Investigation, design and mapping of Shaft O1 on Phase 2 of the Deep Tunnel Sewage System project in Singapore

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Abstract. The Public Utilities Board (PUB) of Singapore is currently progressing Phase 2 of the Deep Tunnel Sewage System (DTSS) project. Leighton Contractors Asia Limited (LCAL) have been awarded Contract T-09 of the project which runs approximately 8 km from the intersection of Clementi Road and the Ayer Rajah Expressway (AYE) to the intersection at Jurong Pier Road and AYE. LCAL have appointed COWI to act as their designer. Contract T-09 includes eight shafts, including Shaft O1 located between the Jurong River to the west and Penjuru Road to the east in the Jurong region of south-west Singapore. This paper discusses the rock engineering aspects of Shaft O1, including the engineering geological aspects and the methods of analysis used to design the reinforcement and support of the section of the shaft excavated in rock. Finally, the conditions encountered and the support installed during the engineering geological mapping of the shaft are described. The geology at Shaft O1 comprises made ground overlying Kallang Formation deposits and then weathered rocks of the Jurong Formation. Development of the ground model included several stages of desk study and ground investigation and ultimately six boreholes and eight probeholes were carried out at and around the shaft location. The analysis methods used included the Q-system, analytical closed-form calculations, use of the Unwedge software package, rock bolt and sprayed concrete design and a stand-up time assessment. The design was prepared during 2018-19 and the shaft was successfully constructed during 2019.

1. Introduction

The Public Utilities Board (PUB) of Singapore is currently progressing Phase 2 of the Deep Tunnel Sewage System (DTSS) project. Leighton Contractors Asia Limited (LCAL) have been awarded Contract T-09 of the project which runs approximately 8 km from the intersection of Clementi Road and the Ayer Rajah Expressway (AYE) to the intersection at Jurong Pier Road and AYE. LCAL have appointed COWI to act as their designer.

This paper discusses the rock engineering aspects of Shaft O1 including the engineering geological setting and the methods of analysis used to design the reinforcement and support of the section of the shaft excavated in rock. Finally, the ground conditions encountered, and the support installed during the construction of the shaft are described.

2. Background

The Deep Tunnel Sewerage System Phase 2 Project (DTSS2) comprises an approximately 50 km long tunnel of 3 m to 6 m span. The main tunnel runs from the southern end of downtown Singapore towards the industrial Tuas district in the west where a new centralized water reclamation plant (WRP) is
proposed. Five branch sewer tunnels will be constructed to collect used water and connect to the main tunnel forming a sewerage network in southern Singapore.

Contract T-09 (see figure 1) includes eight shafts, including Shaft O1 located between the Jurong River to the west and Penjuru Road to the east in the Jurong region of south-west Singapore (see figure 2).

![Figure 1. T-09 project site and shaft location plans. Note red arrows are indicative TBM drives.](image1)

![Figure 2. Shaft cross-section from design drawings](image2)
3. Engineering geology
Development of the ground model included several stages of desk study and ground investigation. Ultimately six boreholes and eight probeholes were carried out at and around the shaft location.

The ground conditions encountered during the construction of Shaft O1 were found to be as expected from the ground investigation. The shaft was progressively excavated through Fill, the Kallang Formation, weathered Jurong Formation, with the base of the shaft being below rockhead. Approximately 80% of the rock recovered from the site was sandstone, the remaining 20% was siltstone (possibly belonging to the Tengah Formation). An extract from the geological map (Lee & Zhou, 2009) relevant to the site is shown in figure 3.

The Kallang Formation is a sedimentary drift deposit of marine, alluvial, littoral and estuarine origin (Pitts, 1984), formed during the Holocene and late Pleistocene. The underlying Jurong Formation is of late Triassic to early Jurassic age. Deposition of the Jurong was in terrestrial, transitional, and shallow marine environments, leading to the formation of interdigitating mudstones, siltstones, sandstones, conglomerates, limestones and occasional volcanic units.

Whilst significant faulting and folding can be present within the Jurong Formation, no such features were encountered during the construction of Shaft O1.

4. Temporary support design and analysis
The design was prepared during 2018-19 and the shaft was successfully constructed during 2019. The upper part of the shaft through soil is a diaphragm wall. The temporary support in rock utilised a combination of rock dowels, sprayed concrete and reinforcement mesh as required. The support within the shaft was divided into three main support scenarios:
- Prescribed support to support the load of the overlying soils and diaphragm wall onto rockhead
- Support based on the Q-method (NGI, 2015) for standard lengths of shaft
- Support based on the Q-method for the sections of shaft impacted by portals and junctions.

The temporary support was developed in stages as follows:
- Design Stage 1: Determination of prescribed support required at the interface between diaphragm wall toe and rockhead
- Design Stage 2: Determination of the temporary support using the Q-system supplemented by Barton (1974)
- Design Stage 3: Determination of rock dowel requirements
- Design Stage 4: Wedge stability check using Unwedge
- Design Stage 5: Sprayed concrete lining capacity
- Design Stage 6: Determination of unsupported height and stand-up time
Details of all the design stages will not be provided herein, with only Design Stages 1 and 2 being discussed as there are few examples detailing similar scenarios within published literature.

4.1. Design Stage 1: Determination of support at interface of D-wall and rock.

It was identified that the diaphragm wall would impose a load onto the rockhead and there were concerns that loading of the jointed rock mass here may lead to wedge failure, in turn leading to instability of the overlying diaphragm wall. To account for this, a prescribed support was applied to 5.5 m below the toe of the diaphragm wall which accounted for a full range of joint angles.

Two load cases were assumed at the toe of the diaphragm wall as shown in figure 4. These considered local failure of the rock mass beneath the toe of the diaphragm wall due to potential sliding blocks.

![Figure 4](image-url)

**Figure 4.** Model for Case 1 - Global stability (left) and Model for Case 2 - Local stability (right), not to scale.

Given the circular shape of the shaft it was identified that side friction on any wedge would have a beneficial impact on the required restraining force to be applied by the prescribed support. To allow for this, a modified version of Hoek & Bray’s expression (1981) was developed, where $T$:

$$T = \frac{F.L.W. \sin \omega_P + F.L.V. \cos \omega_P - L.c.A - L.W. \cos \omega_P. \tan \theta + L.U. \tan \theta + L.V. \sin \omega_P. \tan \theta - (2(c.A_{sf} + K.\sigma_f.\tan \theta.A_{sf})x0.8)}{\cos \phi. \tan \theta + F.\sin \phi}$$

The prescribed support was finalised by modifying the rock dowel spacing and sprayed concrete thicknesses to achieve the optimum support requirements.
4.2. Design Stage 2: Determination of the temporary support using the NGI Q-system.

The Q-system is a well-established method for assessing rock quality and determining the required support in hard rock. However, the use of the Q-system in shafts is not well established compared with tunnels and only a few published case studies are available in the literature. Barton (2013) provides some guidance on the use of the Q-system for such structures.

For the initial design of Shaft O1 COWI adopted the following factors:

- ESR = 2.5 to account for the shaft being circular.
- Wall factor of 2.5 for Q-values ranging between 0.1 and 10, increasing to a factor of 5 for Q-values greater than 10.
- Temporary support factor of 5 to account for the temporary nature of the shaft.
- The diameter (span) of the shaft and the height of the excavation in rock were anticipated to be similar. The smaller of these dimensions was adopted due to the shaft being considered as a 'wall'.
- At portals and junctions factors of Q/2 and Q/3 were applied respectively.

Subsequently, it was decided with the main contractor that the temporary support factor would be removed from the design for specifying sprayed concrete thickness to ensure the design was robust. However, the factor was still applied for determining rock dowel spacing.

5. Construction

At Shaft O1 diaphragm walls extend down to competent Grade III or better rock. The remainder of the shaft is constructed within competent rock using shotcrete / rock bolt support in combination with fissure grouting to final formation level. If suitably competent Grade III material was not encountered during construction, the piles would have been installed to final formation level.

Due to the varying ground conditions, an observational approach was adopted. COWI worked closely with the contractor and compiled a 'rock support manual' to ensure that the site engineering geologist was aware of all the assumptions made in the design, the risks and problems that might occur during excavation and when to apply the contingency measures. Certain contingency options could be applied based on the type of ground that was encountered during excavation. For instance, all piles would be terminated at a specified 'design toe level' (DTL). If the DTL could not be reached – for example if the rock was locally much better than anticipated – the design allowed for some piles to terminate at a pre-determined contingency level. This collaborative approach in design proved efficient and achieved successful results during the design and construction process.

5.1. Engineering geological mapping.

On site the site engineering geologist had the following responsibilities:

- Carry out geological mapping and determine a Q-value for the exposed rock faces.
- Liaise and coordinate with the Shotcrete Lining (SCL) Representative.
- Carry out inspection of the rock exposed at the base of the shaft.
- Specify the temporary support to be installed by LCAL.
- Identify individual features requiring specific/additional support and specify the required support.
- Liaise with technical staff employed by other stakeholders.
- Observe and record probe hole drilling within the mined tunnels and shafts with rock support.
- Produce all geological records and compile a full set of as-built records.

Drilling and blasting was adopted for excavation in rock of Shaft O1 from rock head level -23.0 mSHD to final excavation level -48.1 mSHD. It took 2.5 months to complete the 25.1 m deep
excavation in rock, including drilling & blasting, mucking, engineering geological mapping, installing rock dowels and applying shotcrete. The average productivity was about 0.34 m/day.

According to the design, steel fibre reinforcement concrete (SFRC) was proposed for the temporary support. However, during construction the contractor requested that this be changed to shotcrete reinforced with wire mesh. The drilling & blasting work was carried out in 2 m lifts and the subsequent activities were divided into two parts (half of the shaft area), each part of works took 2~ 3 days to complete. The excavation works were carried out smoothly without any additional mitigation work such as grouting, strengthening etc.

The rock mass conditions during construction were found to be:
- The rock mass generally comprised thick- to medium-thickly bedded sandstone and siltstone, the dip angle of bedding was generally 10~20 degrees and thinly laminated mudstone was occasionally observed.
- The fissure grouting was very effective and the rock face was generally dry or damp, with the only water seepage occurring at the joints in the diaphragm wall above.
- No major faults or folds were observed at this shaft, although there was a very minor fault along a bedding plane and the bedding was very gently folded.
- There were two major sets of joints with NW-SE and NE-SW strike, both with steep dip angle (70~90 degrees), plus random joints, the joints were generally tight.

As shown in figure 5, the mapped Q-value based on site engineering rock mapping was generally between 0.2 to 1.2. Some site photos taken during the engineering rock mapping are presented in figure 6.

**Figure 5.**: Shaft O1, Q-value measured during engineering geological mapping

**Figure 6.**: Site photographs (from shaft level -37.0 to -39.0 mSHD).
5.2. Instrumentation monitoring. Convergence monitoring points were installed in the shaft during construction and the arrangements are illustrated in figure 7. The work suspension level (WSL) was set as 15 mm and alert level set as 11 mm. The convergence points were monitored and reviewed daily during excavation, and the measured maximum convergence was 6 mm (refer to figure 8), well within design alert level. Figure 9 shows Shaft O1 at the end of excavation.

![Figure 7. Plan showing convergence monitoring arrangement](image-url)

![Figure 8. Convergence monitoring results at -31.5 and -36.5 mSHD](image-url)
Figure 9. Site photo showing the shaft O1 excavation completed and TBM installation

6. Summary
Shaft O1 was safely and efficiently excavated during 2019, in no small part due to the collaborative approach that was adopted between the designer and the contractor during the rock engineering design and excavation of the shaft. Definitive published guidance on the design of shafts in rock is not as readily available as for rock tunnels. This deficiency was managed on this project by detailed engineering geological assessment and through ground investigation, modifying the recommendations by Barton for the use of the Q-system for shafts, the use of supporting analytical calculations, the preparation of a 'rock support manual' for use by site staff to ensure they understood the design, and the deployment of competent engineering geological staff during construction.

References
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