SECANT PILE WALL FOR CONSTRUCTING THE NEW METRO STATION SOFIA IN STOCKHOLM

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KEYWORDS

Deep excavation, Ground Conditions, Secant Pile Wall, Rock Socket, Ground Anchors, Large Boulders

ABSTRACT

Station Sofia in Södermalm, Stockholm, Sweden is part of the expansion of the new blue metro line towards Gullmarsplan (southbound) and Nacka (eastbound).

Retaining walls were necessary to support the excavation works for the rock foundation of the station building. The retaining walls consist of a drilled soldier pile wall above the groundwater level and a watertight secant pile wall below the groundwater level. Both walls are rock anchored with self-drilling ground anchors.

Construction of Station Sofia also includes the rock excavation for an approximately 90-meter deep elevator shaft (20x20 m) down to the station space in the rock. Consequently, the station becomes one of the deepest in the world.

This paper reports on the construction of the secant pile wall, which consists of 90 overlapping bored piles, Ø 1200 mm, with lengths ranging from 6 m to 20 m. The excavation depth is approximately 19 m, of which about 15 m are below the groundwater table. The secant pile wall has been embedded into the rock and has up to two anchor levels work with anchor grout lengths in rock ranging from 4 to 5 m.

The ground conditions have been extremely challenging, with extensive large boulders, significant soil depths, groundwater-lowering measures, a strongly inclined rock surface, and a weakness zone, significantly impacting the difficulty of executing the secant pile wall.

Despite the challenges, it can be concluded that a continuous and robust secant pile wall with the required watertightness has been achieved.

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1. INTRODUCTION

Station Sofia is part of the expansion of the new blue metro line towards Gullmarsplan and Nacka. See Figure 1 and Figure 2. Owner of and responsible for the Stockholm's new metro is Region Stockholm.

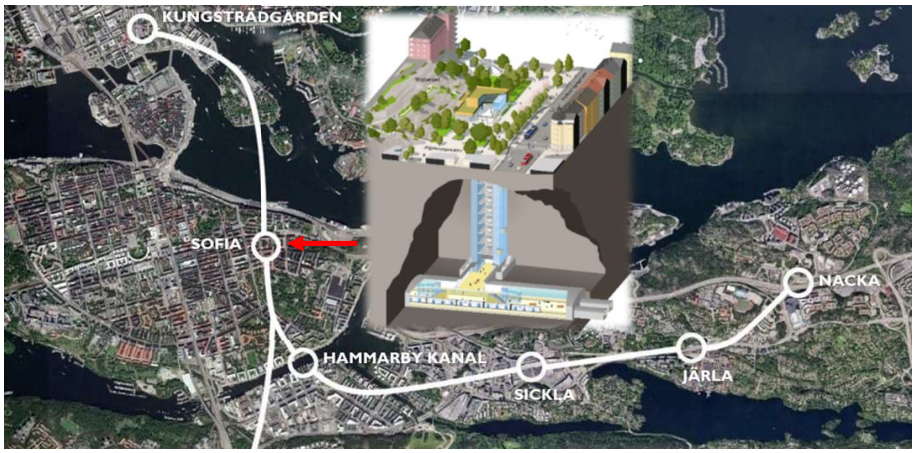

Figure 1 Location and cross-section of the new metro station Sofia.

The contractor Implenia has been responsible for various tasks, including the construction of retaining walls, earth and rock excavation for the foundation of the new station building, and the rock excavation for an approximately 90-meter deep elevator shaft (20x20 m) down to the station space in the rock.

The type of contract for the retaining walls is design and build.

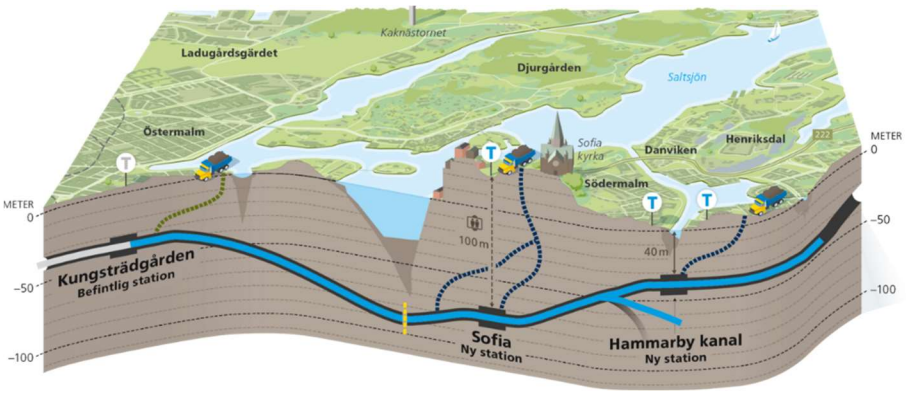

Figure 2 Profile of the eastbound part of the new blue line with Station Sofia.

2. GROUND CONDITIONS

Topographic conditions

The immediate surroundings consist of an urban park environment surrounded primarily by streets and old buildings.

Soil conditions

The soil profile generally consists of fill on clay underlain by frictional soil and moraine on bedrock. In the northern part of the area, bedrock is exposed.

The thickness of the fill varies between 0.5 and 4 meters and consists mainly of frictional soil, boulders, building debris, and organic material.

The clay layer varies in thickness between 0 and 3 meters.

The thickness of the friction soil varies across the area between 0.5 and 12 meters and consists of silty sand transitioning to gravelly sand.

The thickness of the moraine reaches up to approximately 13 meters. The moraine is sandy/silty and is assessed as firmly deposited.

Both boulders and large boulders have been encountered at various depths in the soil profile.

According to the soil-rock investigations, the depth to estimated bedrock varies between exposed bedrock (outcrop) in the north to about 20 meters in the south. The bedrock surface generally slopes at an average of 45° in a north-south direction. See Figure 3 for point of the compass.

Rock conditions

The bedrock in the area is predominantly medium-coarse grained sedimentary vein gneiss, which transitions to coarse-grained granite at depth.

Along Folkungagatan (Figure 3 and Figure 12), there is also a longitudinal weakness zone with a RMR_{bas}-value ≤ 30, indicating poor to very poor rock quality.

Hydrogeological conditions

Within the work area, there is only a lower groundwater aquifer in the frictional soil beneath the clay. The groundwater pressure level varies between +15.5 and +17.5.

The groundwater generally flows through the area in an eastward direction along Folkungagatan and further descends towards “Saltsjön” in the east. The hydraulic gradient is moderate within the working area.

A groundwater recharge also occurs through precipitation from higher elevations in the north down towards Folkungagatan (south side). See Figure 3.

Environmental conditions

Within the working area the soil has been assessed to be contaminated down to level +19. The groundwater has also been assessed to contain contaminants.

3. DESIGN OF THE SECANT PILE WALL

To perform excavation works down to the foundation level of the station building and for the construction of the elevator shaft in rock, two types of retaining walls has been required along three sides of the foundation pit.

No retaining wall has been required on the northern side due to exposed bedrock (outcrop), which however constitutes a rock slope ⩾20 m. See Figure 3 and Figure 4.

The size of the pit is 35 m (west/east) times 45 m (north/south).

Additionally, a watertight retaining wall was partly required to minimize the risk of impact on groundwater-sensitive objects in the adjacent surroundings.

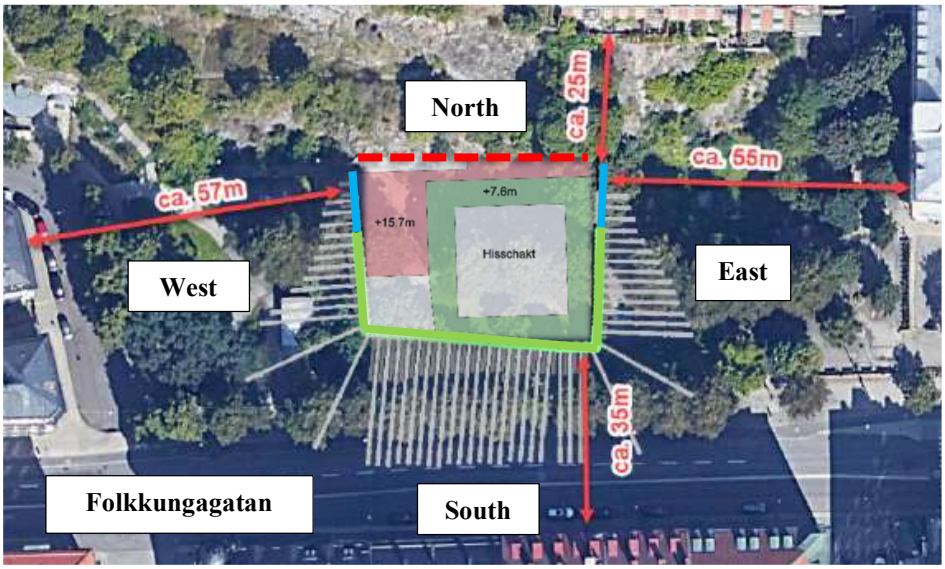

Figure 3 Lay-out of the secant pile wall (green) and soldier pile wall (blue), as well as the rock slope along the north side of the pit (red dotted line).

Based on the ground conditions, which necessitates a drilled solution, and the need for ground water lowering during excavation along with a high requirement for watertightness down to the bedrock a secant pile wall was chosen.

The secant pile wall is designed according to Geotechnical category 3 (GK3) and safety class SK2. The design life is 10 years.

The secant pile wall consists of 90 bored piles with lengths ranging from approximately 6 to approximately 20 meters, see Figure 4.

In Figure 4, the extent of the secant pile wall and the rock foundation levels for the station building, as well as the location of the elevator shaft, are shown.

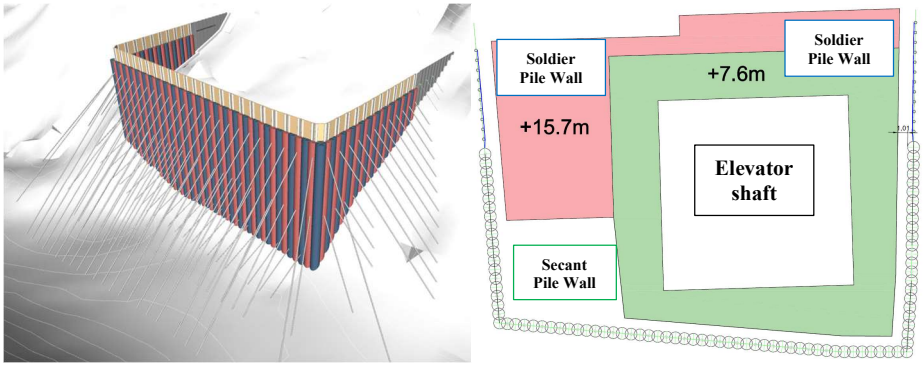

Figure 4 Lay-out of the secant pile wall, the soldier pile wall and rock foundation.

The secant pile wall consists of bored piles, Ø 1.2 m, with center-to center spacing of 0.9 m. Every secondary pile is reinforced. The overlap between each pile is 0.3 m (Figure 5).

Each pile is embedded in the bedrock to ensure a watertight connection to the bedrock surface. Additionally, every secondary pile had a minimum rock socketing depth of 0.3 m ensuring the entire cross-section is fully engaged to handle both vertical loads and horizontal earth pressure. See Figure 5.

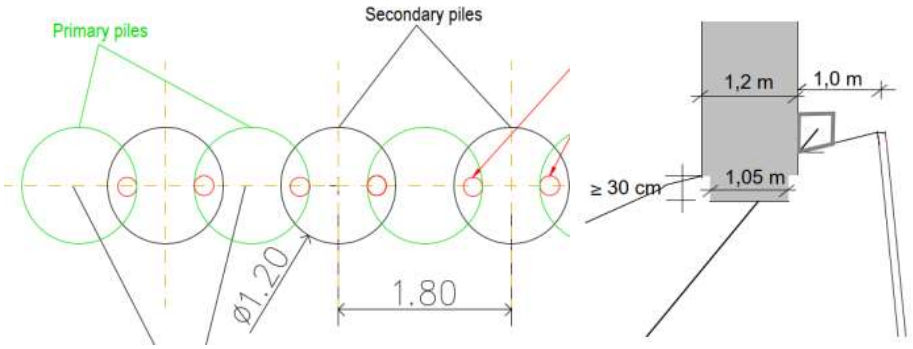

Figure 5 Left - lay-out of the secant pile wall including steel casing in each secondary pile for further curtain grouting. Right - requirement for rock socketing.

Ground anchors

The secant pile wall is anchored with tie-backs in bedrock with up to two levels according to Figure 4 and Figure 13. The bond lengths in rock vary between 4 and 5 meters.

The ground anchors consist of self-drilling Ischebeck Titan rods with dimensions of 103/72, 103/51, and 103/43. The prestressing load varies between 900 kN and 1435 kN.

Sealing demands

Sealing demands for the secant pile wall have only been specified as the maximum allowable groundwater drawdown during a pumping test, which needed to be approved by the Owner before pumping of groundwater could commence.

4. EXECUTION OF THE SECANT PILE WALL

The ground conditions have been extremely challenging, significantly impacting the difficulty of installing the secant pile wall. Challenges include drilling into steeply inclined rock, drilling through both boulders and large boulders (>630 mm), and meeting drilling tolerances to ensure overlapping secant piles from top to bottom.

The secant piles have been installed through rotary drilling, minimizing environmental impact on the surroundings compared to percussive drilling.

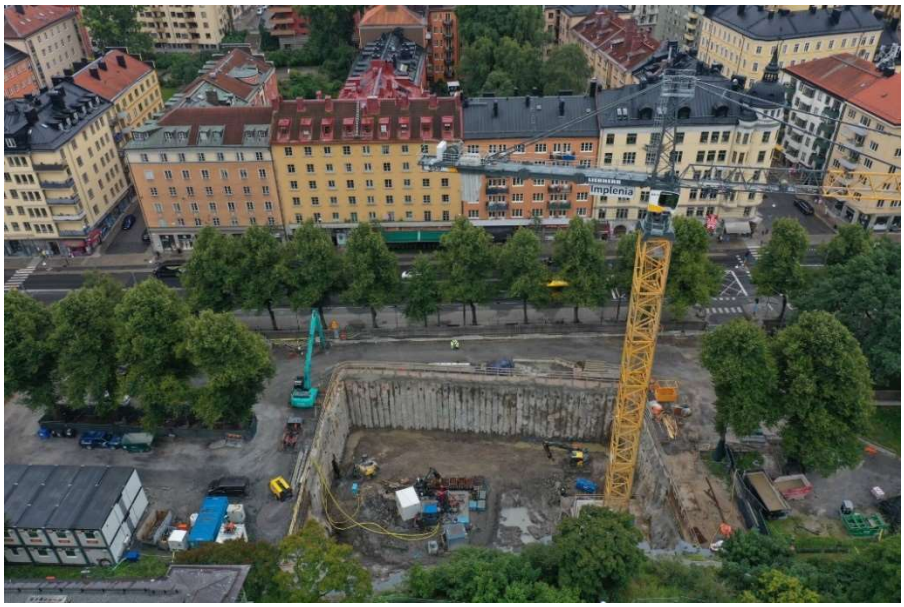

Figure 6 Picture showing time for installation of anchor level 2 as well as ongoing raise boring for the elevator shaft.

Considering the sloping rock surface, a pile test was conducted to optimize the approach for installing each secant pile with the required rock socketing in sound rock (Figure 5). Despite the pile test, achieving the necessary rock socketing has been one of the major challenges in installation, both in terms of time, verification, and with extremely high costs for rock drilling.

However, the results after excavation have shown that all secondary piles are properly rock socketed with an average depth exceeding 0.3 meters. The high

likelihood that all secondary piles were embedded in sound rock before rock excavation has also been verified during drilling for curtain grouting, via the pre-installed steel casings (Figure 9).

Furthermore, drilling for tie-back anchors, besides facing the same difficult soil conditions, posed challenges in determining the transition between soil/rock and drilling and anchoring in the weak zone along Folkungagatan (Figure 13).

Drilling rigs and drilling equipment

For the installation of the secant pile wall, two drilling rigs have been used as follows.

One drilling rig from the manufacturer Liebherr, LB36-410, equipped with a Kelly-system (telescopic drill string) for rotary drilling with casings down to the rock surface. The machine has a mast height of approximately 26 meters and weighs around 115 tons.

After the installation of the casings a second drill rig have executed the socketing. For rock socketing a drilling rig, BG28, from the manufacturer Bauer, equipped with an air-powered down-the-hole hammer (DTH), Ø 1050 mm, has been used. The machine has a mast height of approximately 22 meters and weighs around 84 tons.

Considering the extent of frictional soil, casings (outer diameter 1220 mm and inner diameter 1180 mm) have been required to stabilize the borehole, thus enabling concreting of each secant pile.

Tools for excavating inside the casings have included various types of augers and drilling buckets. DTH drilling has also been required to penetrate or break up large boulders inside the casings, if necessary, that could not be excavated with standard tools. See Figure 7 below regarding the extent of boulders.

Figure 7 Pictures showing the extent of boulders and of large boulders (>630 mm).

Sequence of installation

In connection with a secant pile wall, the unreinforced primary piles are first constructed, followed by the reinforced secondary piles, see Figure 8.

Concrete quality for the primary piles is C12/15 and for the secondary piles is C30/37.

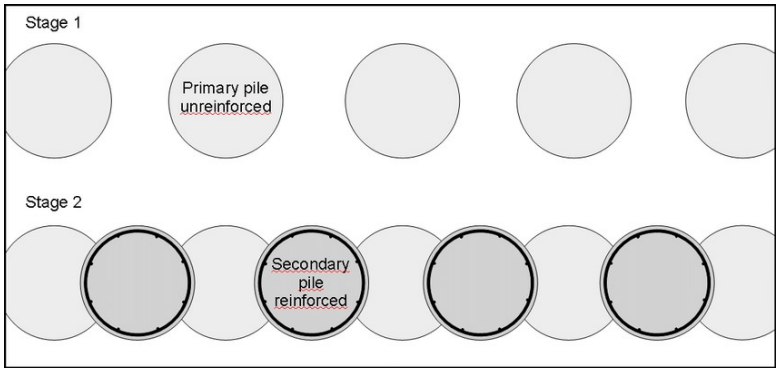

Figure 8 Installation stages for the secant pile wall.

Reinforcement cages

The reinforcement cages have been prefabricated and delivered to the construction site. Cages with a total length exceeding 12 meters were delivered in two parts (upper cage/lower cage), which were assembled on-site before installation. See Figure 9.

Additionally, welded spacers were attached to the reinforcement cage to ensure its verticality and centering within the casing before concreting, as well as to meet the requirements for concrete cover.

Figure 9 Pictures showing reinforcement cages incl. steel casing for curtain grouting.

Tremie concreting

The piles have been cast using ready-mixed concrete of prescribed quality for both primary and secondary piles. Casting was performed using underwater tremie concreting method, employing a system consisting of jointed steel pipes, Ø 220 mm, in sections of 3 m.

After cleaning the borehole, the tremie pipe was lowered to the bottom of the secant pile. Subsequently, the pile casting was carried out by gradually raising the tremie pipe and simultaneously extracting the casing as concrete was poured in.

Drilling tolerances

To achieve a continuous and watertight secant pile wall, the following drilling tolerances have been required for the construction of the secant pile wall:

- Collaring deviation ± 30 mm.
- Drilling and angular deviation 1.0%.

To facilitate and ensure the alignment of each secant pile, a concrete drilling template has been constructed prior to installation. See Figure 10.

Figure 10 Pictures showing a typical drilling template for aiding alignment.

During construction, each secant pile has been surveyed at the pile top and checked for drilling deviation through inclinometer measurements.

The results show that the drilling tolerances have been achieved (Figure 10).

Figure 11 Result of deviation measurements at hole bottom, showing 100 % overlap.

Ground anchors

To install the anchors, it is first necessary to drill two holes through each secondary pile. The holes are made using core drilling, as shown in Figure 12.

Each anchor has been installed according to SS-EN 1537. Drilling was carried out using top hammer drilling with water flushing, and no casings were used.

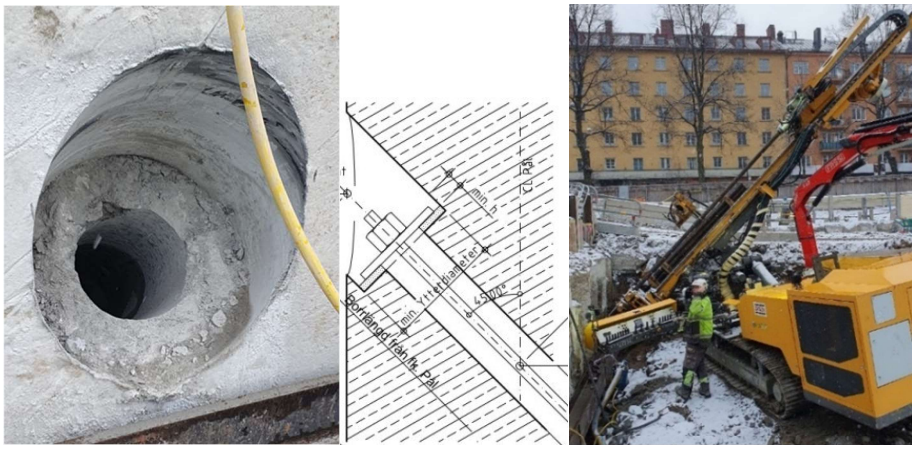

Figure 12 Left and middle– holing in each secondary pile for further anchoring. Right- ongoing drilling for anchoring.

The anchors are grouted into the rock with a theoretical volume (plus 10 %) with a cementitious grout, w/c ratio of 0.45, and shrinkage-reducing admixture. Type of cement CEM II 42.5 R. Grouting has been made via the anchors.

Acceptance testing of each anchor (method 1) was conducted according to SS-EN ISO 22447-5:2018. All anchors have passed the acceptance test.

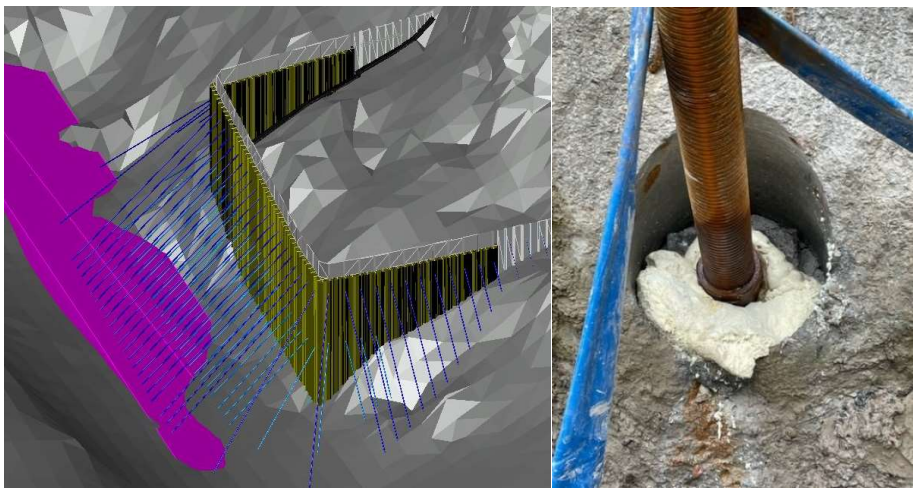

Figure 13 Left – assessed location of the weakness zone (magenta). Right – permanent sealing of the anchor hole using polyurethane resin.

For anchor level two, sealing against groundwater ingress through the tie-back penetrations in the secant pile wall has been performed both temporarily during drilling and permanently after acceptance testing. Permanent sealing of leaking tie-back holes has been done using polyurethane resin, see Figure 13.

Geotechnical monitoring

Monitoring (Figure 14) during installation and excavation has shown ground movements of approximately 1–5 mm, manhole covers approximately 1–3 mm, and in the street of Folkungagatan approximately 1 mm.

Settlements of around 1–2 mm has been measured at block Buketten 15 to 18 (groundwater-sensitive buildings).

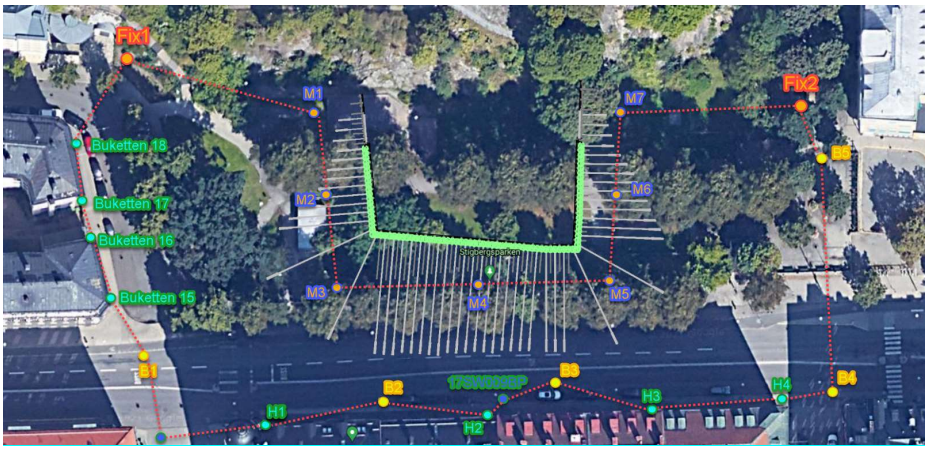

Figure 14 Scope of measuring points for geotechnical monitoring.

Thus, the results of geotechnical monitoring have shown that no harmful impact on the surroundings has occurred, as well as no impact on the ground water levels.

5. CONCLUSIONS

Despite challenging ground conditions, it can be concluded that a highly robust and continuous secant pile wall has been achieved with the required watertightness as shown in Figure 15 and Figure 16 below.

It has taken approximately a year to install the secant pile wall, which clearly reflects the difficulty posed by the ground conditions. Furthermore, no adverse effects on the surroundings have occurred, neither in terms of ground movements, settlements, nor groundwater.

Executing the secant pile wall considering the difficulty, requirements, and ground conditions has been an unparalleled challenge. However, with great

dedication and fighting spirit from all parties involved, a fantastic result has been achieved.

A secant pile wall is an extremely unbeatable technical solution when the ground conditions demand a drilled retaining wall and with high demands on watertightness.

Figure 15 Secant pile wall, facing east and south.

Figure 16 Secant pile wall, facing south and west, rock slope facing north.

ACKNOWLEDGEMENT

We'd like to acknowledge Region Stockholm for letting us present this paper.