An Innovative Design of Retaining Wall in Lung Shan Tunnel Construction

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Abstract

The Heung Yuen Wai Highway opened on 26 May 2019. The 4.8km Lung Shan Tunnel, as one of the main sections of the Heung Yuen Wai Highway, is the longest land-based road tunnel in Hong Kong. It was a success after 5 years of efforts by the project team. Most of tunnel excavation commenced at its Northern Portal near Princess Hill where a mega-sized tunnel boring machine was launched. The original design of the Northern Portal required 3m diameter bored pile walls for supporting a slope cutting to reach the invert level of the tunnel. Early completion of the portion formation works would be essential to accelerating the overall construction programme for the project. An innovative design involving composite retaining walls and gravity wall with sloping wall backs was proposed to replace the bored pile walls to enhance the programme and improve works quality. The composite wall involved installation of a soldier pile wall temporarily supported by tie-backs. Upon reaching the final excavation level, the soldier pile wall was integrated with a reversed L-shaped R.C. wall to form a permanent composite wall with a maximum retaining height of 29.33m under the temporary stage and 20.975m under the permanent stage for supporting the cut slope behind the wall.

Keywords: Site formation, Retaining wall, Design optimisation

1 Introduction

1.1 The Project

The Heung Yuen Wai Highway (HYWH) under the Liantang / Heung Yuen Wai Boundary Control Point project is an approximately 11-km dual two-lane carriageway connecting the Fanling Highway and the Heung Yuen Wai Boundary Control Point. The section of 4.8km long Lung Shan Tunnel (LST) of the HYWH was constructed by Dragages Hong Kong Limited (DHK) (a member of the Bouygues Construction Group) using mechanical and drill and blast excavation techniques, together with the largest earth pressure balance (EPB) tunnel boring machine (TBM) with a diameter of 14.1m used in Hong Kong (Storry et al, 2017). The TBM was launched from the Northern Portal to form the northern section of the road tunnel to deal with the challenges of excavating through multiple faults and mixed ground conditions.

At the Northern Portal, major site formation works involving a relatively large volume of materials to be excavated (650,000m^3) were necessary under the temporary conditions to create the space necessary for the logistic of tunnel construction and under the permanent conditions for formation of the trunk road. The original ground level of the site varied from approximately +50mPD to +30mPD.

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Cut slopes or soil-nailed cut slopes were to be formed to lower the existing ground level. In addition, cantilever bored pile walls comprising mostly bored piles of 3m in diameter were proposed in the original design with retaining height up to 17.5m to support the existing or new cut slopes to be formed above the retaining wall. Conventional rectangular-shaped mass concrete wall had also been proposed as permanent retaining walls with a smaller retaining height. The permanent formation level in front of the Northern Portal would be about +9.45mPD.

Plate 1 shows the site formation works needed to create the formation profiles at the Northern Portal.

Plate 1: Aerial view of Northern Portal taken in the end of 2016

1.2 Site Description and Ground Conditions

The Northern Portal is located at the foothill area of Princess Hill. The hillside is covered by Colluvium approximately 2m to 5m thick. The Colluvium layer is typically described in the drillhole records as 'firm, sandy silt with occasional subangular fine gravel sized Tuff fragments' and "firm, slightly sandy clayey silt". The thickness of Colluvium decreases downslope. Alluvium of approximately 4m to 8m thickness occupies most of the lowland area. The superficial deposits are underlain by completely decomposed Tuff (CDT) of approximately 30m thick, followed by slightly to moderately decomposed coarse-ash crystal Tuff bedrock. The CDT is typically described in the drillhole records as 'extremely weak, firm to stiff, slightly sandy silt'. Soil/rock materials comprising partial rock (PR) 10/30 (IV/V) and PR 50/75 (IV) (up to 5m thick) are anticipated above the bedrock in the area. The Princess Hill is bounded by the NE-SW striking Sha Tau Kok Fault and the NW-SE striking photogeological lineaments. Fault related features, e.g. fault breccia, fault zone, quartz breccia, fault gouge and brecciated tuff were logged in drillholes. Bedrock is encountered at the level varying between +15mPD to −20mPD approximately.

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2 Programme Constraint and Solution

2.1 Portal Formation for Tunnel Excavation and TBM Launching

The tunnel project was scheduled to utilize a single TBM to complete two TBM drives for twin tubes of the Northern section of LST. To achieve this goal, it would require launching of the TBM for southbound tunnel at the Northern Portal to be commenced early. An initial programme assessment indicated that the site formation works based on the original design would require approximately 20 months before the tunneling works could be commenced. This was because temporary platforms would be required for construction of the bored piles on sloping ground and that lowering of the ground profile could only be commenced after completion of the bored pile walls. This would render the goal of using a single TBM for both tunnel drives impossible to meet the tight construction programme.

To secure earlier launching of TBM for the southbound tunnel at the Northern Portal, two alternative designs of retaining walls to replace the bored pile walls were adopted:

(1) Gravity walls with sloping wall backs (also known as the goose-shaped wall).

(2) Composite retaining walls formed by integrating a permanent soldier pile wall temporarily supported by tie-backs with a permanent reversed L-shaped reinforced concrete wall.

The concepts of the above two alternative designs had been used with great success in past projects for widening of Tuen Mun Highways and Tolo Highways (Li, 2012 & Li & Chung, 2013). The scheme of composite retaining wall has also been proposed recently for the site formation works of a project at Yau Tong commissioned by the Civil Engineering and Development Department.

The goose-shaped walls were used to replace the bored pile walls with design maximum height of up to 16.1m above the site formation level. For larger retaining heights, composite retaining walls with a maximum retaining height of 29.33m temporarily supported by 444 nos. of tie-backs were used as an alternative. The advantages of a composite retaining wall in performing both as a temporary embedded wall and a permanent retaining wall had been fully harnessed in this project to allow early commencement of the tunneling works for the southbound tunnel.

By adopting these alternative design schemes, tunnel excavation could be commenced for the southbound tunnel 10 months after the commencement of the contract, saving 10 months of time than would otherwise be required if the original bored pile wall scheme was to be used. This had made the option of using only one TBM for both tunnel drives possible for meeting the target construction programme.

Plate 2 shows the construction of the southbound tunnel while the construction of soldier pile wall for the composite retaining wall was in progress well before completion permanent retaining walls.

Plate 2: Southbound tunnel at the Northern Portal in phase with construction of the soldier pile wall

3 Design of Goose-Shaped Wall

The design concept of a goose-shaped wall is simple and well discussed by Li (2012) and Li & Chung (2013). It is based on the key factor that the active earth pressure acting on a retaining wall will be reduced if it has a sloping wall back slanting against a cut slope. Figure 1 shows some geometries of a goose-shaped wall proposed by Li (2012) used for road widening projects in Hong Kong. They are designed to keep the total volume of concrete low. This will necessitate an extended reinforced concrete wall toe to be provided to enhance the stability of the wall against bearing and overturning failure. The term of a goose-shaped wall was coined by Li (2012) and Li & Chung (2013) for retaining wall geometries shown in Figure 1, particularly that of Figure 2(b), because they resemble a swimming goose. Perhaps, a swan-shaped wall would have been nicer name.

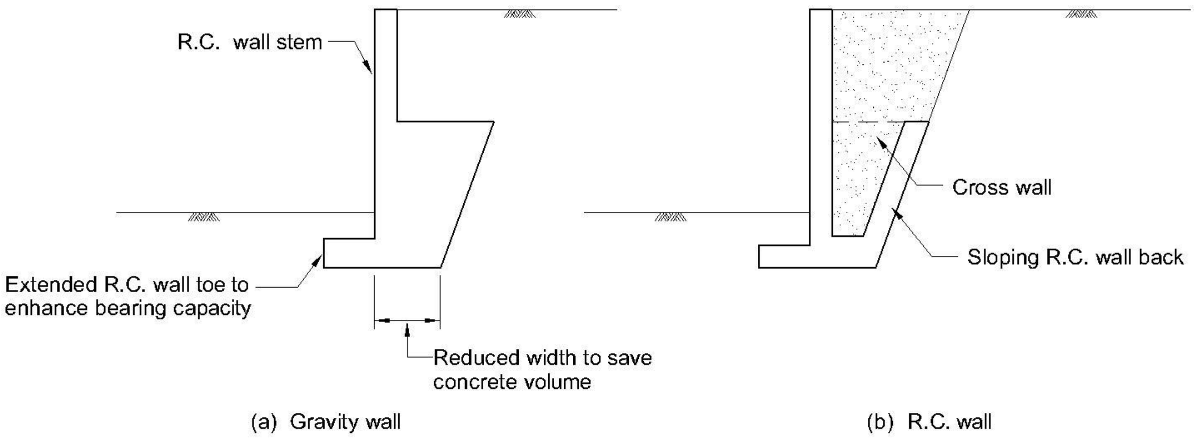

Figure 1: Some geometries of goose-shaped wall (after Li, 2012)

The goose-shaped wall can be formed by initially forming a temporary soil cut slope stabilized by soil nails and then the permanent retaining wall in front of the soil-nailed cut slope. Although the temporary soil nails are ignored in the design of the permanent goose-shaped wall, they will in fact contribute significantly to further reducing the earth pressure and enhancing the stability of the retaining wall.

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For this tunnel project, goose-shaped walls were used as alternative for replacing some of the bored pile walls as well as the conventional L-shaped rectangular walls at the Northern Portal and Southern Portal. The gradient of the soil-nailed cut slope was 70° for forming the goose-shaped gravity wall. Plate 3 shows the construction of a goose-shaped wall in progress. Figure 2(a) compares the geometries of tallest goose-shaped gravity walls for some of the past projects in Hong Kong described by Li & Chung (2013) with those of this tunnel project at the Northern Portal (Figure 2(b)) and the Southern Portal (Figure 2(c)).

Plate 3: Construction of goose-shaped wall in progress

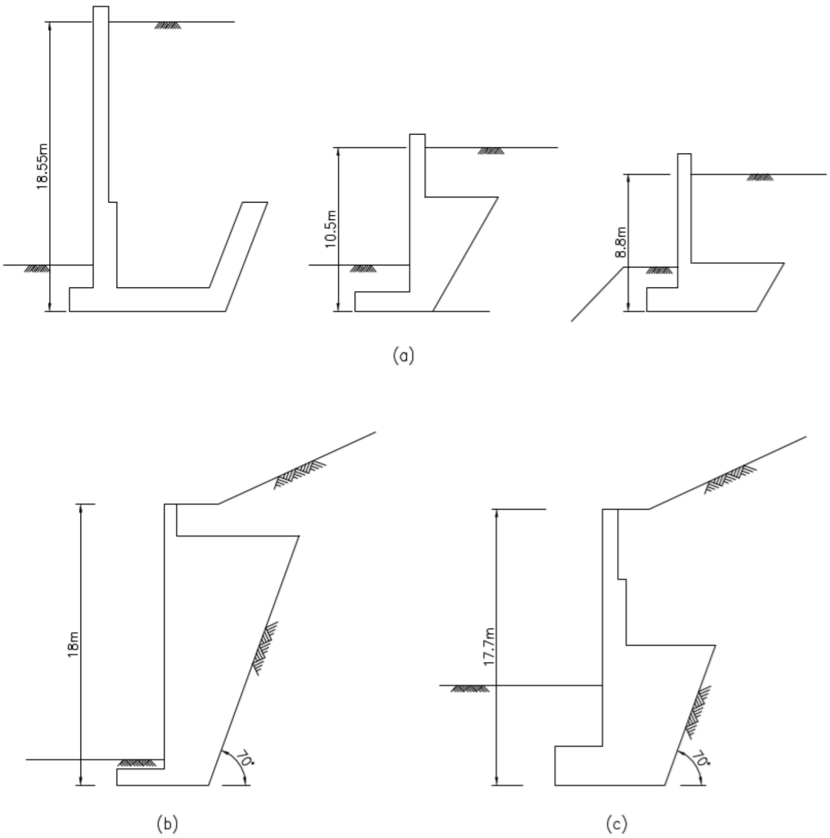

Figure 2: Geometries of completed goose-shaped wall

4 Design Of Composite Wall

The scheme of composite retaining wall used in the LST construction was first developed by Li (2012) and Li & Chung (2013) by modifying the concept of a retaining wall with a stabilizing based described by Carder et al (1999) and Powrie et al (1999). The scheme as depicted in Figure 3 was first used with success for the project of widening of Tolo Highways as an alternative scheme to bored pile walls.

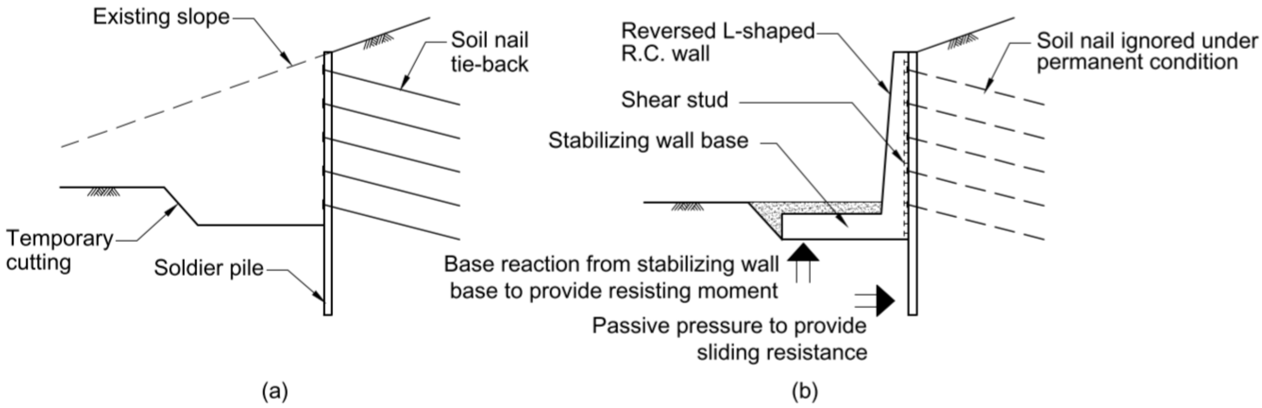

Figure 3: Design scheme of a composite retaining wall (after Li, 2012; Li & Chung, 2013)

For the tunnel project described in this paper, the flexibility offered by the scheme of a composite retaining wall, which can act as both a temporary and a permanent wall, was fully utilized to enable ground profiles to be lowered sufficiently quickly to allow early commencement of the tunnel works. The construction procedures of the composite wall are described in Figure 4.

The upper part of the permanent soil-nailed cut slopes above the composite retaining wall, which formed an integral part of the site formation works, was commenced early to create a working platform on sloping ground sufficient for construction of the soldier pile wall and to serve as a haul road (see Figure 4(a)). The extent of the working space required would have been much larger if the original scheme of bored pile walls were to be used. Once the soldier pile wall was completed, it could serve as an embedded wall for supporting the bulk excavation to enable the ground surface to be quickly lowered to create a working area sufficient for launching of the TBM for the southbound tunnel.

After launching of the southbound tunnel, further bulk excavation was carried out in front of the soldier pile wall to reach the bottom level of the R.C. wall as indicated in Figure 4(b). By then, there would be sufficient space for construction of the northbound tunnel, allowing the construction works for the tunnel and the composite retaining wall to be decoupled.

The R.C. wall in front of the soldier pile wall could then constructed to integrate with the permanent soldier pile wall to form the complete composite wall as shown in Figure 4(c). The beauty of the composite retaining wall scheme is that the R.C. wall could be constructed while upper part of the soldier pile wall could still be used a temporary embedded wall for supporting the temporary working platform behind the wall. Finally, the remaining part of the permanent soil-nailed cut slope was

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formed and the temporary part of the soldier pile wall would be removed to complete the permanent composite wall as shown in Figure 4(d).

Although anchor heads of the tie-backs were progressively disconnected in phase with construction of the R.C. wall, the presence of the left-in-place tie-backs would help to reduce the earth pressures acting on the composite retaining wall.

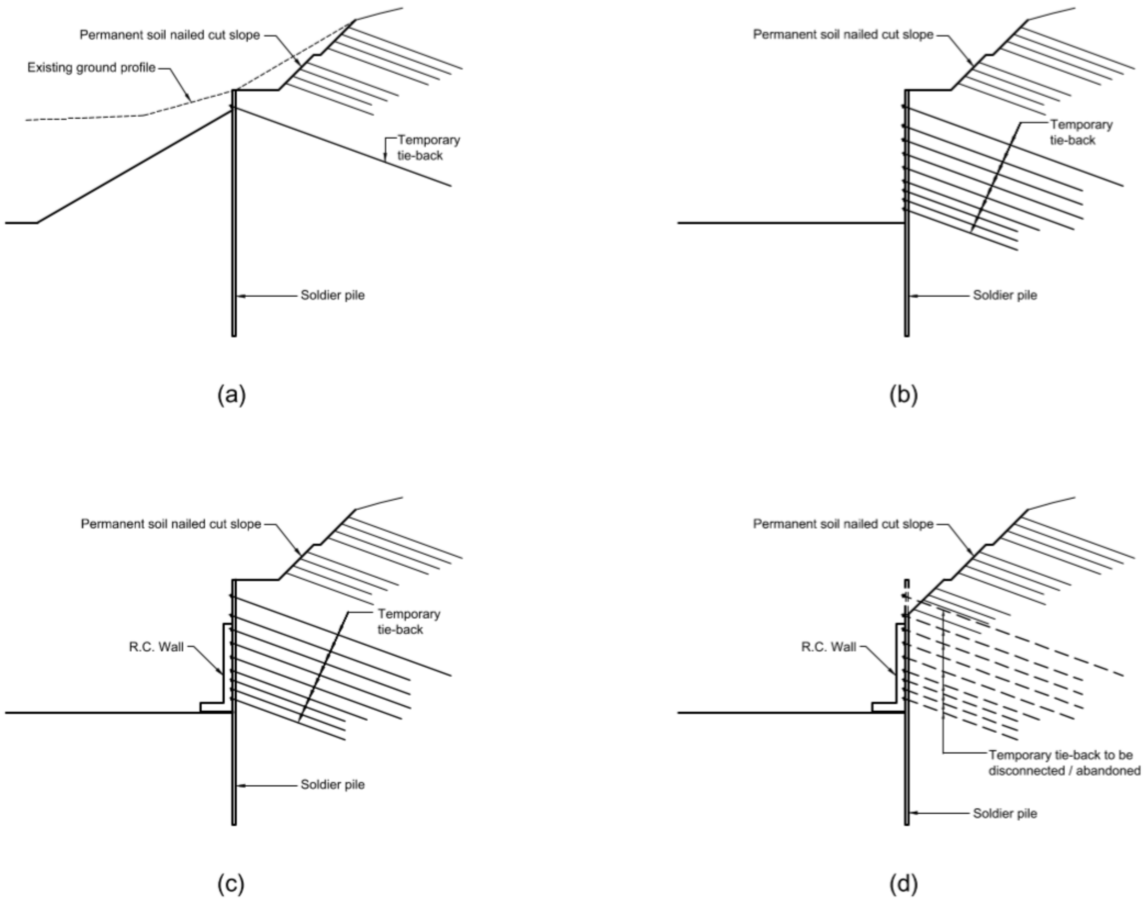

Figure 4: Construction sequence of composite retaining wall

Figure 4 clearly demonstrates the advantages of the composite retaining wall in offering a high flexibility in planning the construction works. As the soldier pile wall acts both as a temporary and permanent retaining wall, it can be utilized as an embedded wall for supporting a deep excavation both before and even after integrating it with the R.C. wall. For the LST construction work, details of the composite retaining wall are as follows:

Max. retaining height of soldier pile wall under temporary condition: 29.33m
Max. retaining height of composite wall under permanent condition: 20.975m
Number of tie-backs: 444 nos. plus 9 nos. for pull-out test
Maximum length of tie-backs: 48m
Types and strength of tie-back: Dywidag bars (yield strength 555 / 670 / 835 / 930MPa)

Figure 5 compares the geometry of composite retaining wall for used in the road widening works for the Tolo Highway (Figure 5(a)) with those of the LST construction (Figure 5(b) & 5(c)). The composite retaining wall geometry in Figure 5(b) was located adjacent to the proposed ventilation building, thus limiting the maximum base width of the R.C. wall. To achieve stability of the wall, the base slab was designed to be propped against the pile caps, transferring some of the soil loading to the foundation of the building. Away from the building, a wider base of the R.C. wall could be used as shown in Figure 5(c) to provide stability of the composite retaining wall.

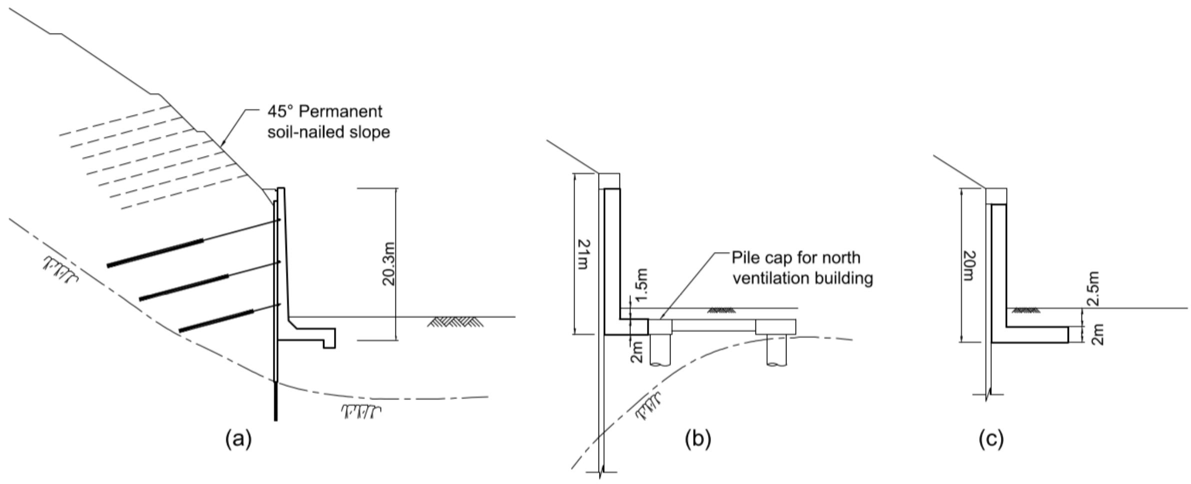

Figure 5: Geometries of completed composite retaining wall (a) Tolo Highway; (b) & (c) The LST construction

(a)

(b)

(c) (d)

Plate 4: Construction of composite retaining wall at Northern Portal

Plate 4 shows some photographs of the composite retaining wall at the Northern Portal under construction. Plate 4(a) shows the installation of tie-backs; Plate 4(b) shows the bulk excavation in front of the soldier pile wall to close the final formation level; Plate 4(c) shows construction of northbound tunnel once bulk excavation had reached the invert level of the tunnel and Plate 4(d) shows the R.C. wall under construction.

5 Construction and Instrumentation

The proposed tie-backs for the composite retaining walls of the LST construction work were designed to be embedded in soils based on the guidelines described in Geoguide 7 (GEO, 2008). The tie-backs for this project, with lengths of up to 48m maximum, were perhaps the longest tie-backs of this kind in Hong Kong. The long design length and the many layers of tie-backs used for the composite retaining wall of this project were a direct result of a maximum limit of 300 kPa recommended in Geoguide 7 for the bond resistance between cement grout and soils. This is in stark contrast to only three rows of relatively short tie-backs used for another project shown in Figure 5(a) for which a much higher design bond resistance of closed to 1MPa was used in the design based on the recommendation of British Standard BS8081:1989.

Given the long length of tie-backs, a specialist subcontractor was commissioned for forming the boreholes for the tie-backs. No hole collapse issue was observed without the use of casing. Drilling rig, Soilmec SM-14, was utilized for the drilling and also for installation of bars after adding a clamp to the rotary head. The drilling was carefully executed with a special drag bit and with air as flushing system. Although water ingress was observed for boreholes at lower levels, there was no major difficulties encountered during the works.

The design of soldier pile wall under the temporary conditions and the composite retaining wall under the permanent condition were based on certain profile of groundwater table. As a measure of risk control under the temporary condition, an active dewatering system together with a passive drainage system of raking drains were proposed to prevent the phreatic surface of the groundwater water exceeding the design profiles.

Standpipes were installed behind the soldier pile wall for the composite retaining wall and temporary soil-nailed cut slope for the goose-shaped wall to monitor the groundwater level. The groundwater monitoring records indicated that the groundwater levels were, as expected, dropped progressively during excavation works, generally in line with the design assumptions.

Strain gauges were installed on the tie-backs at one particular section of the soldier pile wall to monitor the loading distributions along the tie-backs and compare the maximum measured loads with their design pullout capacities. 8 rows of tie-backs were instrumented in 9 locations along their length, giving a total of 72 strain gauges installed. Although the strain gauges recorded uneven distribution of load between different rows of tie-backs, they consistently indicated the stress in the tie-back reached at peak near the boundary of the active zone and then diminished beyond the location of peak stress. Plate 5 shows a photograph of the strain gauge installed on a tie-back.

Plate 5: Strain gauge installed on a tie-back

6 Conclusions

The use of innovative retaining wall designs, optimized construction sequence and a comprehensive geotechnical instrumentation monitoring system have contributed to a success in delivering of this major scale project on time. The Heung Yuen Wai Highway – Lung Shan Tunnel Section was honoured as the "Tunneling Project of the Year (over USD$500M)" by New Civil Engineer (NCE) Tunnelling Awards 2019.

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