Use of 3-D seismic survey to determine soil-rock profile along bored tunnelling route

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ABSTRACT

The Thomson Line (TSL) is a 30 km underground train line that is expected to be fully completed in 2021, and will be the sixth Mass Rapid Transit system in Singapore. The line will run through the north-south corridor, starting in the northern Woodlands area, passing through the industrial estate of Sin Ming, down to the residential Thomson area and the shopping districts of Orchard and Marina Bay, before ending at Gardens by the Bay. One of the key challenges is bored tunnelling through the soils and rocks of Bukit Timah Granite near to existing buildings, especially within the densely built-up regions near Orchard. Specifically, there are pockets of areas where it is not possible to conduct conventional borehole investigation method due to accessibility issues for the drilling rigs. To overcome the challenges in investigating the soil-rock interface at these locations, seismic survey methods were proposed to enhance the clarity on geological profile. The paper first explains the nuances and limitations between various seismic acquisition methods, such as 2-dimensional (2-D) methods, and 3-dimensional (3-D) methods. These have used in combination for oil and gas exploratory functions, but is uncommon to see their application in ground investigations for land infrastructure projects in Singapore. Eventually, a decision was made to make use of 3-D seismic refraction in the ground investigations for Thomson Line in Singapore. In practical sense, the paper presents an instance whereby 3-D acquisition method is scaled down to solve a civil engineering problem which in LTA's case was determining bedrock depth that the bored tunnels will encounter during construction phase. The target depth for the soil-rock interface was between 30 m to 60 m, and is small-scale as compared to hundreds of metres of potential information that could be mapped using the acquisition method. Other than discussing the technicalities in implementing the 3-D survey, the effectiveness of the seismic acquisition in mapping the soil-rock interface of the Bukit Timah Granite Formation will be discussed. Future application of the seismic acquisition for LTA projects is also briefly included.

Keywords: seismic reflection, bored tunnel, reflector, velocity, bedrock, geophones, energy source

1 INTRODUCTION

The 30km underground Thomson Line (TSL) runs through the north-south corridor of Singapore from Woodlands to Marina Bay. Site investigation (SI) in Singapore typically employs borehole sinking, cone penetration tests and seismic surveys (2-D) along bored tunnelling routes and station footprint to determine stratigraphy profiles and soil parameters for design and construction purposes. For the latter, SI assesses the risks of tunnelling and impact on overlying structures; and mitigates with suitable measures. Apart from risk of excessive ground movements, risk includes sinkhole formation.

Specifically, a section of about 140 m of twin, stacked tunnels will be constructed by bored tunnelling method directly under private properties between the Napier and Orchard Boulevard Stations. See Fig. 1. Fig. 2 shows a cross-section profile of the bored tunnels directly below one of the private properties, where the tunnel axis of upper-stacked tunnel ranges from 94 m Reduced Level [RL] near Napier Station to 97 m RL towards Orchard Boulevard Station. The axis of the lower tunnel ranges from 81m RL to 82 m RL near Napier and Orchard Boulevard Stations respectively.

The bored tunnels will be constructed within the Bukit Timah Granite Formation, which is of igneous origins and widely distributed in the central and northern parts of Singapore Island. The granite is typically encountered in various states of fracturing and weathering from residual soils (G-VI) to intact unweathered, fresh rock (G-I). The weathering of the Bukit Timah Granite is graduated with stratified layers,
and the degree of weathering of Bukit Timah Granite according to its grade is described in LTA Design Criteria (2010). The granitic soil comprises of completely weathered material (G-V) to residual soil (G-VI). Zhao et al. (1995) reported that the depth of the residual soil could range from a few metres to 70m with an average value of 30m. The granite rock head generally follows the ground surface elevation and the completely weathered granite rapidly becomes slightly weathered granite (G-II) with the heavily (G-IV) to moderately weathered (G-III) intermediate zones often missing or thin. Engineering properties of the Bukit Timah Granite are also described by Goh et al (2012).

A key concern was of tunnelling in the Bukit Timah Granite Formation was whether the tunnel boring machine will encounter bedrock of the Bukit Timah Granite (G-III or higher grade taken as bedrock), instead of the completely weathered soils as anticipated from nearest boreholes outside the property.

As it is not possible to conduct borehole investigations within the property, 3-D seismic survey along the perimeter of the premises was conducted to determine the soil-rock interface along the tunnel route.

2 ACQUISITION OF SEISMIC REFLECTION DATA

2.1 Comparison between 3-D and 2-D seismic survey

Seismic reflection survey is a suitable method\(^\text{1}\) to determine soil-rock interface, and was the method employed for determining bedrock depth along the tunnel route. The incident P wave (compression wave) is reflected at the boundary of two materials having differing velocity and seismic density. Fig. 3 illustrates the mode conversion of incident P wave into compression (P) and shear (S) waves that are reflected and refracted.

A 2-D seismic reflection survey arrayed along the tunnel route will suffice if accessibility to the private property was possible. The 2-D receiver array is arranged with receivers in straight albeit bent lines within the objective area; and energy source is moved along the array in similar interval as receiver spacing. Traces (receivers’ response in terms of 2-way time to single shot by source) are acquired along a single plane. As the name of 3-D seismology implies, source wave is transmitted and received by receivers along a different plane in addition to waves transmitted and received by receivers along the 2-D plane. Traces acquired will be multi-planed, and substantially greater in terms of quantity of data.

![Fig. 3. Transmission of P Wave at boundary of two strata with differing velocity, v, and density, ρ](image)

2.2 Methodology

The seismic reflection setup consists of geophones which are receivers for ground acquisition, an energy source to generate seismic wave into ground, and data recorders to record the arrival time (two-way time) of data received by the individual geophones. To conduct the seismic survey, a total of 177 geophones were placed along the three arrays at 2.5m centre spacings, and were connected to recorders.

\(^{1}\text{ASTM D 6429 Standard for Selecting Geophysical Methods}\)
The seismic waves were generated using an Accelerated Weight Drop (AWD) method, which makes use of a 39kg hammer accelerated towards the ground to generate a higher impact for each shot. Each energy source was placed in between adjacent geophones at 2.5m spacing.

The simple seismic velocity equation is as shown below:

\[
\text{Two-way depth} = v t \quad (1)
\]

The second unknown velocity was to be assessed from acquired readings at known wells (boreholes). The seismic survey for placement of geophones and source was lined along three arrays (lines A, B and C) that partially encircled the inaccessible ground as shown in Fig. 4.

For better calibration of the seismic survey using existing borehole data, lines A and C traversed within close proximity of borehole point ST/5580D near junction of Holland Road and Napier Road and also borehole ST/5511 near Ritchie Road to enable reflector identity at those points. Borehole data of ST/4628 and ST/5511 which are within close proximity of tunnel shows bedrock at 73.1 m RL and 80.4 m RL respectively.

The seismic energy source is moved along the geophone array and data is recorded, processed and interpreted. Total shooting length is 467.5 m.

A total of five thumps of the AWD hammer were made for each shot in order to stack the acquired seismic data and minimise interference from ambient noise and vibrations, especially those disturbance arising from traffic. For each shot of the source, the timing for all the equipment is synchronized and all the geophones along the three arrays were capturing data simultaneously from each source location. Data is then recorded on a seismograph to determine the velocity distribution. This was pre-processed involving data transformation, trace arrangement, filtering and correction. Fig 5 shows the geophones and recorder; and Fig 6 shows the energy source machine used in this investigation.

![Fig. 5. Photos of geophones and recording instrument](image1)

![Fig. 6. Photo of energy source for generating seismic wave into ground](image2)

### 2.3 Acquisition equipment and specification

Some specifications of the equipment used for the seismic survey consists of the following:

- **i** Array Type: Geophones 4 Hz.
- **ii** Array length: 442.5 m
- **iii** No of groups: 177
- **iv** Source type: Gisco Geo ESS100
- **v** Recording System: i-Seis Sigma
- **vi** Recording length: 2 sec
- **vii** Sampling rate: 0.25 ms
- **viii** Low-cut filter: 3 Hz at 6dB/oct
- **ix** Hi-cut filter: 206 Hz at 276dB/oct
- **x** Data Recording media: Hard Disk/i-seis

### 3 PROCESSING AND INTERPRETATION

#### 3.1 Processing

Source cable noise during data acquisition had been significant. However due to high fold coverage it was possible to eliminate the noise. Defective trace due to distortion and phase shift with greater than 1 millisecond; and electrical leakage were absent during acquisition.

Processing sequence of data involved the following:

- **i** Reformat to GNS format
- **ii** Application of 3-D geometry
- **iii** Shot summation
- **iv** F-K filter with 14ms per trace dip limit and 500
ms AGC wrap
v  Deconvolution before stacking
vi First and second pass velocity analysis (40 m interval)
vii First and second pass residual statics calculation
viii FX domain coherency filter
ix  Deconvolution after stacking
x  Band pass filter (20 Hz – 135 Hz)
xi  500 ms AGC

Under velocity analysis, reflection time is known to increase by NMO (Normal Move-out). Through a series of equations involving NMO and rms (root mean square) velocity, the seismic velocity \(v\) could be calculated by plotting a graph of reflection time against total offset resulting in gradient of \(1/v^2\).

3.2 Interpretation

Geological knowledge of the area targeted is useful. Much of interpretation is done at processing stage, in particular, the velocity analysis part. The line with well data of ST/5580D and ST/5511 should be studied for presence of strong reflector, and note for distinct reflector character of the rock bed horizon. The average velocity analysed and obtained, and resulting depth compared with bedrock depth of well data. They should match.

Fig 7 and Fig. 8 show the velocity profile with depth along the three arrays that were measured (line A, line B, line C). In interpreting, picked reflector must be tied around the loop of survey lines. Problems preventing tying of picked reflector are 1) poor navigation; and 2) reversal of polarity between sections. Fig. 7 and Fig. 8 shows where picked reflector along line B is tied with line A at its intersection between the two lines; as well as tied with line C at its intersection with line C.

Furthermore, the interface between the granitic soil and the granite bedrock can be observed from the signature of the velocity profile, and these also coincide with the available boreholes at the edge of the seismic lines. The bedrock level was estimated to vary between 35m to 75m from the ground level at this location.

4 DISCUSSION AND RESULTS

Through calibration with available borehole data, the derived velocity of the compression waves in granitic rocks (G II, G III, G IV) was found to be in the range of 4500m/s to 7000m/s. Fig. 9 is the end result of derived 3-D Common Depth Points and stacking bins; and shows bedrock to lie within the range of RL 55.0 m (northern end of tunnel) and RL 73 m (southern end of tunnel).

Comparing the interpreted bedrock levels with level of bored upper tunnel, the upper-stacked tunnel will not be expected to encounter any igneous rock of the Bukit Timah Granite formation. In taking the 6.5 m tunnel diameter into account, the northern and southern ends of lower-stacked tunnel path will be between 78-85 m RL and 79-86 m RL respectively. At the northern end, the lower tunnel will traverse at least about 23 m above bedrock. At the southern end, the lower tunnel will also traverse above bedrock. The clearance is estimated at least about 6 m. Fig. 10 shows the bedrock depth obtained from seismic survey that was superimposed onto the longitudinal cross-section of the stacked tunnels.
CONCLUSION

A 3-D seismic survey was carried out successfully in the Thomson Line project, where a clear velocity signature was helpful in identifying the bedrock from the soils of Bukit Timah Granite. Characteristic seismic velocity of granitic rocks (G II, G III, G IV) at the area was found to range between 4500m/s and 7000m/s. Findings from the 3-D seismic survey concluded that the stacked bored tunnelling will be conducted in a full-face soil condition, as the granite bedrock is below the stacked tunnels where the TBMs undercross the private property. As the findings using this seismic investigation appeared to be plausible, the 3-D seismic method was again engaged for subsequent sections of tunnel route of the TSL. A good understanding of the geological condition using the 3-D seismic survey technique will be helpful to the tunnel contractor with regards to his planning and implementation of mitigation measures as necessary.

REFERENCES