehole infilled with grout.

The response zone - needs to be at least four times the hole diameter and not less than 0.4m length, typically taken to be 0.5m (GEO, 2000). The filter for:

- *Saprolites and residual soils (derived from in-situ weathering) – comprises washed sand particles of 0.2 to 1.2mm dia. grain size*
- *Coarse transported soils (gravels, alluvium and marine sands) - needs specific design (GEO, 1993)*

The bentonite seal - is a minimum 0.5m length, both above and below the response zone. Time is needed to allow the bentonite to swell prior to grout placement (GEO, 2000).

The grout backfill – typically comprises bentonite cement with a similar or lower permeability than the surrounding ground. The typical Bentonite, Ordinary Portland Cement (OPC) and water mix ratio is 1:8:12 measured by mass. For the grout mix to remain pumpable the bentonite must not exceed 12kg in 100 litres of water. Special mixes are needed for installations in sea or more acidic water. Considerations are needed for the required permeability, type of bentonite, borehole condition, groundwater level, pump-ability and segregation.
The standpipe should have a minimum 19mm inside diameter to prevent air being trapped and allow easy accessibility for the measuring device (dip meter), particularly if there is a slight bend in the pipe.
Multiple piezometers within the same borehole, placed using standard installation methods, are not typically recommended due to the potential migration of groundwater between different monitoring devices and damage to the existing installation from a subsequent installation(s). Close supervision of the workmanship is needed should multiple piezometers be required. The spacing between piezometer tips should account for a 0.5m length sand pocket and 0.5m bentonite seal (GEO, 2000) with a 1m grout separator zone, giving a minimum separation of about 2.5m between piezometer tips.

4.2 Measurement

The water level within a standpipe piezometer is recorded manually, using a dip-meter, or by left in place automatic groundwater monitoring device (AGMD). The following items should be considered to ensure accurate readings are taken:
Agitation of standing water before taking readings, to release trapped gas;
the dip meter should have a sensitivity regulator to allow volume changes to suit water salinity changes;
Check for a splash once the dip meter reaches standing water level to allow a cross check
Measuring devices need to be immersed in electrolytic water to allow signals to be generated. If "Pure, distilled" water is present records cannot be taken.

Water samples can be taken using a bailer.

4.3 Interpretation (installation)

Rapid response times are needed to record rapid changes in groundwater pressure. Figure 3 compares the response times for different piezometer installations.

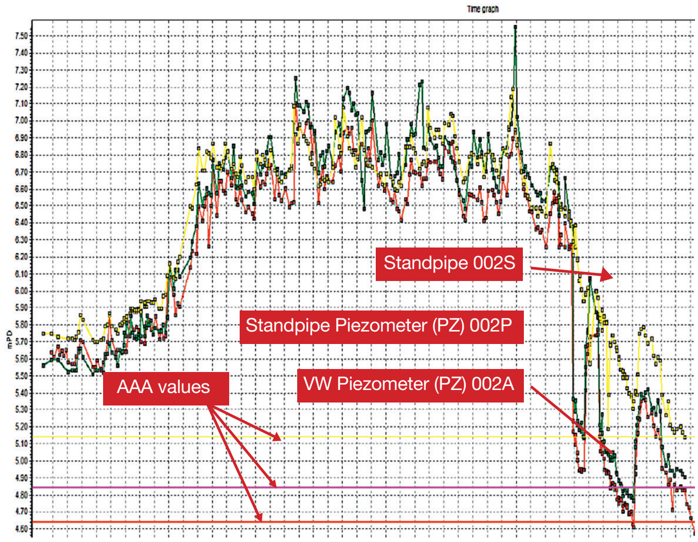


Figure 3 – Fully grouted and traditional installations

The installations recorded groundwater fluctuations in saprolitic granite. Records were taken daily between January and November, 2013 with groundwater levels ranging between 4.6 to 7.5 mPD. Standpipe 002S and Piezometer 002P were installed in the same borehole and Piezometer 002A in a nearby borehole; the installation details are summarised in Table 2.

Table 2: Standpipe and Piezometer installation

Inst. No	RZ depth	RZ type	PZ depth	PZ type
002S	1-10.5m bgs	40mm max. Dia. gravel	10m bgs	Standpipe
002P	25-30.2m bgs	Sand filter	29.5m bgs	Standpipe PZ
002A	NA	B/C/W 0.4:1.6:6	29.5m bgs	Diaphragm (VW PZ)

m bgs - metres below ground surface; NA – not applicable

The piezometers were installed at similar levels and therefore experience similar groundwater fluctuations during periods of intense rainfall. The fully grouted piezometer however had a more rapid response time and dissipation rate than the standpipe piezometer.
The rate of response from records taken over 15 minutes intervals from an AGMD placed in a standpipe piezometer are shown in Figure 4 (Mackay et al, 2008).

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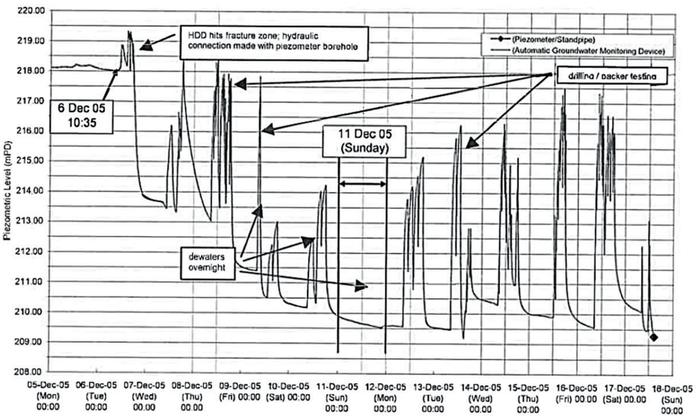

Figure 4: "Real time" groundwater monitoring.

These groundwater fluctuations were generated by water flush used to advance a nearby horizontal drillhole. As shown the responses were recorded instantaneously.

5. HYDROGEOLOGICAL CONSIDERATIONS

The monitoring device and installation needs to account for the hydrogeological condition and feature to be monitored. The type and number of piezometers and response zone location is established from representative hydrogeological models used to determine the installation, further refined after detailed logging has been carried out. Hydro-geological conditions may have the following influences (GEO, 2007 and Mackay, 2008):

- *Groundwater variability - typically caused by highly transmissive pathways, such as soil pipes, open discontinuities and coarse grained infill;*
- *Pore water pressure variation - from perching, confinement or damming resulting from the presence of relatively impermeable barriers such as decomposed dykes, faults and man-made effects like retaining walls or foundations, and*
- *Environmental - such as precipitation and infiltration due to changes in climate and vegetation; annual variations in precipitation; seasonal climatic effects, resulting from individual rainstorms; and variations in infiltration due to factors such as hill fires, bioturbation, stress relief and opening of fissures.*

Hydrogeological processes potentially requiring monitoring are presented in a schematic model of a cut slope in Figure 5 (Hencher, 2000).

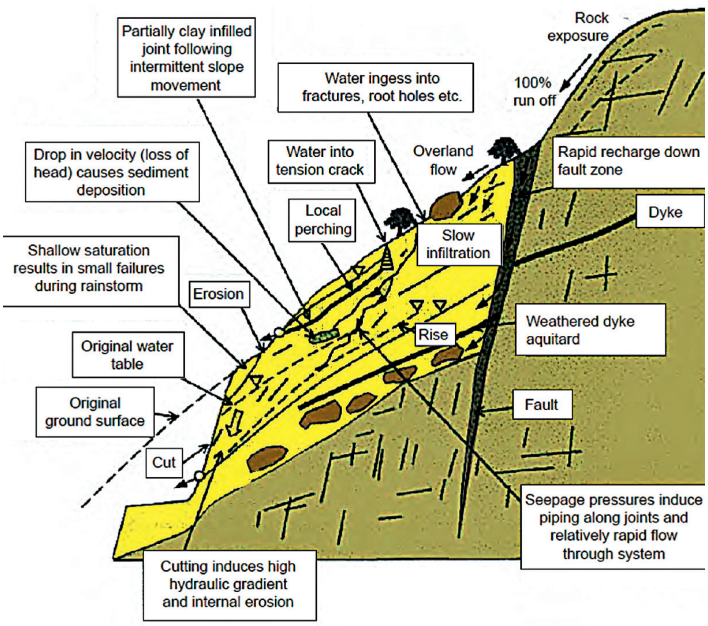

Figure 5: Hydrogeology affecting groundwater

Potential locations requiring groundwater pressure monitoring based on the examples shown above may include:

- *Upslope and downslope of steeply inclined geological features with potential aquitards.*
- *Within discontinuities, which may potentially be high cleft-water pressure during rainstorms,*
- *Within permeable zones in the weathering profile, which may include Grade III/IV materials (perched or confined groundwater).*
- *Directly above low-angle clay-infilled discontinuities saprolite / superficial deposit interface, allowing potential perching.*
- *Below the rock to soil interface; potential confined groundwater.*

6. EXAMPLES OF MONITORING SITUATIONS

Monitoring devices used for different hydrogeological and monitoring situations are summarised below:

6.1 Slopes

Figure 6 shows decreases in response to rainstorms with increased depth in completely decomposed granite (CDG) and perched water with rapid response to rainfall in the overlying colluvium (GCO, 1982).

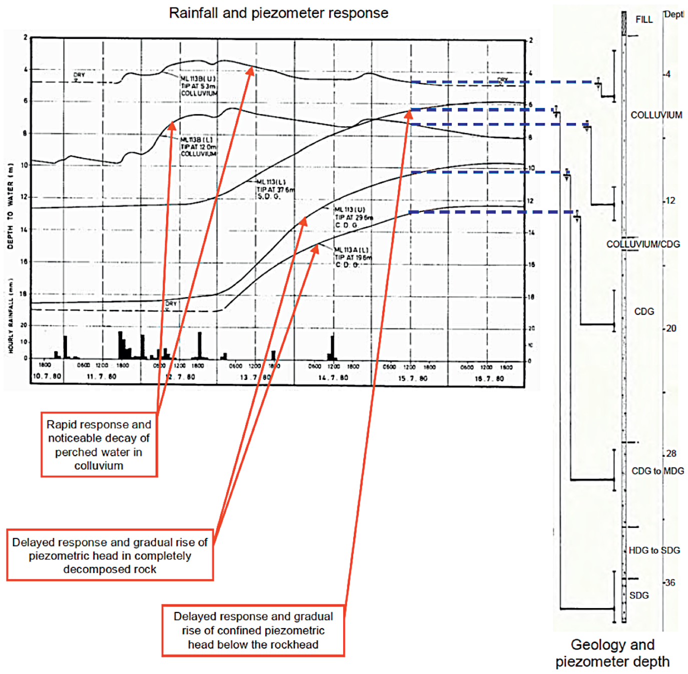

Figure 6: Response zone variations.

Rock slopes typically have a high degree of hydrogeological variability dependent upon the discontinuity characteristics, such as spacing, persistence, orientation, type and thickness of infill, openness and connectivity with the ground surface and / or aquifers and partial weathering effects. An example of the hydro-geological variability in rock slopes is given in Figure 7 (Cowland and Richards, 1985).

Eight piezometers (SP1 - 8) were installed to target sheeting joints (persistent joints formed from stress relief effects such as erosion). As the response periods were anticipated to be rapid and along planar zones, diaphragm piezometers were installed. During intense rainfall periods the hydro-geological variability was revealed by:

- *zero groundwater fluctuation (SP8),*
- *immediate rise (SP3), and*
- *delayed responses ranging from 10 hours (SP7) to 30 hours (SP9).*

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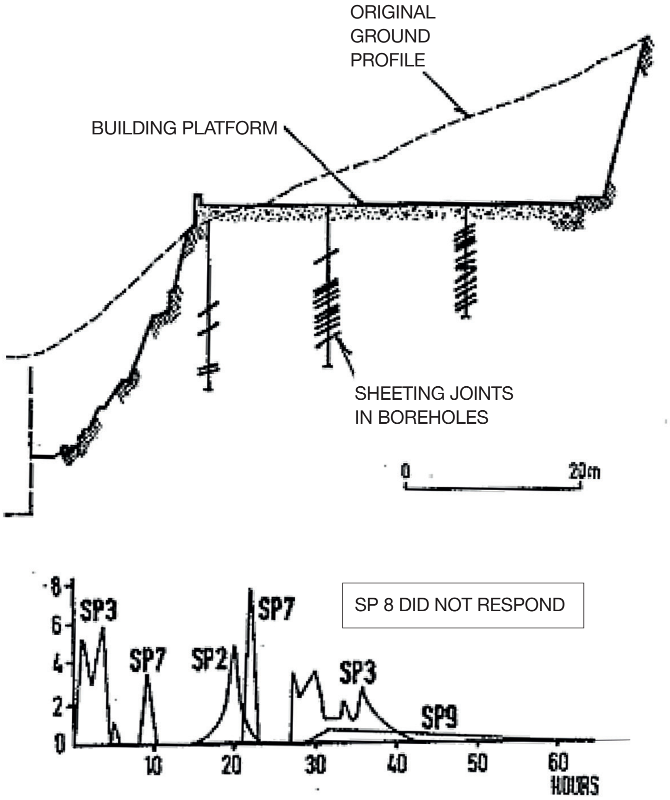

Figure 7: Groundwater responses in rock.

The tunnel excavation progressed from west to east with an excavation cycle comprising probing, grout injection and drilling and blasting. Increased, pronounced rises and falls in groundwater levels were recorded in PZ 1 and 2 when the tunnel excavation was in close proximity (see Figure 9)

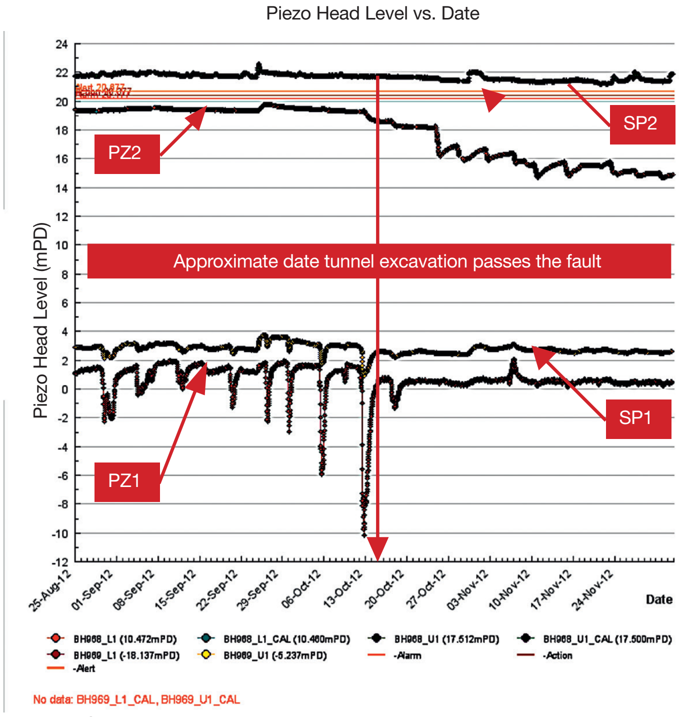

Figure 9: Groundwater level verses real time.

6.2 Sub-surface excavation

Sub-surface excavation, such as tunnels, caverns and deep excavations, can initiate groundwater drawdown. Ground water cut off, typically by grout injection, is therefore needed to mitigate these effects, the reliability of which is monitored by piezometers.

Detailed groundwater records were taken from a drill and blast tunnel excavation through complicated ground for the Harbour Area Treatment Scheme, Cyberport section (Maxwell, A., 2012). Refer to Figure 8 for the relative locations of the tunnel alignment, Boreholes (BH1 and 2), with piezometer (PZ) installations and a sub-vertical fault.

Both BH 1 and 2 had standpipe (SP) and piezometer (PZ) installations located towards the upper and lower borehole levels respectively. PZ 1 and 2 were installed immediately above the tunnel crown level.

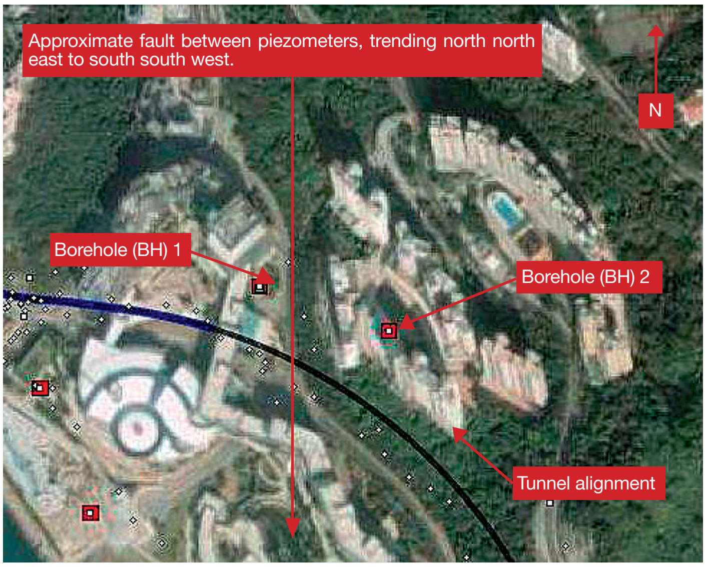

Figure 8: Piezometer, fault and tunnel locations.

The fault formed an abrupt boundary between rock, moderately decomposed tuff (MDT) to the east (BH 2), and soil, completely decomposed tuff (CDT) to the west (BH 1). The different effects this had on the groundwater drawdown and recharge from the probing and grout injection excavation cycles are summarised in Table 3.

PZ	Installation in	Influence on groundwater level from	
		Probing	Grouting
1	CDT (soil)	immediate drawdown	immediate recharge
2	MDT (rock)	Delayed drawdown	Minimal recharge

Table 3: Evaluation of Piezometer Types

The difference in groundwater fluctuations from the probing and grout injection influences occurred from:

- *PZ1 (CDT); groundwater flow and grout injection into homogenous ground conditions, allowing flow in multi directions;*
- *PZ2 (MDT); groundwater flow restricted to a dominant discontinuity set, aligned sub-parallel to the fault; restricting flow to one direction and preventing flow west of the fault*

6.3 Reclamation

Reclamations require pore water pressure monitoring to check increases induced by loading during reclamation placement. A large number of piezometers were installed for the Chek Lap Kok (CLK) Airport reclamation (Plant et al, 1998). The piezometers, installed in "clusters", included:

- *Diaphragm piezometers to provide rapid pore water pressure responses;*
- *Casagrande piezometer to provide more robust piezometric data, and*
- *An inclinometer / extensometer located centrally to compare displacement with pore water pressure changes.*

Intermediate piezometers were also installed and spacing reduced in areas located beneath structures sensitive to differential settlement and in areas with geological conditions more prone to settlement.

(Special thanks to Ms Ada Chan and Mr Sandy Mackay for preparation of this guideline)

7. RELEVANT CONTRACTUAL CONSIDERATIONS

Given the complications of obtaining reliable groundwater records, particularly recording rapid increases in levels during heavy rainfall, stringent monitoring requirements are typically set out. A summary from documents typically used in Hong Kong is shown below:

Mass Transit Railway Corporation (MTRC) Material and Workmanship (M&W) specifications; GEO, Landslip Preventive Measure (LPM), Ground Investigation (GI) Specification

Include provisions for installation methods, calibration, record presentation, post installation acceptance and monitoring frequency

Practice Notes for Authorised Persons (PNAP) 132 for private works, or equivalent government and MTRC practice notes.

Typically state the need for a "Competent Geologist" for borehole logging prior to the installation.

Code of Practice (CoP) for Foundations, 2004, BD, and MTRC New Design Works Manual

This provides robust assumptions for foundation and deep excavation design; including buoyancy requirements taken to be either the "Highest Anticipated Groundwater Level", or in the absence of reliable data the "Highest Possible Groundwater Level" which is taken to be the level the groundwater would rise to under all possible extreme events, generally taken to be the ground surface.

Building Department PNAP – APP 109 (private works) and equivalent Environment and Transport Works Bureau (ETWB, government works).

The design requirements for slope upgrading works note the Factors of Safety (FoS) to be 1.1 to 1.2 for "existing" slopes, provided that rigorous studies of the groundwater regime has been carried out and that this has remained substantially the same over time. If rigorous studies have not been carried out the FoS is increased to 1.4.

8. DATA RECORDING

Piezometric monitoring data needs to be effectively used through a specified and agreed monitoring process. It is vital that rapid data transfer be effectively made to interested parties and that pre-determined actions be taken should the agreed Alert, Action and Alarm (AAA) threshold values be exceeded. The AAA values may be adjusted as further data becomes available during the monitoring and construction process and be determined from the effects of drawdown on EBS or the on-going construction.

An automated wireless system with rapid groundwater monitoring transfer was set up to monitor groundwater drawdown into the Po Shan Road tunnel (see Figure 10, Solomon et al, 2008). As the tunnel was constructed to improve slope stability by lowering the groundwater accurate and rapid monitoring data transfer was vital to ensure the hillside remained stable (Mackay et al, 2015). Data loggers were installed to provide transfer to a central base station and automated groundwater control was carried out by adjusting flow through the vertical drains (See Figure 11, Mackay et al, 2015).

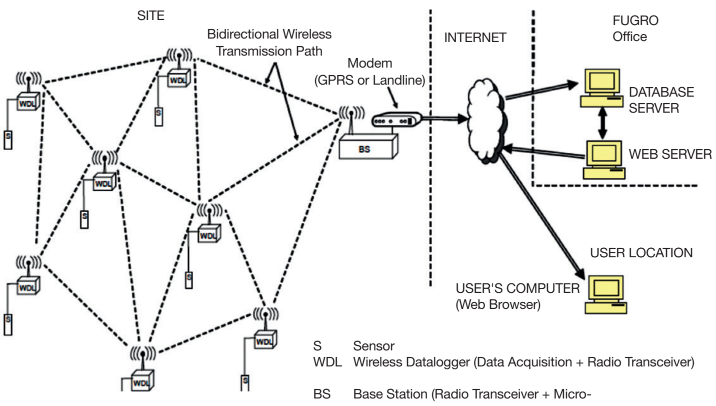

Figure 10: Automated Wireless monitoring.

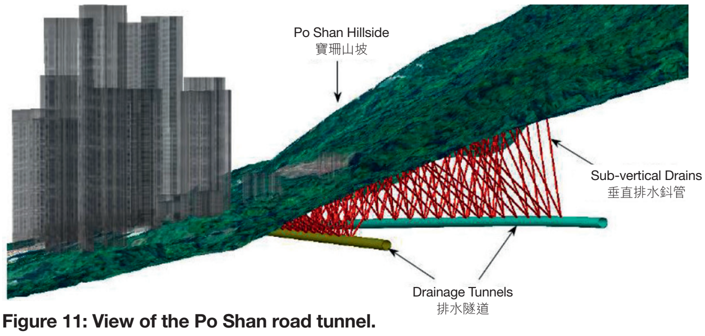

Figure 11: View of the Po Shan road tunnel.

9.SUMMARY

Groundwater pressure monitoring is required to varying frequencies, intensity and levels of detail for construction work in Hong Kong. The installation method and hydrogeological condition targeted is of prime importance. The data can be required over long periods lasting from site access to post construction and maintenance. The reliability of the data often depends upon the care of installation and the use of the appropriate groundwater pressure monitoring devices.

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