Enhancing Pore Water Pressure Monitoring by Fully Grouted Piezometers: A Case Study of Crossrail and Prospects of Application in Hong Kong

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ABSTRACT

This paper presents a comprehensive case study on pore water pressure measurements using fully grouted piezometers for London Crossrail project, focusing on the insights gained and exploring their potential applications in Hong Kong. Multi-level vibrating wire piezometers, strategically placed in single boreholes fully backfilled with carefully designed cement-bentonite grout, were deployed in a 'greenfield' research site in Hyde Park, London, anticipating the passage of two earth pressure balanced tunnel boring machines (EPBMs) constructing twin-bore Crossrail tunnels through London Clay. The performance of these fully-grouted piezometers are discussed, while presenting the pore water pressure measurements in low-permeability ground before, during and after Crossrail tunnel construction. It is evident from the steady-state measurements that there exists an under-drained steady-state pore water pressure profile within the low-permeability ground separating the upper and lower aquifers, also being influenced by a nearby London Underground tunnel. During the EPBM passage, these fully-grouted piezometers were capable of reliably measuring the rapid response of pore water pressure. The advantages and practical challenges of employing fully-grouted piezometers for pore water pressure monitoring are explored, accompanied by their potential applications in Hong Kong, particularly reclamation and deep excavations in low-permeability ground. This paper shares perspectives on enhancing the reliability and benefits of pore water pressure measurements for civil engineering projects in Hong Kong.

1 INTRODUCTION

Standpipes and piezometers have widely been used for monitoring groundwater levels and pore water pressures for civil and geotechnical engineering projects in Hong Kong and overseas. The most common type of piezometer used in Hong Kong is open-hydraulic standpipe piezometers with a Casagrande-type piezometer tip. Typically, standpipe piezometers are installed in a borehole with the piezometer tip embedded in a granular filter response zone between bentonite seals.

Forming an effective seal to the response zones is crucial to the performance of the piezometer. In practice, the seals are formed by backfilling bentonite balls or bentonite pellets into the borehole with a minimum 500mm thickness beneath and above the response zone (which itself is formed by backfilling a sand pocket around the piezometer tip). To ensure an effective seal, sufficient time should be allowed for the swelling action of the bentonite pellets before bentonite-cement grout is placed in the remaining section of the borehole.

Because of the need for effective seals, it is not normally desirable to install more than two response zones in a single borehole. Geoguide 2 (GEO, 2017) highlights this practical constraint in relation to the typical installation method: "*Poor sealing of the piezometer will permit the migration of water from one level to another, and may render the readings meaningless. The installation of more than one piezometer in a single borehole is not generally recommended. If two piezometers are placed in a single hole, great care must be taken to achieve proper seals.*"

The use of vibrating-wire (VW) piezometers has become increasingly popular thanks to recent advances and improved performance of VW instrumentation. The authors observe that in Hong Kong the current practice of installation of VW piezometers in boreholes appears to mostly involve the traditional method of creating

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granular response zones and bentonite seals, with the VW piezometer sensor either simply being lowered within a standpipe (Figure 1a) or directly embedded in the granular response zone (Figure 1b).

For the traditional method of piezometer installation, the restriction of no more than two response zones in a single borehole remains. Furthermore, if a standpipe is used to host the VW sensor, the response time of the pore water pressure measurement is greatly increased, especially in low-permeability ground, as a significant volume of water flow into the standpipe is needed for the sensor to register the pore water pressure in the ground (which is balanced by the hydrostatic pressure in the water column by the raised water level inside the standpipe).

It has been demonstrated through analytical (Vaughan, 1969) and numerical analysis (Contreras et al., 2008) that for the operation of diaphragm (including VW) type piezometer devices, theoretically the presence of a granular filter response zone is not necessary and the piezometer sensors can be installed by grouting the borehole fully with a grout of suitable permeability (Figure 1c). The fully-grouted method, having a major advantage of the straightforward backfilling procedure, eliminates the need for granular filters and bentonite seals and hence all the associated restrictions. This allows multi-level (more than two) VW piezometer sensors to be installed in one single borehole, and makes it possible to obtain a higher-spatial-resolution pore water pressure profile with depth at the same location, significantly reducing the number of boreholes required and hence the costs. In addition, the VW piezometers fully grouted in a borehole have a rapid response time, which means that measured pore water pressure response to the stress changes in the ground is usually near instantaneous, even in low-permeability ground.

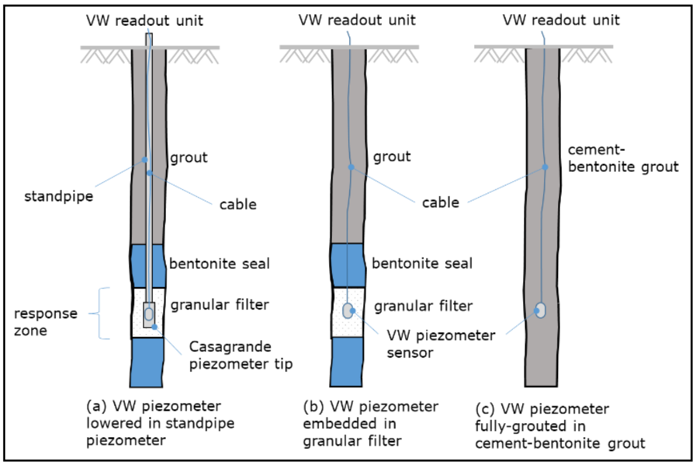


Figure 1: Traditional and fully grouted piezometer installations in boreholes

Despite the benefits, there appear to be only limited applications of the fully-grouted method of VW piezometer installation in Hong Kong. Laver (2020) reported such an application for the cofferdam water drawdown monitoring in the Hong Kong Boundary Crossing Facilities reclamation project, but much wider use of fully grouted piezometers should be welcome and encouraged.

2 FULLY GROUTED INSTALLATION OF VW PIEZOMETERS

The VW piezometers contain a diaphragm sensor which requires only a very small amount of water flow for pressure equalisation and to operate. These devices are therefore suitable for installation in a borehole fully grouted with cement–bentonite grout of suitable permeability, as the grout can transmit this volume of flow over a short distance from the ground to the sensor tip quickly.

2.1 Bentonite cement grout as a filter and a seal

In order for the fully-grouted VW piezometer to measure the pore water pressure in the ground accurately and effectively, the grout in the borehole shall act as both a filter in the radial (horizontal) direction and a seal in the vertical direction. This is so as not to adversely affect the horizontal flow of water to the piezometer and so as to prevent significant vertical flow along the borehole (EN ISO 18674-4:2020), and can be achieved by controlling the relative permeability of the grout to the ground.

Based on the work of Vaughan (1969) and Contreras et al. (2008), the error of pore water pressure measurement induced by the vertical water flow within the grout column is insignificant if the permeability of the grout is no more than 100 to 1000 times the permeability of the ground. For instance, for a typical silty or clayey soil with a coefficient of permeability in the order of 10^{-10} m/s, a backfill grout with a coefficient of permeability up to 10^{-7} m/s can be used. In practice, this order of grout permeability can be readily achieved by bentonite cement grouts of a typical range of mix ratios that is also pumpable into a borehole through a standard tremie pipe. On the other hand, it should be noted that when the grout is less permeable than the ground, response time of the measurement is increased. However, the delay in response time should not be significant for a small diameter borehole.

2.2 Grout requirements – permeability and viscosity

The grout mix shall be designed before installation, with the grout permeability and viscosity being the key properties to consider. Whilst the former is essential for ensuring the functionality as a filter and a seal, the latter is important to ensure the grout (a) is thin enough to be pumped into the borehole and (b) is thick enough to avoid excessive grout loss into the ground, especially in high-permeability soil/jointed rock. As a starting point, there are guide grout mix ratios published in standards (e.g. EN ISO 18674-4) and case histories (e.g. Mikkelsen & Green, 2003). It is strongly recommended that a site trial of the grout mixes based on the design is undertaken before the installation, because the grout properties are sensitive to the mixing environment (e.g. temperature) and procedure (e.g. mixing sequence and duration). The grout mix trial should use the same materials, mixing equipment, mixing sequence (add water to the cement first, before adding bentonite), and mixing environment (e.g. ambient temperature and humidity). The trial should ideally also test the grout pumpability using the same grout pump to backfill a borehole of similar depth. The grout pump should be powerful enough to pump the grout into the bottom of the borehole by tremie method and rise the wet grout to ground level. A borehole not hosting any instrument within the same ground investigation contract would be most suitable for the grout trial. As a minimum, the grout viscosity shall be measured by marsh funnel test on site. Grout cylinder samples shall be made for testing the permeability at 3, 7 and 28 days in laboratory.

2.3. Benefits and limitations

The most practically significant benefit of fully-grouted VW piezometers is its simple, economical, and rapid installation process, allowing multi-level installations in a single borehole saving significant borehole drilling cost. VW piezometers enables fast response time even in low-permeability ground. Since VW sensors measure the frequency of the vibrating wire instead of the amplitude of the electrical signal, the measurement readings are not affected by cable electrical resistance, making the depth of sensors not a technical limitation. VW piezometers can measure small suction so long as all parts of the piezometer system remains saturated, and the use of bentonite cement grout enhances the suction measurements with its ability to sustain hydraulic tensions without desaturation up to a suction pressure of 100 kPa (Ridley, 2015). In traditional installation method involving granular response zones, the piezometer elements embedded in a clean sand pocket would readily desaturate when in touch with soil even with a small suction.

One drawback of VW piezometers in practice, full-grouted or not, is that they, being a closed system, cannot be de-aired once installed (unless for a special flushable type), and therefore care must be taken in ensuring full saturation of the VW sensor (including the reservoir and porous filter) during and post installation. As with all closed systems, VW piezometers measure absolute pressure including the barometric pressure. This is not entirely a limitation but it means that with independent barometric measurements it is possible to validate and correct the piezometer readings.

3 CROSSRAIL CASE HISTORY

Dunnicliff (2008) and Contreras et al. (2008) reported successful installation and monitoring of VW piezometers installed by the fully-grouted method at various sites around the world. More recently, Wan & Standing (2014) and Wan et al. (2019) reported a comprehensive case history of the installation and monitoring of multi-level fully-grouted VW piezometers for the Crossrail project where twin running tunnels were constructed in over-consolidated stiff clay (London Clay Formation) by two EBPMs.

3.1 Crossrail tunnelling work and research instrumentation site

The research site at Hyde Park, London was set up close to where the Crossrail tunnels pass beneath the existing tunnels of the London Underground Limited (LUL) Central Line. The exact location of the crossing is beneath Bayswater Road, which runs alongside the northern boundary of Hyde Park. The relative position of the tunnels is shown in Figure 2 and their respective axis depths are about 24 m (Central Line) and 34.5 m (Crossrail) below ground level (mbgl). At the site, the two Crossrail tunnels are about 16 m apart between their tunnel axes. The twin tunnels were constructed by two EPBMs with excavation diameters of approximately 7.1 m. Both the westbound and eastbound tunnels were constructed with 6.2m internal diameters (6.8m external diameters) bolted precast concrete segmental lining. The tunnel lining comprised seven segments plus a small key and had a nominal length of 1.6m.

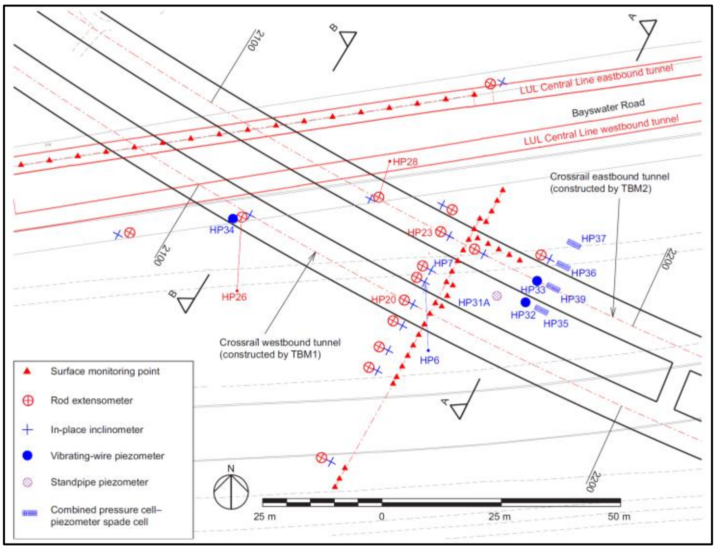


Figure 2: Location plan and instrumentation layout plan of Hyde Park instrumentation site (Wan et al., 2019).

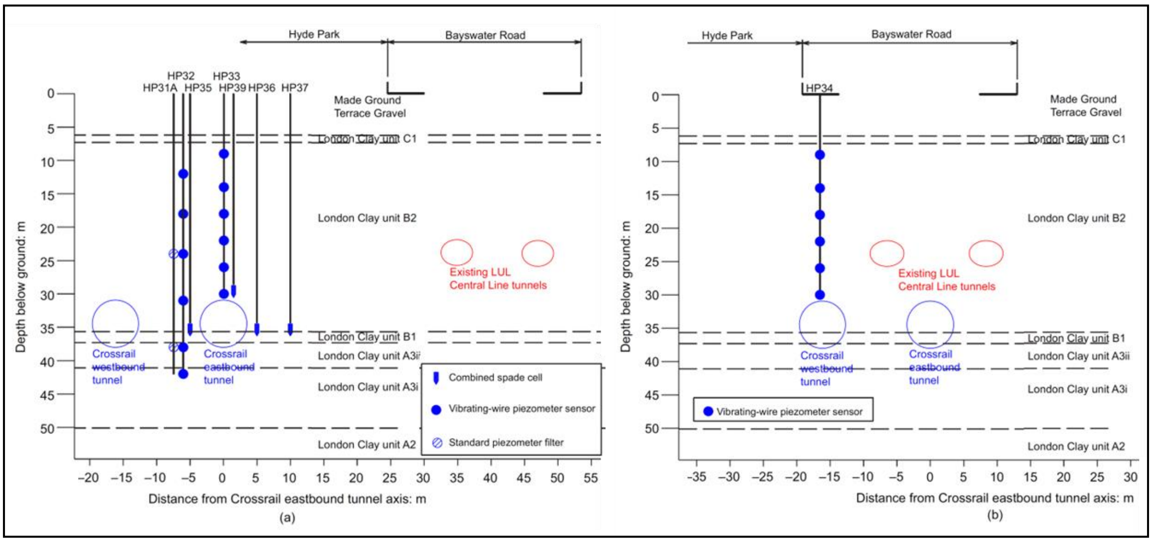


Figure 3: Cross-sections of piezometers installed: (a) cross-section A–A: piezometers in 'greenfield' ground; (b) cross-section B–B: piezometers in the vicinity of the existing LUL running tunnels (after Wan et al., 2019).

The EPBMs for the westbound and eastbound tunnel construction under-passed the instrumentation site in November 2012 and February 2013 respectively. Since then, the instrumentation has been retained and measurements continued. The measured immediate ground response to the EPBM tunnelling have been presented, interpreted and discussed in detail in three papers (Wan et al., 2017a, 2017b, and 2019). The results of the on-going post-construction monitoring of the same instruments are presented and discussed in Wan et al., 2021. The piezometer installations and their pore water pressure measurements are highlighted in this paper.

3.2 Ground conditions

A typical London Basin stratigraphy was found at the Hyde Park site with made ground and Terrace Gravels overlying the descending sequence of the London Clay Formation (LCF), Lambeth Group, Thanet Sand and

Chalk bedrock. Two aquifers are present at the instrumented site - the Terrace Gravels constitute the upper aquifer, and the combined lower granular units of the Lambeth Group (Upnor Formation), the Thanet Sand and Chalk the lower aquifer. These aquifers are separated by the LCF and, if present, the upper and lower mottled beds of the Lambeth Group.

3.3 Types of piezometers installed

As shown in Figure 2, there are in total 38 boreholes with each borehole accommodating one or more instruments for ground movement, total stress and pore water pressure monitoring. Eight of the boreholes were for pore-water pressure measurements. Among other instruments, piezometers and combined total stress-piezometer spade cells were installed around the Crossrail tunnel alignments to measure the pore pressure and total stress response resulting from the new tunnel construction. At locations within Hyde Park, the piezometers and spade cells were installed, as shown in Figure 3(a), with the pressure sensors located at various distances vertically and horizontally around the Crossrail eastbound tunnel. Multiple piezometers were installed within a borehole on Bayswater Road, above the Crossrail westbound tunnel, to investigate the effect of the existing Central Line tunnels on pore-water pressures prior to, during and after tunnel construction (Figure 3(b)).

Figure 4 shows the three types of piezometers in the Hyde Park instrumentation site. Note that fully-grouted multi-level VW piezometers were installed in three boreholes (HP32, HP33 and HP34), each hosting six VW sensors (Figure 4a). A standpipe piezometer with two response zones were installed in a borehole (HP31A) about 10m away from HP32 (Figure 2 and Figure 4c) for the purpose of comparing and verifying the piezometer readings of the multi-level VW piezometers.

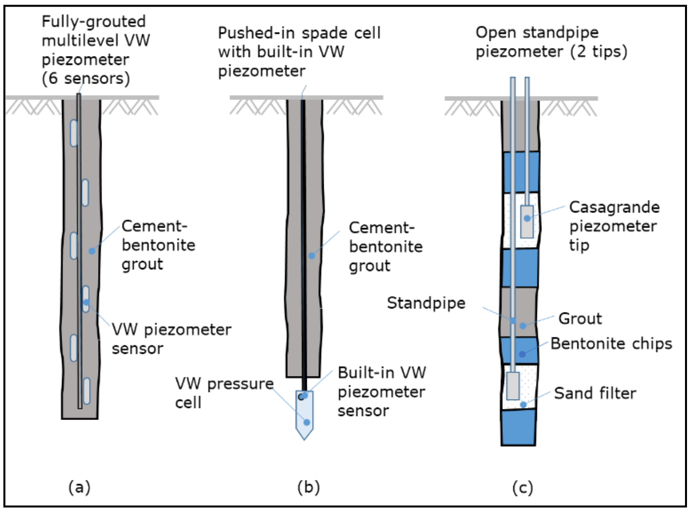


Figure 4: Schematic presentation of three types of piezometers installed at the instrumented site: (a) multi-level VW piezometers in fully grouted borehole (HP32, HP33 and HP34); (b) VW piezometer sensor built in spade-shaped pressure cell (HP35, HP36, HP37 and HP39); (c) conventional standpipe piezometer (HP31A)

3.4 Installation of fully-grouted piezometers

A number of trail grout mixes were undertaken to determine their properties. Four mixes (Mix A to Mix D) were designed with different water/binders ratios aiming to match the permeability of the ground. Laboratory permeability tests were conducted using a triaxial apparatus on cylinder specimens of 100 mm diameter, which were consolidated under different cell pressures before permeability was tested under a constant pressure gradient. The tests were performed in accordance with BS1377, Part 6: 1990, Clauses 5.3, 5.4, 5.5.2.2 to 5.5.2.7 and 6. Table 1 shows the results of the permeability tests on the 4 trial grout mixes.

In the field, falling head tests were performed at the two response zones of the standpipe piezometer HP31A and the results show the coefficients of horizontal permeability at 24.0 mbgl (London Clay unit B2) and 37.0 mbgl (London Clay unit B1/A3ii) of 1.2×10^{-9} m/s and 1.6×10^{-11} m/s respectively.

Grout Mix B has a measured coefficient of permeability of up to 1.5×10^{-9} m/s which is of similar permeability of London Clay unit B2 and about 100 times more permeable than London Clay unit B1/A3ii. Considering the sealing requirement, design grout Mix B was selected for backfilling the fully-grouted piezometers. A trial tremie operation using Mix B was also carried out to backfill a 40m deep borehole at the same site to ensure the pumpability of the grout.

Table 1: Results of permeability test in triaxial apparatus on trial grout mixes

Mix no.	A	B	C	D
Mix proportion by mass (water: cement: fly ash: bentonite)	2.5: 1.0: 0.0: 0.74	2.0: 1.0: 0.0: 0.5	4.0: 1.0: 0.5: 1.0	2.5: 0.8: 0.9: 0.55
Sample void ratio	3.57	2.84	3.72	2.34
(Confining pressure: kPa) Coefficient of permeability: m/s	(200) 6.3×10^{-9}	(200) 1.5×10^{-9}	(100) 9.4×10^{-9}	(200) 1.3×10^{-10}
	(400) 4.4×10^{-9}	(400) 1.2×10^{-9}	(200) 6.0×10^{-10}	(400) 7.0×10^{-11}
	(600) 3.7×10^{-9}	(600) 8.9×10^{-10}	(300) 4.2×10^{-10}	(600) 6.0×10^{-11}

3.5 Pore water pressure measurements - steady state before Crossrail tunnel construction

The steady-state pore water pressures measured by the VW piezometers and standpipe piezometers over one year after the installation and just before the Crossrail tunnel construction (September 2012) are presented in Figure 5. During borehole drilling for the installation of the instrumentation, the upper water table was established to be about 4–5 mbgl within the Thames Gravels. In Figure 5, a hydrostatic pressure line with a water level at 5 mbgl is drawn as a reference line to compare with the pore water pressure measured by the various piezometers.

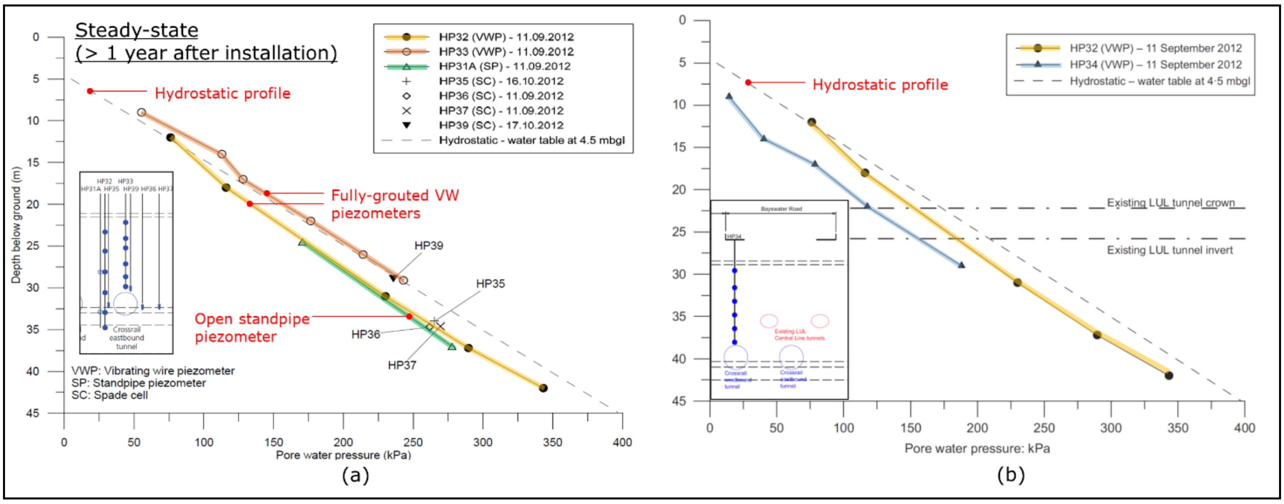


Figure 5: Steady-state pore water pressure profile measured before Crossrail construction (a) ‘Greenfield’ - Section A-A of Figure 2; (b) Near pre-existing LUL tunnels - Section B-B of Figure 2 (after Wan et al., 2019)

Typically in central London, the LCF is under-drained due to excessive abstraction activities in the early 1900s. In Figure 5a, the pore water pressure profile measured by the ‘greenfield’ multi-level VW piezometer (HP32) clearly demonstrates the LCF was under-drained. The adjacent standpipe piezometer (HP31A), at two response zone levels, verified the under-drained profile observed by the multi-level VW piezometers HP32.

It is worth noting that the other ‘greenfield’ VW piezometer (HP33) does not show the same under-drained profile but one that is closer to a hydrostatic profile. This has been interrogated in detail by Wan & Standing (2014) which found that there appears to be interconnectivity between the lower three sensors within the fully-grouted borehole. It is speculated that some grout loss might have occurred during the piezometer installation due to the concentrated presence of claystones in LCF at the horizons of these sensors. As a result, the seal between the lower three sensors may be compromised and therefore they were measuring the same total head.

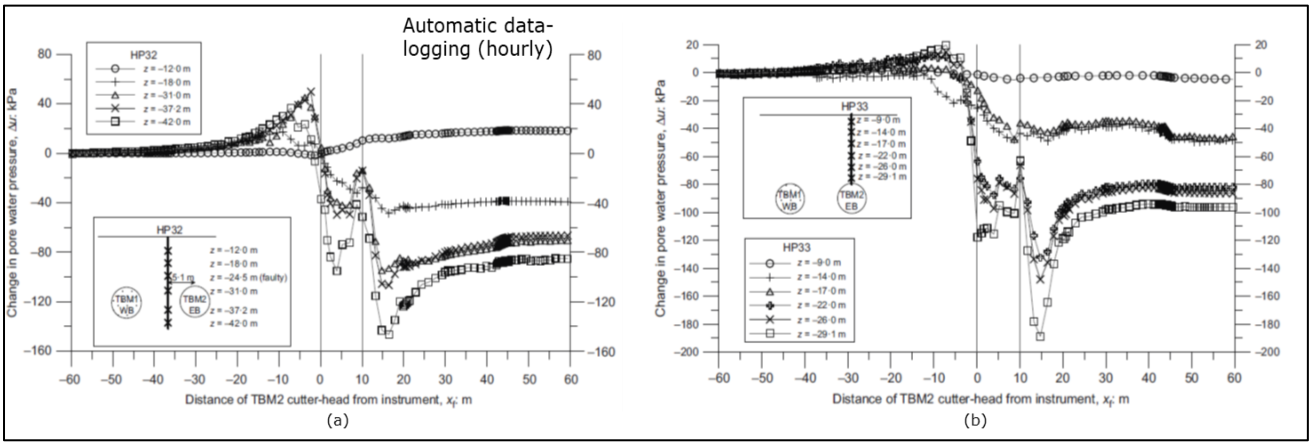
In Figure 5b, the pre-construction steady-state pore water pressure measured at the multi-level piezometer HP34 located about 5 m from the existing Central Line westbound tunnel was shown to be less than for the nearby ‘greenfield’ ground. This is a clear indication that these existing tunnels, with cast-iron segmental linings, drain the surrounding London Clay ground after being constructed in early 1900s. (Wan et al., 2019; Wan & Standing, 2014).

3.6 Pore water pressure measurements – immediate response during Crossrail tunnel construction

During Crossrail tunnel construction, all the VW piezometers, including both the fully-grouted sensors (HP32, HP33, HP34) and pushed-in combined cells (HP35, HP36, HP37, HP39), registered immediate response of pore water pressure changes as each of the two EPBMs passed the instrumentation site. All these VW piezometers were connected to a datalogger housed in the headworks of each borehole which read and logged the piezometer readings every hour automatically. The multi-level fully-grouted piezometer installations in HP32 and HP33, being closest from the eastbound tunnel construction, registered the most prominent response as the EPBM approached, passed and left the instruments (Figure 6).

At the instrumentation site, the eastbound EPBM advanced with an average rate of 35-40 m/day, or about 1.4-1.6 m/hr. As can be seen from Figure 6, the measurable pore water pressure changes started at about 40m ahead of the EPBM cutterhead and the measured pore water pressure stabilised after the cutterhead had left and was about 40m away from the instruments. This means the piezometers were within the passing EPBM's zone of influence for about 2 days only.

In general, five stages of pore water pressure changes (3 rising stages and 2 dropping stages) are observed in the ground in close proximity of the passing EPBM. Wan et al. (2019) interpreted and related the observed pattern to the different EPBM operations (including shield overcutting, tail grout application and tail void closure) and a soil arching mechanism that forms around an advancing shield. Due to the overall unloading of the ground by the tunnelling works, net changes of pore water pressure up to -100kPa (unloading) were measured at the VW piezometer sensors in HP32 and HP33 closed to the tunnel construction.



(a) (b)

Figure 6: Change in pore water pressure measured in piezometers (a) HP32 and (b) HP33 in response to eastbound tunnel construction (after Wan et al., 2019)

The clear pattern of measurement observed was available only because of the rapid response time of the fully-grouted VW piezometers operating in the low-permeability London Clay. It is also worth noting that for the multi-level VW piezometers HP33, even though the lower three sensors appear to be interconnected as demonstrated in the pre-construction measurements (see section 3.5 above), they were still able to register different immediate responses of pore water pressure at the different sensors.

3.7 Pore water pressure measurements – Long-term response post-construction

Monitoring of the instruments continued after the tunnel construction, with the last round of measurements taken in August 2019, about 6.5 years after the eastbound tunnel construction. Figure 7 shows the full histories of measured pore water pressures by the multi-level VW piezometers HP32 and HP33. The events of the westbound and eastbound tunnel construction can be easily identified by the instantaneous changes in pore water pressures (November 2012 and February 2013). The measured pore water pressures at different depths appear to have almost fully equalised (i.e. approaching steady-state conditions) 6.5 years after the tunnel construction. It can be seen that for the ground between the depth of 22 m and 42 m, the pore water pressures were equalising towards values that are lower than their corresponding pre-construction values. Conversely, they tend to equalise towards higher values than the pre-construction values for depths above 18m. However, at these shallower ground levels the pore water pressure could also be affected by the seasonal variation of water level in the upper aquifer. This suggests that the Crossrail tunnels are draining the surrounding ground influencing the pore water pressure distribution up to 9 m above the tunnel crown.

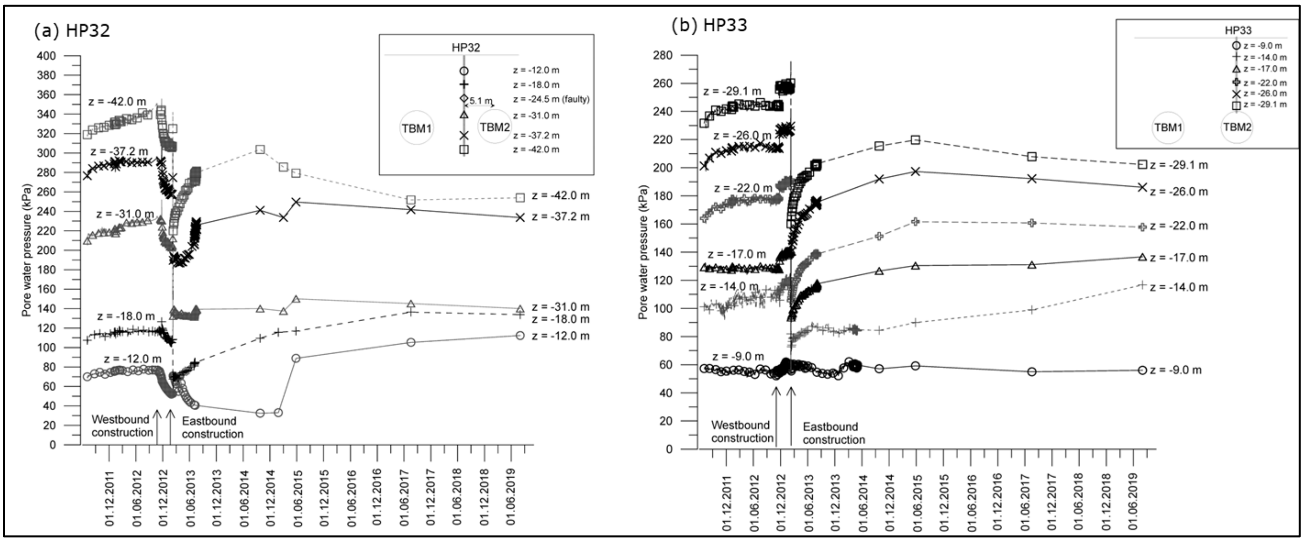


Figure 7: Post-construction pore water pressures measured by multi-level VW piezometers (a) HP32 and (b) HP33 (after Wan et al, 2021)

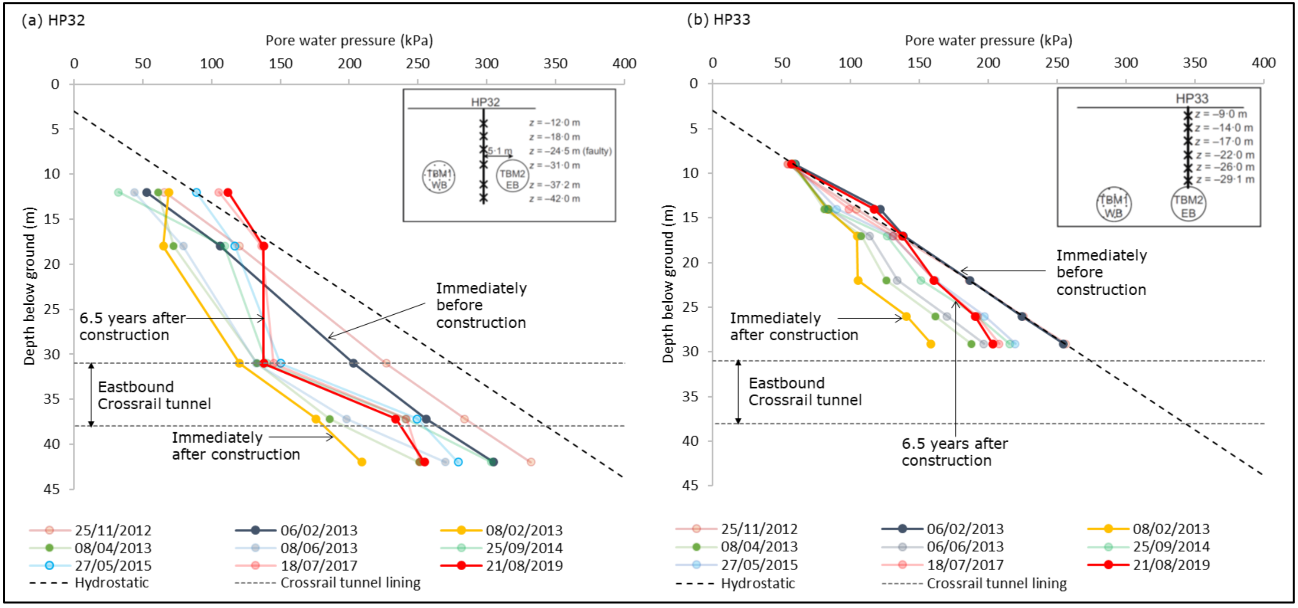


Figure 8: Post-construction pore water pressure profiles measured by VW piezometers (a) HP32 and (b) HP33

The magnitude and extent of the draining effect by the new Crossrail tunnels can be visualised by plotting the development of the measured post-construction pore water pressure profiles in Figure 8. As discussed above, immediately after the tunnel construction up to 100 kPa of negative excess pore water pressure developed due to the overall unloading by the tunnel construction (the difference between the dark blue and the orange profiles). After 6.5 years, the negative excess pore water pressures were measured to have dissipated partially, with the piezometers closest to the tunnel crown level registering the greatest magnitude of residual negative excess pore water pressure. At about 30 m below ground (about 1 m above the tunnel crown), the residual negative excess pore water pressure (difference between the dark blue and red profiles) at 6.5 years after the construction was registered about 80 kPa for both HP32 and HP33.

Because of the waterproof measures especially the presence of the annulus grout around the linings, it seems unrealistic that a significant amount of groundwater is draining into the tunnels. It is possible that groundwater flow could occur via some flow paths longitudinally along the tunnel formed in any gap between the impermeable tunnel lining (including the annulus grout) and the surrounding ground.

In general, the post-construction monitoring demonstrated that the fully-grouted multi-level VW piezometers have performed satisfactorily at least 8 years after installation (n.b. they were installed in the Summer of 2011). Their measurements provided useful insight into the long-term ground response to and the soil-structural interaction with the constructed tunnels. Interestingly, the lower 3 sensors of HP33 seemed to have restored some ability to measure the pore water pressure independently, as the profiles after May 2015 are no longer seen to be hydrostatic.

4 RELEVANCE TO APPLICATIONS IN HONG KONG

4.1 Limited applications of fully-grouted piezometers in Hong Kong

Despite the benefits, there appear to be only limited applications of the fully grouted method of VW piezometer installation in Hong Kong. The authors consider the main reasons for the fully grouted piezometers not gaining popularity in the local ground investigation and geotechnical instrumentation sectors boil down to two key factors: (i) a lack of confidence in the performance of fully-grouted installation and (ii) a lack of appreciation of the benefits that the fully-grouted piezometers could bring to geotechnical projects. More specifically, the followings may have hindered the application of fully-grouted piezometers in Hong Kong:

- A lack of proven records of their performance through well-documented local case histories.
- A lack of quality research on local applications.
- A lack of trusted local guidelines for installation, which would depend on the availability of local case histories and research results.
- A misconception that the hydrogeology in most development projects is always ‘simple’, with experience suggesting that low-permeability soils or isolated aquifers are not often encountered.
- Pore water pressure not often considered a critical monitoring parameter for construction control.

While the Crossrail research work presented in this paper would contribute to a reference of case study, in this section the authors aim to help realise the benefits and potential of the use of fully-grouted piezometers for civil engineering projects in Hong Kong.

4.2 Excavations in reclaimed lands

Land reclamation has played an important role in providing land to support the development of Hong Kong since as early as the 19th century. With Hong Kong’s strategy of increasing land supply and reserves to meet its housing and development needs, reclamation has been revived as one of the means to create land under a multi-prong approach. Soft marine and/or alluvial deposits are often encountered in reclamation works and subsequent development in the reclaimed land.

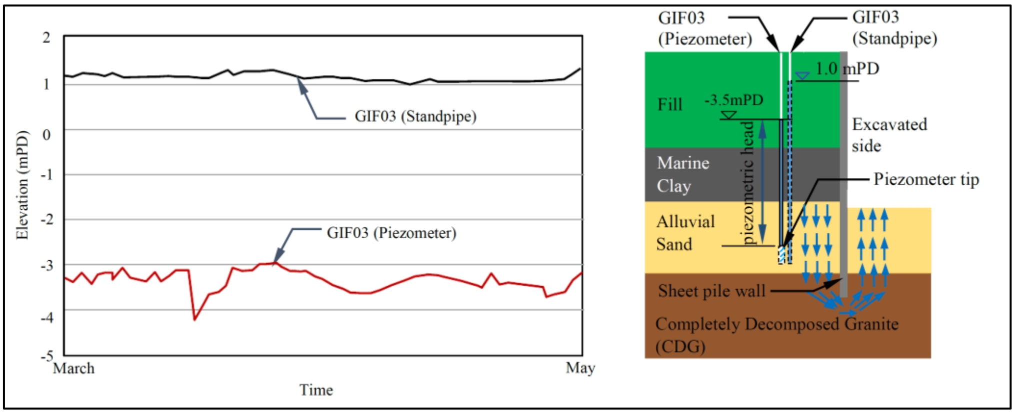


Figure 9: Measured groundwater pressure above and beneath the marine clay layer behind an excavation in reclaimed land in Kai Tak area, east Kowloon, reported in GEO Publication No. 1/2023 (GEO, 2023)

Low-permeability marine mud overlying more permeable alluvial deposits or saprolite is common in both old and recently reclaimed land in Hong Kong. Early reclamations before 1970s were formed mainly by uncontrolled end-tipping of fill placed directly onto the seabed, leaving the marine mud with large mud waves in place (Endicott, 2007; Ng & De Silva, 2007). This low-permeability disturbed marine mud layer with uneven thickness is therefore often encountered and act as an aquiclude in old reclamation areas. Excavations which involve dewatering the confined aquifer (i.e. below the aquiclude) would induce groundwater flow into the excavation around the toe of embedded retaining wall. The groundwater pressure responses behind the retaining wall are separated into two zones by the marine mud: the upper unconfined aquifer without significant seepage; and an underlying confined aquifer with seepage and associated piezometric head drop in the confined aquifer.

The difference in piezometric head across the marine mud layer due to the underdrainage causes consolidation and settlement of the layer, which could in turn cause excessive settlements or damages to structures behind, and even at a far distance from, the excavation.

This is not particularly a new problem unknown to the practitioners and had been seen in the excavation for Chater Station (Davis & Henkel, 1980) and a 90m-deep shaft in Tseung Kwan O (Endicott, 2020). The newly published guidance document GEO Publication No. 1/2023 (GEO, 2023) on deep excavation design and construction has timely reminded and illustrated this mechanism with a recent example seen in an excavation in the Kai Tak area (Figure 9), which resulted in settlements of proximate highway structures. The publication recommends that "*In similar ground and seepage conditions, piezometers should be installed at appropriate depths on the unexcavated sides of the embedded wall (e.g. at a depth below the interface between the permeable and impermeable soils), in order to monitor the changes in groundwater pressure and to facilitate estimation of the potential consolidation settlement.*"

For the traditional piezometer installation method, it is a standard practice that no more than two standpipe/piezometers are to be installed in a single borehole. One of the practical choices that designers have to make is the balance between spatial resolution of piezometers on plan and across depths/strata with a given number of boreholes. For sites with non-uniform stratigraphy, these decisions are not always easy.

In addition, it is not uncommon to find that the piezometric head data obtained with a network of piezometers of low spatial resolution (both vertically and horizontally) difficult to interpret in non-uniform, inhomogeneous ground conditions in a way that could offer meaningful explanations to the observed responses. Sometimes, these measurements that cannot be explained would be treated as 'outliers' and prematurely discarded. This could potentially lead to observations of untoward ground response being overlooked. The value of the monitoring of piezometers is often limited to that for the purpose of directly comparing the measurements with pre-set trigger levels in the instrumentation and monitoring plan.

With the fully-grouted technique, the designers would be able to choose to install multiple piezometers in a single borehole, where necessary. This would greatly enhance the versatility in formulating the instrumentation and monitoring scheme with the aim to collect more extensive data for understanding the site hydrogeology, in particular for sites with complex stratigraphy.

4.3 New reclamations

Non-dredged method has become the de-facto standard practice for reclamations in Hong Kong in light of sustainability considerations. This involves leaving the low-permeability marine mud in place, and improving their mechanical properties to meet the performance requirements of the reclaimed land through various ground improvement techniques. Conventional techniques include perforated vertical drains (PVD) and stone columns. More recently the deep cement mixing (DCM) technique has been successfully introduced in Hong Kong. There are also examples of using low-permeability sediments as the fill materials for reclamation in both local and overseas studies and projects (e.g. Yin et al., 2023; Kitazume, 2016; Karthikeyan et al., 2004 & 2007).

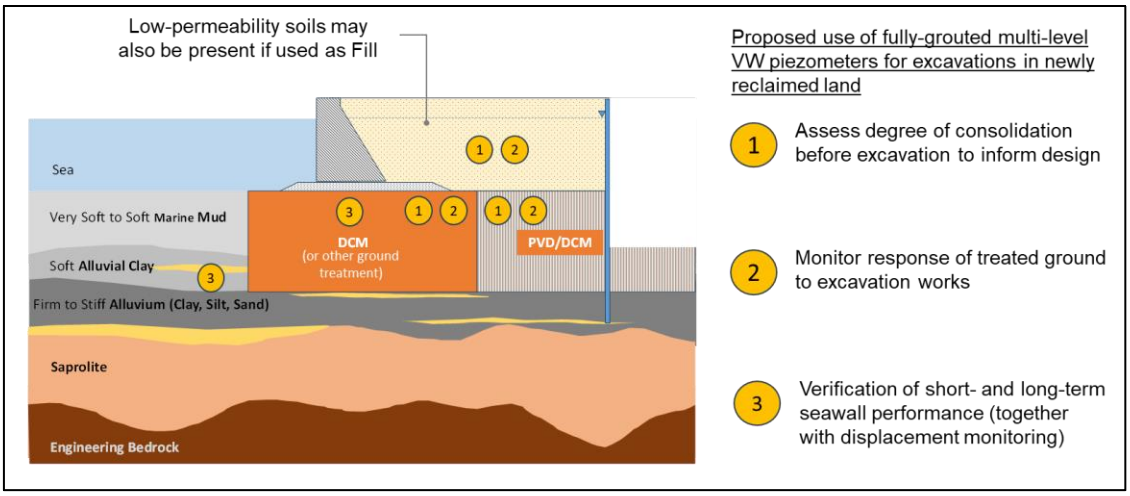


Figure 10: Proposed use of fully-grouted multi-level VW piezometers for construction in newly reclaimed land

The ground improvement and filling works for land formation, as well as any subsequent excavation and foundation works on such land formed, introduce changes to the stress state of these soils. In low-permeability soils, these changes often occur under undrained and subsequently partial-drained conditions, depending on the ground improvement technique used for land formation and the time period concerned for the engineering structures. For instance, the properties and responses to stress changes of soft marine mud improved by conventional PVD with surcharge through consolidation with shortened drainage paths would be very different from those of the same mud between areas replaced by stiff DCM columns, with the latter taking up significant amount of the overburden stress through arching.

Figure 10 presents schematically the typical ground conditions encountered by new (usually non-dredged) reclamations and subsequent excavation works within the reclaimed land. The proposed use of full-grouted multi-level VW piezometers for construction works in newly reclaimed land is also illustrated.

Understanding of the stress state of the treated soft marine mud for the design and construction of excavation and foundations works on the reclaimed land would require knowledge of the actual pore water pressure distribution at the site. For reclamation with PVD, experience has shown that while the overall degree of consolidation might be satisfactorily achieved as indicated by the ground settlements, the dissipation of excess pore water pressures throughout a site could vary, both vertically with depth and horizontally across the site. Slower than expected dissipation of excess pore water pressure or even ‘stagnant’ pore pressures are not uncommon in previous reclamation projects in Hong Kong (Ng & De Silva, 2007). In such cases, simply assuming the marine mud to have fully consolidated could result in an underestimation of the excess pore water pressure and hence an overestimation of its shear strength and stiffness, which could result in geotechnical design not on the conservative side. However, in light of the above-mentioned variabilities, it is often difficult for a designer constrained by the low density of piezometers across the site to fully appreciate the pore water pressure distribution.

Much of the above-mentioned information of pore water pressure distribution may also be obtained by piezometers installed conventionally with granular filter response zones. However, the multi-level, fast-responding fully grouted VW piezometers certainly offer a more versatile and cost-effective tool in the designer’s tool kit. As multiple piezometers can be placed in a single borehole, a higher density of sensors across depths can be achieved with the same number of boreholes. This can provide more complete information to facilitate interpretation of the initial stress state of the soils and their actual responses to the construction works.

4.4 Other applications

Apart from applications in reclaimed land where low-permeability sediments are often encountered, the versatility of installing multiple piezometers in a single borehole could also be useful for measuring groundwater pressure in slopes, in particular where the hydrogeology is complex and/or site access is limited.

5 CONCLUSIONS

This paper has presented a detailed case history of the installation and application of fully-grouted VW piezometers for monitoring the immediate and long-term response of pore water pressure changes to the construction of Crossrail tunnels by EPBMs in London Clay. It has demonstrated the satisfactory performance of these instruments, highlighting the key benefits of the fully-grouted installation in (a) allowing fast, straightforward installation of multi-level VW piezometers in a single borehole, and (b) providing high spatial resolution of fast-responding pore water pressure measurement points in the ground. Because of these benefits, the fully-grouted piezometers offer a cost-effective and reliable tool that is versatile and enables almost-instant measurements of pore water pressure, which is useful for gaining important insights into the responses of the ground with low-permeability soils or complex stratigraphy/hydrogeology to construction works.

In particular, for design and construction of reclamations and deep excavations in reclaimed land, to more holistically investigate the field behaviour of low-permeability soils of substantial thickness during and after reclamation, there is a huge potential of making use of multi-level, fast-responding fully-grouted VW piezometers as part of the instrumentation and monitoring scheme. It would greatly complement other instrumentation such as those for displacement monitoring to enhance both construction control and understanding/verification of the performance of geotechnical structures. Comprehensive and reliable instrumentation and monitoring results are essential when developing and optimising innovative solutions of geotechnical works.

More well-documented local and overseas case histories would help promote confidence and wider use of fully grouted piezometers in Hong Kong. Guidance on the installation of fully grouted piezometers has now been included in the European Standard EN ISO 18674-4:2020. It is suggested that technical research and development on the use of fully-grouted VW piezometers in local conditions are pursued to support development of specific guidelines for Hong Kong practice.

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