3D Wireless Seismic Survey Technology and its Application in Hong Kong

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ABSTRACT

Design and construction of underground structures, such as basements and tunnels, always face the risk of unforeseen ground conditions, which are difficult to determine based on preliminary GI information. Traditionally, GI information, such as desk study, trial pits, and boreholes can only provide discrete details. This leads to unnecessary design review and introduces additional time and cost implications to the project. Seismic surveys, commonly used in the "Oil & Gas" industry, may provide an alternative solution to allow the interested parties to acquire valuable underground information through a non-destructive approach. In this paper, an advanced 3D wireless seismic survey technology will be introduced, which has recently been conducted in Hong Kong to collect additional underground information for the construction work. The technology uses unique seismic sources combined with an expandable wireless multi-channel seismic data acquisition system and GPS to collect comprehensive seismic data. These recordings are taken and, using specialised seismic data processing, transformed into 3D visual images of the earth's subsurface in the survey area. And geoscientists can indirectly use those seismic data to obtain a picture of the structure and nature of the stratum and rock layers' structure and character. The technology is instrumental in urban areas as it possesses the flexibility and mechanism to scan the location where the surface is obstructed by structures.

Keywords: Seismic Survey' Subsurface, Underground Obstructions

1 Introduction

Mapping the shallow near-surface geology for construction purposes in a "City" environment has always been a challenge. In the case of this subject matter, we are engaged to construct a subway tunnel beneath the major high-speed road (RED route) by the trenchless method, where the road comprises eleven lanes of highway lanes, one small side road, one wide pedestrian path and several central reservations and verges. The subway will be constructed by the Jack-in place segment RTBM method; it is essential fully understand the underground geology condition before the machine design. As the highway structure is the primary route for vehicular traffic in the East Kowloon area, any lane closure for the destructive survey is impossible. A seismic survey is then deployed as an alternative approach to achieve the objective.

The challenge, therefore, was to acquire high resolution, high-quality geophysical data, to a depth of 100+ meters, beneath a highway that is subject to 24 hours heavy traffic flow, where the random acoustic noise that such an environment creates needed to be attenuated, and where the artificial seismic source signal needs to be amplified.

This project had demonstrated that with the advanced wireless seismic devices and details work planning, a comprehensive seismic survey (3D mapping) to the area of interest, which is obstructed by existing structures or even inaccessible, can be done. The team included a task force in Hong Kong which was responsible for field equipment and facilities setup and operation; the acquired data were

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positioned by GPS and instantaneously sent to the data centre in Singapore, which was supported by a crew of geophysics technicians, verifying and accepting the data and gave a real-time response in case abnormality was found during the operation. The results from the survey are sent to geophysics experts for analysis and interpretation in Australia. The whole process was a joint effort by specialists worldwide, and the findings will benefit designers / interested parties in the project.

2 Wireless Seismic Survey Technology and its Application in Hong Kong

In land seismic surveying, sound waves are mechanically generated and sent into the earth. Some of this energy is reflected back to recording sensors, measuring devices that record accurately the strength of this energy and the time it has taken for this energy to travel through the various layers of geological layers and back to the locations of the sensors. Some of this energy is also refracted back to the recording sensors, giving precise velocity information of the underlying strata as well as a velocity profile picture. These recordings are then taken and, using specialised seismic data processing, are transformed into visual images of the subsurface of the earth in the seismic survey area. Geoscientists use seismic surveying to obtain a picture of the structure and nature of the rock layers indirectly.

Energy from a sound source is released. The magnitude of the pressure is called ‘amplitude’, and the excited waves are P-waves or compressional waves. The energy source will propagate P-waves, and the sensors that will make accurate measurements of the amplitudes of P-waves are geophones. P-waves will hit the rock, and the reflected signals will be recorded.

In Land 2D operations, a single land seismic array is deployed together with a single seismic source. The reflections from the subsurface are assumed to lie directly below the line, providing an image in two dimensions (horizontal and vertical). In Land 3D operations, two or more land seismic arrays are deployed together with single or multiple seismic sources. The reflections from the subsurface are collected through a range of azimuths delivering what is generally known as wide azimuth 3D data. The two operations supplement each other.

Where obstructions and impediments prevent continuous/contiguous data acquisition, use a wireless seismic recording system to either “shoot around” or “undershoot” any such obstructions. This array layout shall be designed on a case by case basis based on experience in acquiring data in such conditions. To meet the geophysical objectives, a high-density spread of geophones was deployed and placed in closed lanes. The geophones were positioned to give wide azimuth, near, mid & far offsets from the seismic source, delivering (>1,500,000) common data points across the entire area of interest. The whole survey took 17 days to acquire, where one “traffic lane” of data and two “verges” of data was obtained during each nighttime data acquisition period (2 hours only per night) to minimise disturbance to the traffic flow.

Geological objectives of this survey are summarised as follows:-

a) Measure the interface between the Fill, Alluvium, Weathered Granite and Fresh Granite.
b) Geological target depth of interest was 5 meters to 100+ meters depth range.
c) Identify any geological anomalies, including boulders > 250 mm in size, cavities and voids
d) Compare results with known geological data, including borehole data.
e) Deliver an accurate geological interpretation of the seismic survey results showing the geological profile, identified and unidentified objects, cavities, voids, faults and fracture zones.

The Resulting “Survey plan and method” to meet the geological objectives:-

a) The most appropriate identified geophysical method was a 3D seismic survey, using a wireless seismic recording system with a portable seismic energy source.
b) Seismic spread layout required to meet geological objective was;
    i. 1 x Floating geophone sub-array patch comprising 48 Geophones (arranged in a 3 x 16

Geophone array) (rolling across 13 traffic lanes) and

ii. 2 x Fixed geophone sub-array patches comprise 96 Geophones (arranged in two separate 3 x 16 Geophone arrays) (Placed on the central verges) across the defined survey area.

c) Source to receiver offsets were arranged such that the shallow to deeper geological target ranges could be imaged with a wide range of offsets and a broad range of azimuths.

d) Conduct 3D reflection seismic data processing and data interpretation.

e) Survey Geometry requirement; Receiver interval 1 meter, Shot interval 0.5 metres, asymmetrically derived CMP interval was 12.5 centimetres, and resulting CMP bin size of 12.5. x 12.5 centimetres.

f) Deliver the investigation results and interpretation in a compiled report with supporting documentation.

(More conventional seismic methods (i.e. Cabled reflection, refraction, MASW, downhole cross-hole, GPR were all excluded as viable geophysical methods as a) they Cannot be deployed across a highway, b) Resulting data would not be conducive to nor meet the prescribed geological objectives, i.e. depth, accuracy, resolution, wide azimuth 3D spatial coverage and resolution.)

Technical Objectives:

a) Acquire high-quality seismic data within or exceed manufacturers' specifications and capabilities.

b) Record data within 0 - 100+ m below ground level.

Operational Objectives:

a) Acquire data set on time, with no accidents, no harm to people and no damage to the environment.

b) To implement all necessary HSE measures according to Industry and regulatory authorities.

Survey Area overview

The survey area was located in Hong Kong, beneath the Prince Edward Road East highway. See Figures 1 & 2.

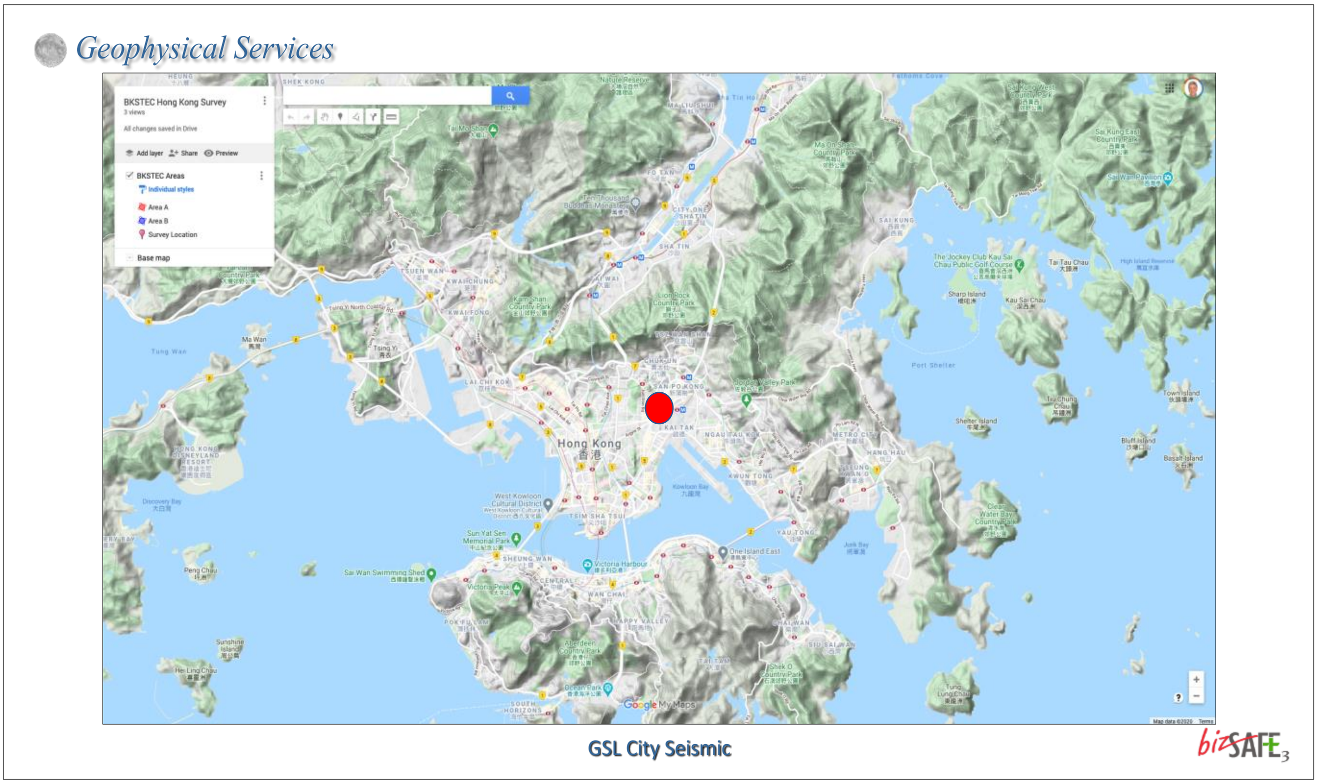

Figure 1; Showing survey location in Hong Kong (Red marker)

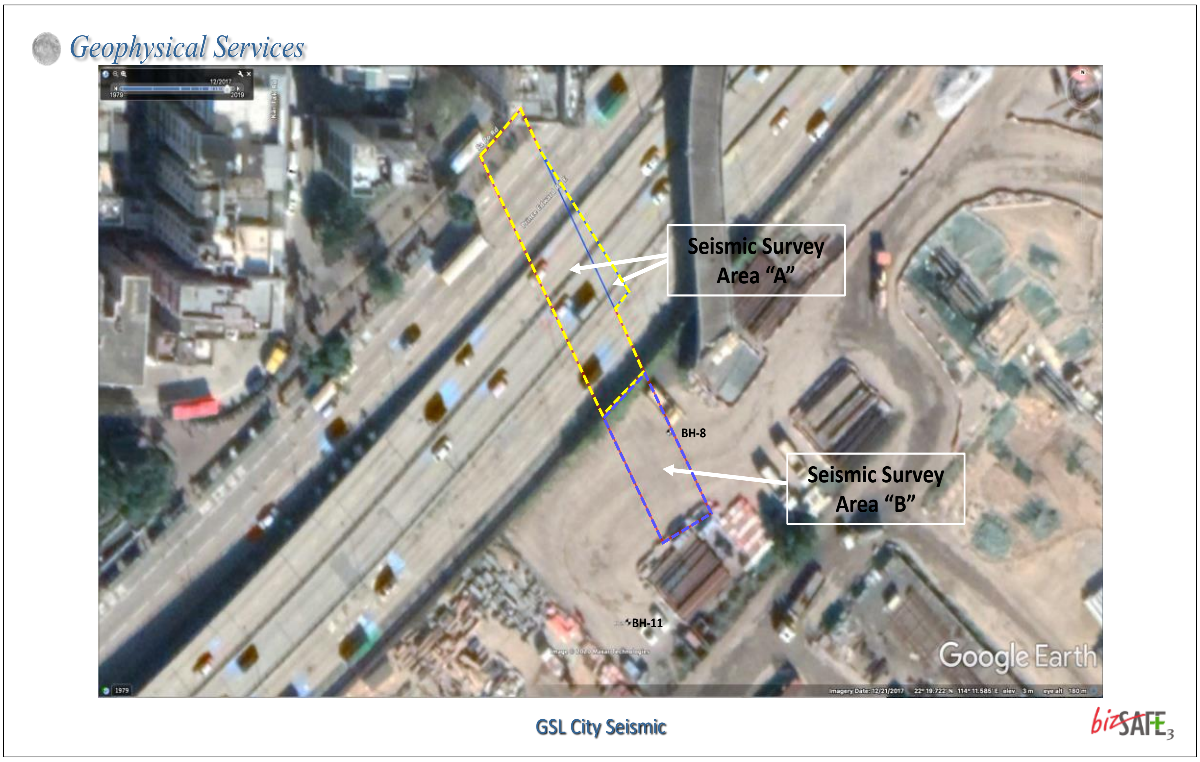

Figure 2; Showing satellite view of survey area across the Prince Edward Road East highway

The area can be described as residential on the north side of the highway, with many high-rise residential apartment blocks on the periphery of the work area. This presents environmental challenges concerning the noise emitted by the seismic energy source.

The main issue was balancing heavy vehicular traffic noise interference with the seismic signals versus disturbance to the residents during the early hours when the noise created by the seismic source could disturb the residents' sleep.

The geology based on borehole information and historical geological information indicates that the area comprises the following:

a) Reclaimed land, road tarmac and path surface; b) Land Fill; c) Alluvium; d) Weathered Hong Kong Granite; e) Fresh Hong Kong Granite

Figures 2 & 3 show the survey area depicted across the PERE Highway. One can clearly understand from this satellite picture the operational challenges involved with acquiring geophysical data across an extremely busy highway. Figure 4 is an excerpt from the Geological Interpretive Baseline Report showing the work area versus the roads and local building infrastructure, including three nearby boreholes.

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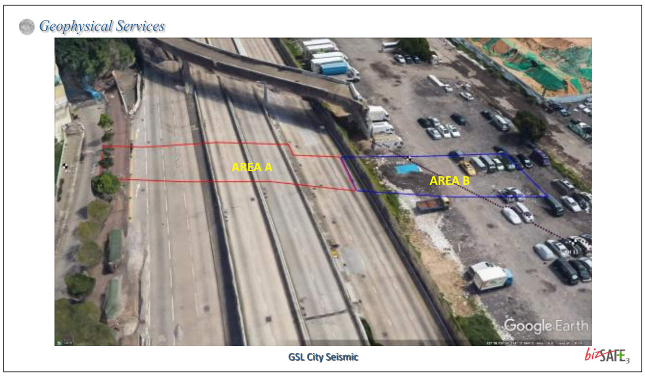

Figure 3; Showing satellite view of survey area across the Prince Edward Road East highway

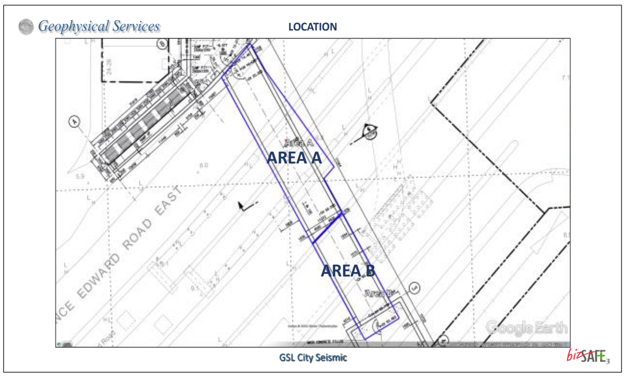

Figure 4; Showing GIBR plan of seismic survey area overlay onto topo map

The local environmental situation as described above clearly shows the physical limitations imposed on the survey design and survey acquisition teams. Further to this, there are practical limitations imposed upon the planned survey, including the following:-

a) Working hours are limited to 2 hours per day between 2 a.m. to 4 a.m.
b) Noise limitations imposed during night hours. (Use noise enclosure)
c) Traffic disruption, one traffic lane, for 2 hours/day during off-peak hours.

Final resulting survey patch layout (See figures 5, 6, 8 & 9) comprised the following:-

Array Type	Patches	Geophone Arrangement	Location
Floating Sub-Array	13	One x 48 geophones laid out in a symmetrical 3 x 16 geophone array with 1 meters receiver spacing	Traffic lanes 1 to 13
Fixed Sub-Array	2	Two x 48 geophones laid out in a symmetrical 3 x 16 geophone array with 1 meters receiver spacing	Verges 1 & 2
Offset ranges		0 - 75 meters Shot to Receiver, horizontal distance	

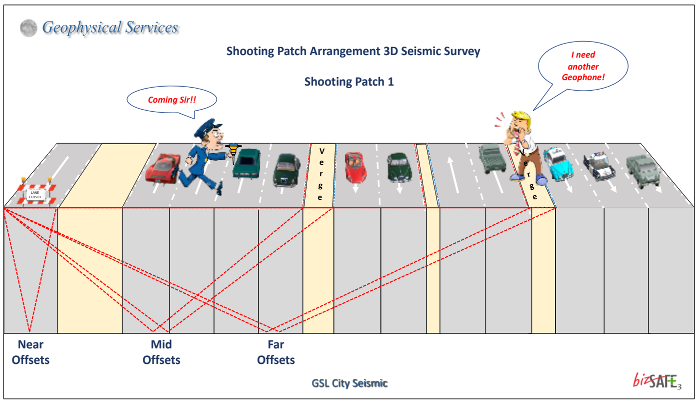

Figure 5; Showing Geophone sub-arrays and seismic ray-paths where seismic source is in lane 1

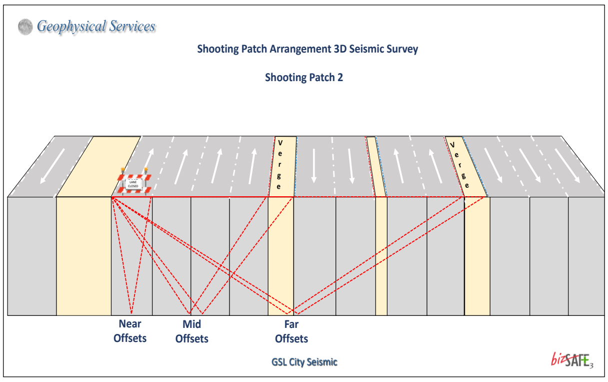

Figure 6; Showing Geophone sub-arrays and seismic ray-paths where seismic source is in lane 3

The resultant Geophone plan and shooting arrangement based on area access and geological objectives are described as follows:

a) Geophones (Floating Sub-array) were placed in the one (1) closed traffic lane, and this sub-array was moved across the traffic lanes, one new lane each night, onto a newly closed lane. (See figs 8 & 9)

b) Geophones (Fixed sub-arrays) were placed in two of the central verges, permanent throughout the survey. (See figs 8 & 9)

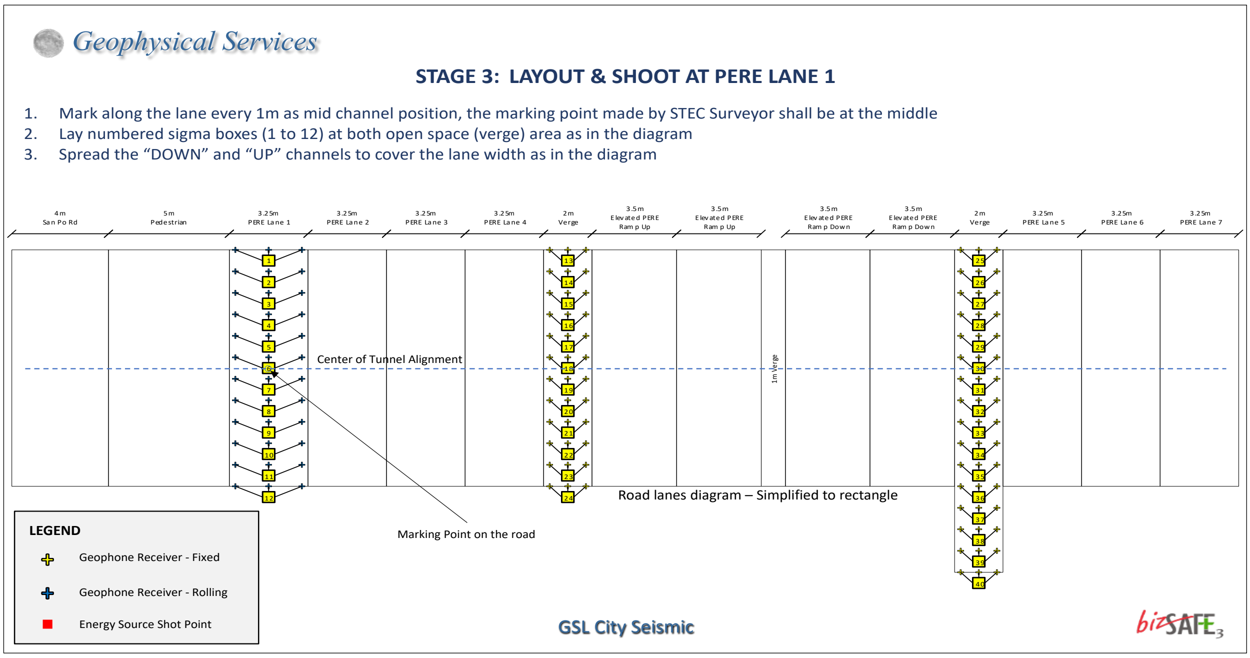

Figure 8; Showing Seismic survey sub-array(s) geophone deployment

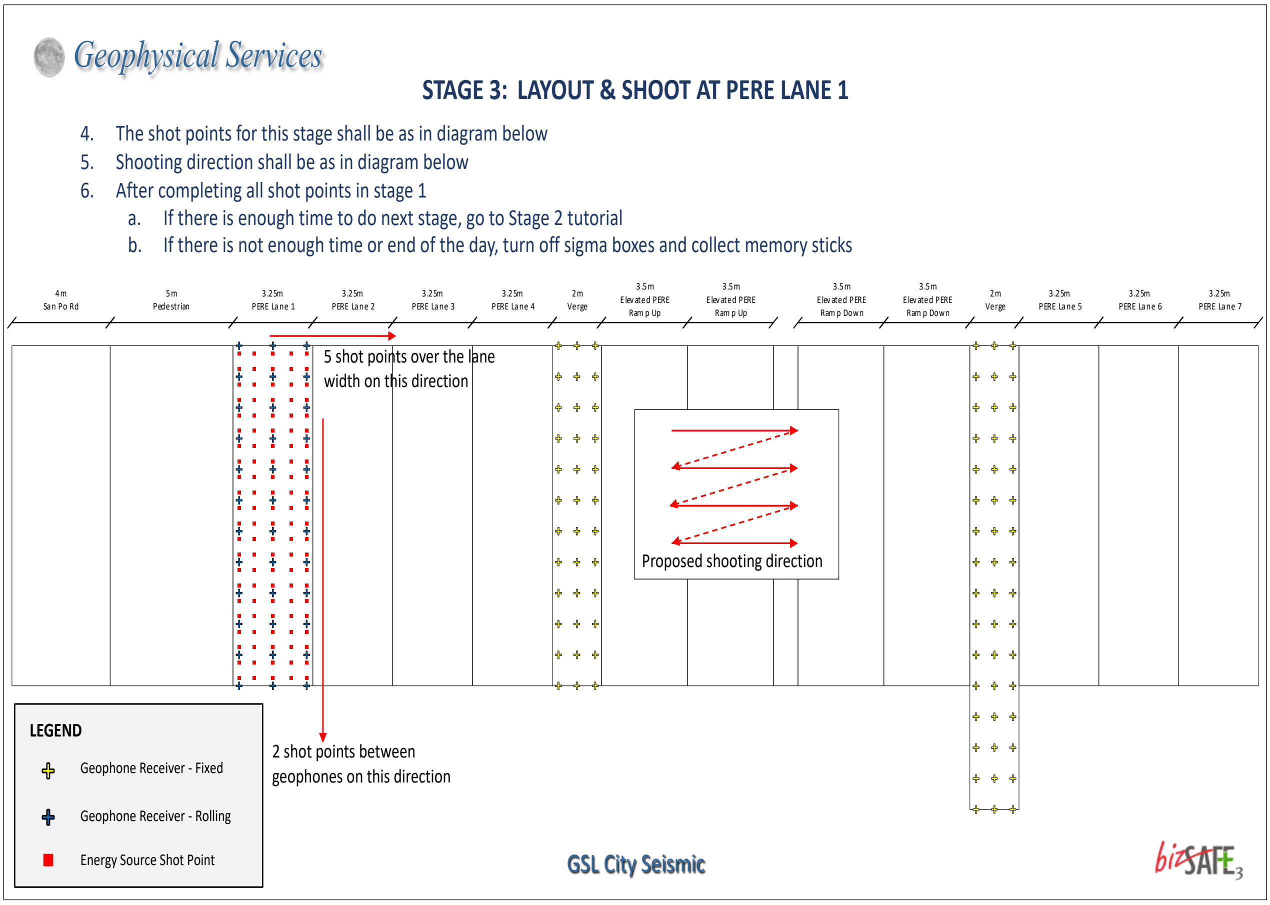

Figure 9; Showing Seismic survey sub-array(s) geophone point and shot point arrangement

2.1 Data Acquisition

For this survey, the following survey parameters were used:-

Type of Seismic Survey:	3D Land / Onshore
Recording System:	i-Seis Sigma
Recording Length:	1 second
Sampling Rate:	0.25 ms
Energy Source Type:	PSS-100 Portable Source
Thumps Per Shot:	3 thumps per shot point
No. of Groups:	3 x 48 GS-One geophones sub-arrays (15 meters x 3.5 meters)
Shot Interval:	0.5 m
Group Interval:	1.0 m
CMP Bin Size:	12.5 x 12.5 cms

Access to the survey area was restricted to two hours per day (between 2 a.m. to 4 a.m.).

The receivers were laid out in the pattern shown in figure 8, where one (1) road lane was closed for the Floating Sub-array (Near seismic channels) during each data acquisition period and where two Fixed Sub-arrays (mid and far seismic channels) were placed permanently in the centre of the highway on easily accessible road verges. (See figure 10 & figure 11). There were 13 x Floating sub-array rolls across the highway (figure 2. Seismic Survey Area "A"), with additional patches shot in the waste ground to the south of the highway (figure 2. Seismic Survey Area "B").

Figure 10; Showing Seismic survey Floating sub-array & Fixed Sub-array geophone deployment

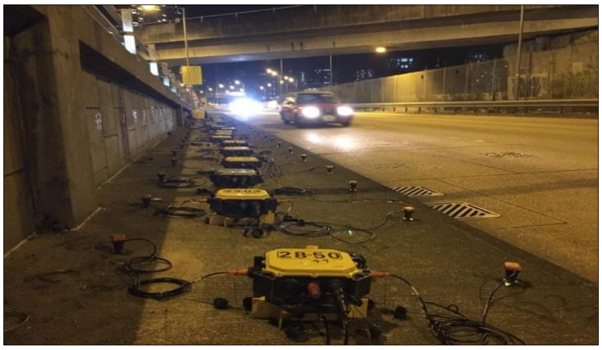

Figure 11; Showing Seismic survey Fixed sub-array(s) geophone deployment

Resulting data, Raw data, 3D binning & Fold coverage;

- At each shot point, three (3) thumps were emitted from the energy source.
- The three thumps were stacked into a single V-Stack in processing, thus eliminating a significant amount of the surrounding area generated ambient noise, i.e. improving the signal to noise ratio by a factor of 3:1
- The fold coverage achieved was in the order of 150 fold, further eliminating the ambient noise.
- The entire survey area was a rectangle of dimensions 15m x 100m. For seismic survey purposes, this rectangle was further sub-divided (in processing) into small squares (12 cms x 12 cms). The common midpoints were accurately binned, resulting in an almost perfectly symmetrical binned data set.
- Figure 12 shows the midpoint distribution of the acquired 3D seismic data set.

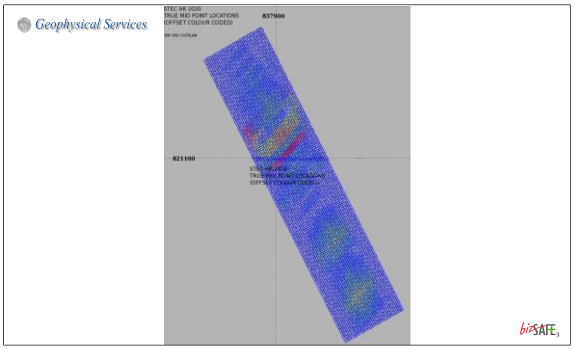

Figure 12; Showing True Mid-Point scatter of CMP data.

- Figure 13 shows Raw Shot data
- Figure 14 shows the final post-plot shot & receiver points across the entire area

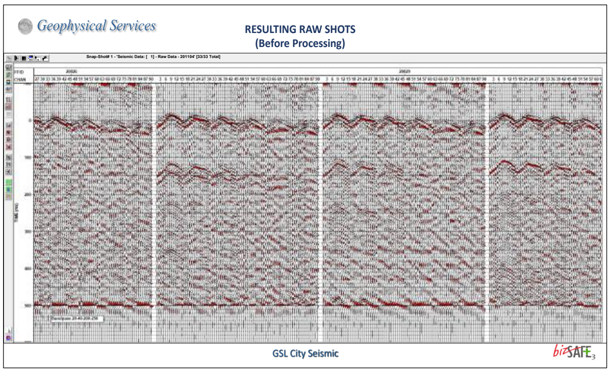

Figure 13; Raw Shot records across 3 Sub-Arrays

Figure 14; Post-Plot diagram showing each and every shot point and receiver points across the entire survey area

3 Data Processing

Acquisition and survey parameters

3D survey description

The 3D survey consisted of approximately 11300 shot records acquired at 3876 shot locations over an area of 1435 square metres.

Trace parameters		**Source parameters**	
Record length:	600 milliseconds	Source type:	Accelerated weight drop
Sample interval:	0.25 milliseconds	Thumps per shot location:	3 (nominal)

	AREA "A" (Northern Area)	**AREA "B" (Southern Area)**
Receiver line spacing:	1.25 metres	2.0 metres
Receiver interval:	1.0 metres	1.0 metres
Source line spacing:	0.6 metres	1.0 metres
Source interval:	0.5 metres	0.5 metres

The live patch typically consists of 9 receiver lines, with up to 144 live channels.

2D survey description

Line length:	54 metres	Shot interval:	1.0 metre
Receiver interval:	1 metre	CMP interval:	0.5 metres

Output grid was aligned with the planned tunnel, and the Bin dimensions were: 0.5m x 0.5m

Comments on input data, output data, and processing

The survey consisted of a full-azimuth, high-density, high-quality 3D field. The receiver and source arrays were filled-grid, apart from a small number of gaps due to obstacles. The polarity convention used is such that a positive impedance change results in a positive deflection. The ambient noise was moderate. The hard tarmac surface in places was a cause for high-frequency reverberation, largely ameliorated by adaptive noise removal techniques. To suit various purposes, three different versions of the data were produced with different spectral weighting, referred to as non-spectral weighting, milder spectral weighting and stronger spectral weighting. The strong spectral weighting option resulted in a volume with a dominant frequency of 290 Hz at the target depth, and the milder option had a dominant frequency of 215 Hz. In the target area, the maximum frequency of useful reflection data was approximately 400 Hz.

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Processing sequence summary

Three different versions of the output were produced, referred to as the non-spectral weighting, milder spectral weighting, and stronger spectral weighting options, to give the interpreters a choice of which frequency balance was suitable for various aspects of the analysis.

1. Reformat to Globe Claritas internal format
2. Apply geometry headers from observer's logs, apply 0.5 x 0.5 rectilinear grid geometry
3. ad shot and trace edit
4. Shot summation (diversity summation)
5. First break picking and refraction model calculation
6. Spherical divergence correction (G=V^2*T) using regional velocities
7. Random & linear noise attenuation (Mintox ANA)
8. Gap deconvolution (adaptive deconvolution used in some areas)
9. Refraction statics application
10. First-pass velocity analysis at 10 m x 10 m intervals
11. Residual statics calculation
12. Second pass velocity analysis at 5 m x 10 m intervals
13. NMO using 2nd pass velocities
14. Residual statics application
15. CMP trim statics calculation and application
16. Stacking mute, hand-picked
17. Pre-stack scaling
18. Stack
19. Post-stack spectral weighting, coherency filtering, bandpass filtering, scaling
20. Phase correction
21. Shift to final datum
22. -> SEG-Y out time-domain stacks
23. Depth conversion using a simple velocity model
24. -> SEG-Y out depth domain stacks at final datum

4 Data Interpretation

4.1 Geology of the Area

The geology of Hong Kong is described in detail in the "Geology Of Hong Kong (Interactive On-line)" publication of the Civil Engineering and Development Department (CEDD) of the Government of the Hong Kong Special Administrative Region. Figure 1 is taken from that report and is a map of the geology of Hong Kong.

Geophysical Services

Figure 1

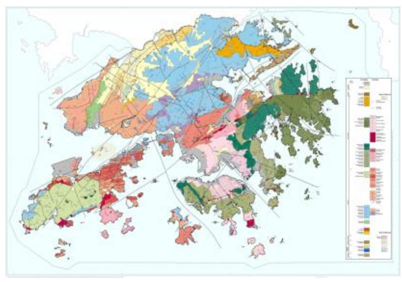

Figure 1. Generalized Geology Of Hong Kong (CEDD)

GSL City Seismic

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The survey was in the Kowloon area (Figure 2), where granite is exposed at the surface north and west of the survey area. Granite is also found underfill and Quaternary alluvial and colluvial sediments in the specific survey area. A marine survey map of 1841 (Figure 3) shows the presence of granite cored islands just offshore of the survey area in an area now entirely covered by fill. It is possible that similar pinnacles of fresh granite could be present in the survey area.

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Figure 2

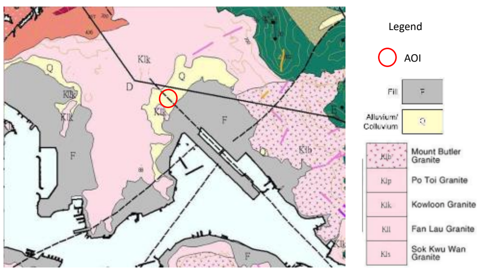

Figure 2. Generalized Geology Of AOI (CEDD)

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Figure 3

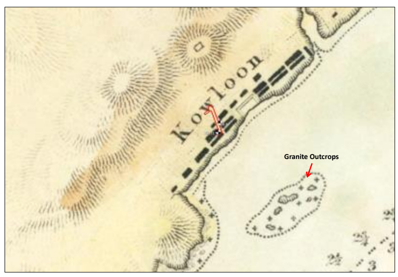

Figure 3. 1841 Marine Chart HMS Sulphur

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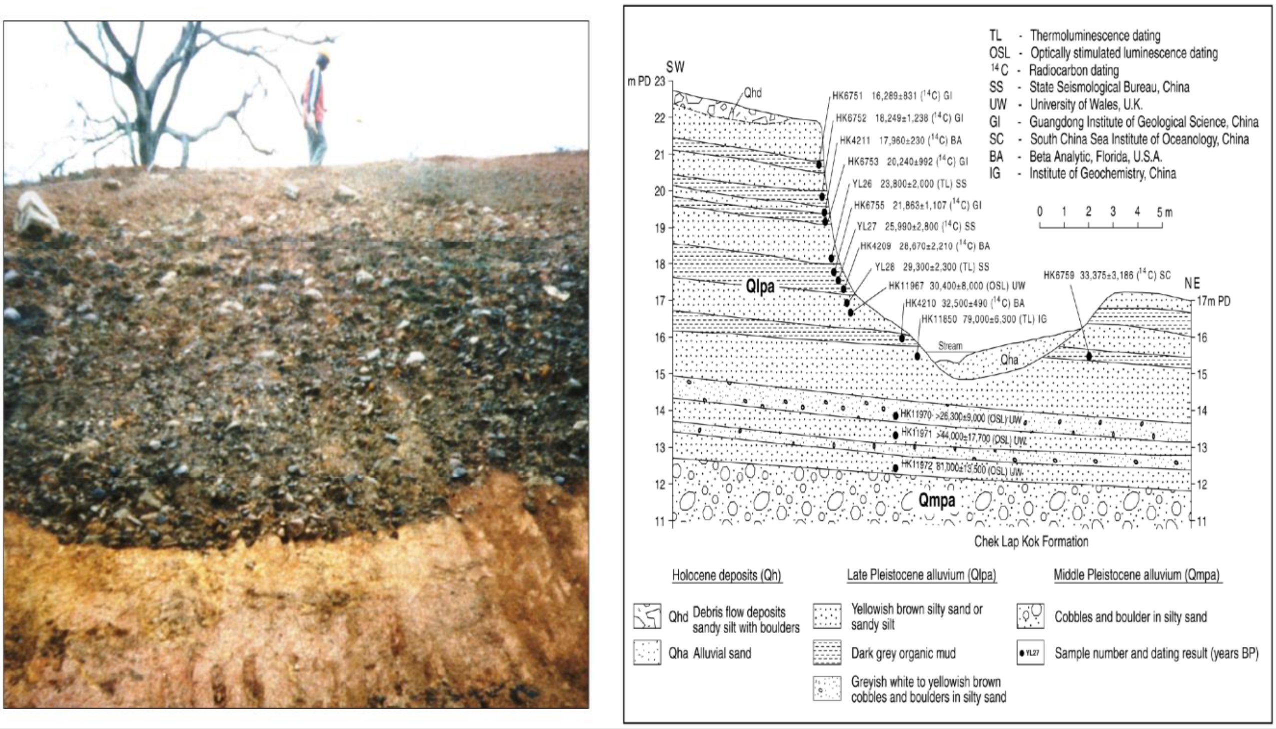
Mesozoic granitic and volcanic rocks make up almost 85% of the rock outcrop on land. Several distinct granitic terrains are recognised. The remaining area is comprised of Pleistocene to recent colluvial and alluvial deposits. Colluvium covers most hillsides in thin layers and can be thick in granitic terrains. Cobbles and boulders can be present. Alluvium can be found in river valleys, coastal floodplains, and deltas. In the survey area, 15 to 30 meters of alluvium is measured. Figure 4 is taken from K. W. Lai and shows an outcrop of alluvium with abundant cobbles present.

Figure 4

Geophysical Services



4.2 Kowloon and Mt Butler Granites

The survey area is underlain by the Kowloon and Mount Butler Granites that form sub-circular plutons centred on Kowloon and Hong Kong Island. The Kowloon Granite is uniform in texture and composition and is typically a biotite monzogranite. The Mount Butler Granite, a subcircular leucocratic monzogranite, intrudes the Kowloon Granite. Pegmatite patches and miarolitic cavities are common, particularly close to the granite–volcanic contact.

4.3 Weathering Profiles

The weathering profile of the Kowloon and Buter Granites has been established (Shaw, 1997) using borehole records supported by field mapping. The correlation between the topography of the weathered profile base and the main structural trends is evident. Zones of deep weathering have been preferentially eroded to create valleys, which subsequently became sites of alluvial and colluvial accumulation. Variations in weathering patterns are primarily a function of the geometry and infilling of relict jointing, which determines local hydrogeology and hence the intensity of weathering. Corestones are generally restricted to weathered profiles over topographically high areas, the locations of which are controlled by regional joint spacing and orientation. Corestone-bearing profiles are rare, and more commonly, deeply weathered granite without corestones passes abruptly into relatively fresh rock. This has important implications for engineering ground models derived from borehole interpretation.

Granite exhibits a multi-layered weathering profile near the surface, as described in Figure 5. In engineering terms, the GIII is generally considered the "Rockhead", although GIV is a transition zone that may comprise highly weathered intact rock, fractured rock or a mix of GV and GIII rocks. In some cases, GIV is considered "Rockhead". While GV and GVI are considered soils, they are often described as hard, dense to very dense and may impact engineering projects such as dredging.

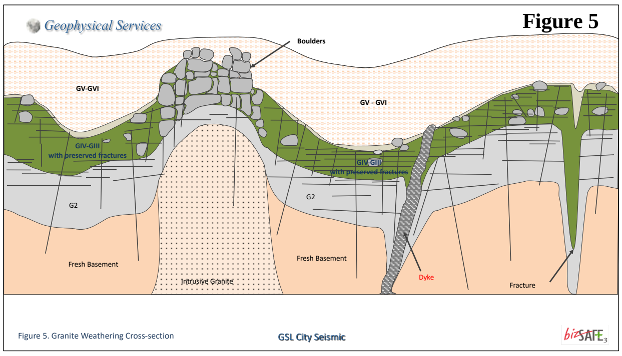


Figure 5. Granite Weathering Cross-section

The Rockhead granite (GIII/GIV or greater) is typically undulating, with frequent domes and valleys as seen. Intrusive granite domes may cause harder rock to be nearer the surface, and occasionally, intrusive dykes may be present. Fractures can often result in a deeper weathering profile.

4.4 Data

- Three boreholes, BH-5, BH-8 and BH-11, which prove relevant to the survey, were provided. Additional boreholes that are not within the survey were also offered. The borehole locations are shown in Figure 6a.
- Potential Hazard objects were also provided. These included five pipeline locations with depths Figure 6b.
- An elevation model derived from the seismic survey data.
- The 3D seismic survey comprised 1435 square meters of high-resolution seismic reflection and velocity data coverage. The data was provided in Time and Depth domains with a low-frequency 3D cube for event mapping and a high-frequency 3D cube for attribute analysis. The data quality is good to very good.
- Interval Velocity Volume for the 3D cube.

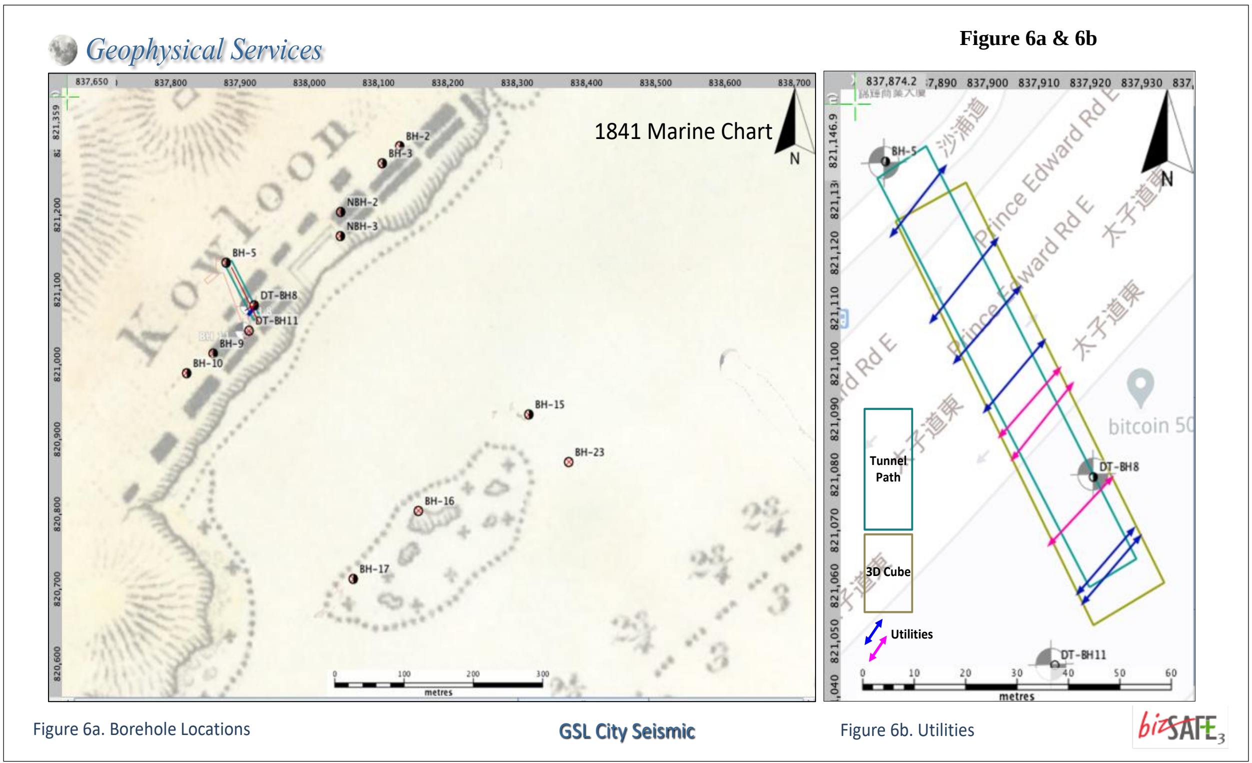


Figure 6a. Borehole Locations

Figure 6b. Utilities

- A 2D seismic profile crossing the 3D and tying to BH-8 and BH-11. Also, in Time and Depth. The data quality is good to very good.
- Various geological and geophysical data available in the public domain were collected and referenced herein.

5 Analysis

5.1 Borehole descriptions

The boreholes describe mixed fill comprised of rock and concrete fragments, some asphalt and clayey sand, silty sand and gravels to a thickness of 6.6 meters. There are thin layers of pavement in places. The alluvium comprised of mixed sand, gravel, clayey sand, and silty sand is encountered. The alluvium is up to 30 meters in thickness. There is no mention of cobbles or boulders being encountered in the alluvium. Marine deposits encountered in BH 11 are sandy with shell fragments. Completely decomposed granite Grade V is described as extremely weak, white and pink to dark brown-grey to spotted white, medium-grained. It reaches 36 meters in thickness. Grade IV granite is described as white to pink and medium-grained. This is transitional to Rockhead (Grade III). The granite is described as pink, spotted white to yellowish-brown, moderately strong to strong with weaker intervals. Jointing and fractures are observed.

5.2 Borehole to seismic ties

Borehole 8 ties to both the 3D volume and the 2D profile. Borehole 11 ties to the 2D profile only. Figure 7 shows the tie to BH 8 within the 3D cube. The key surfaces identified are Base Fill (orange), Granite GV/Base Alluvium (yellow) and "Rockhead" Granite GIII/GIV (Purple). Additionally, three intra alluvium events A, B, and C, are identified. Boreholes 8 and 11 are tied to the 2D seismic profile in Figure 8. The same key surfaces are tied to both boreholes, while an additional Base Marine E surface can be mapped in the BH-11 area. In 2D, the GIV and GIII GRANITE grades can be differentiated, while in 3D, the surface is more gradational between the two grades.

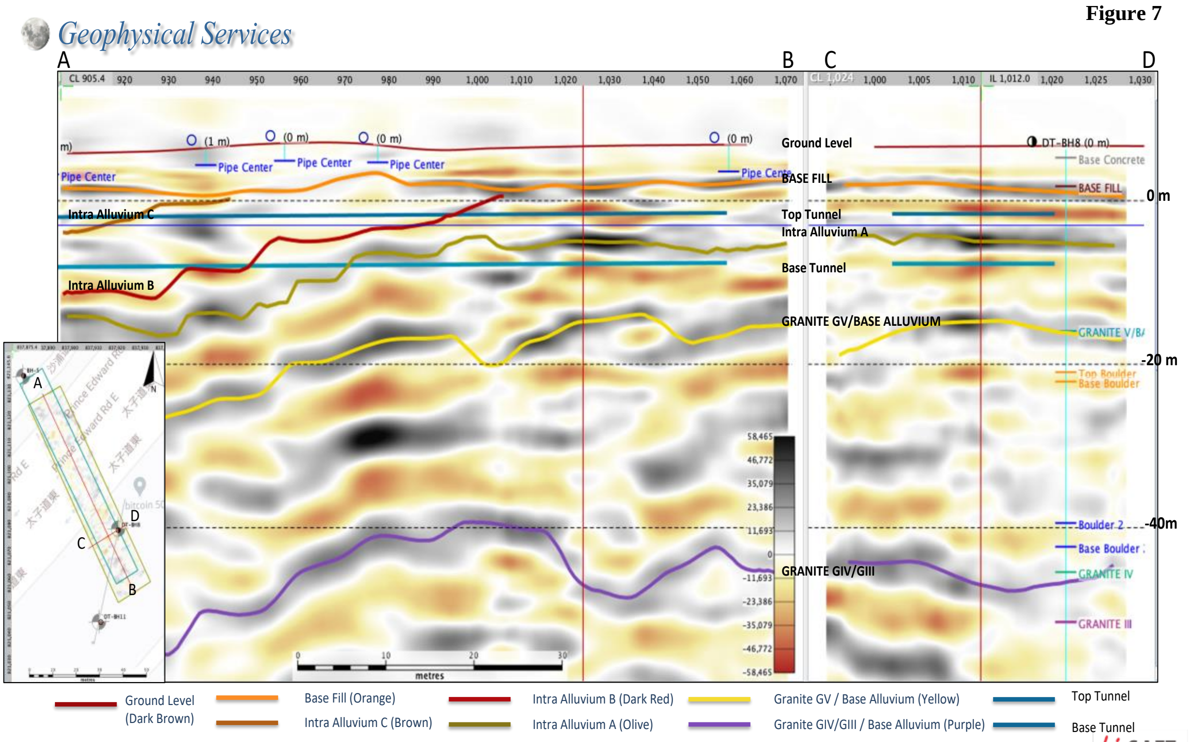


Figure 7. Seismic To Well Ties 3D

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The pre-survey analysis of the three boreholes indicated that the tunnel would pass through alluvium with some possible marine deposits in the southern end. This finding is supported by the Borehole to Seismic ties.

Figure 8

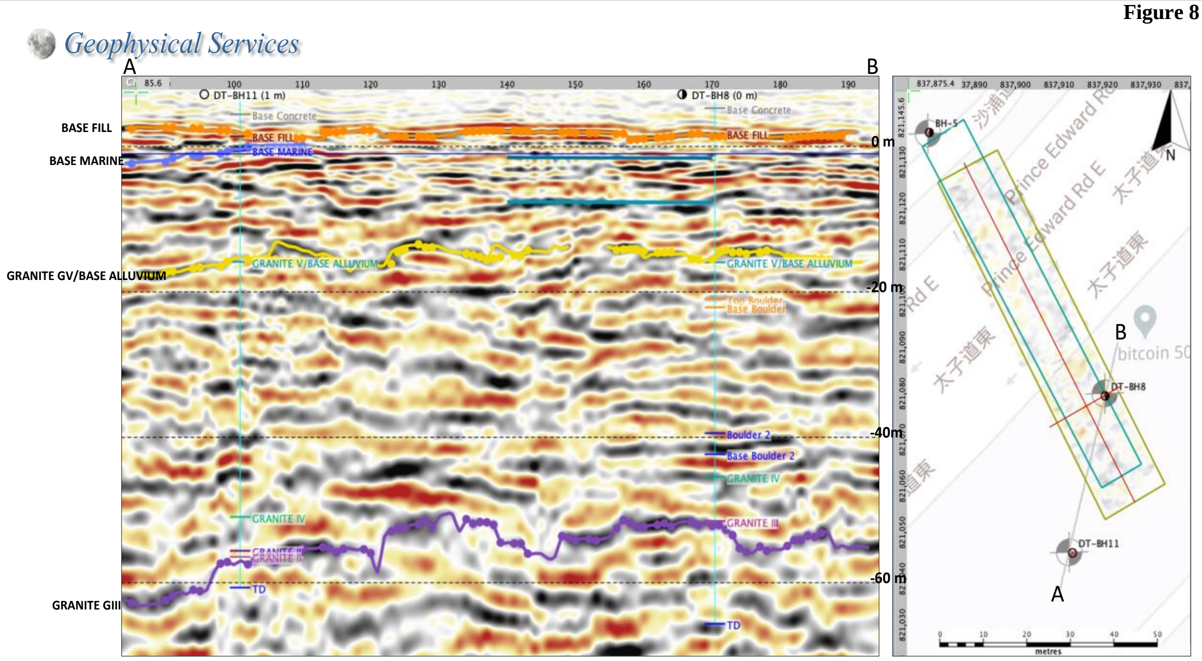

Figure 8. Seismic To Well Ties 2D

GSL City Seismic

5.3 Resolution

Figure 9

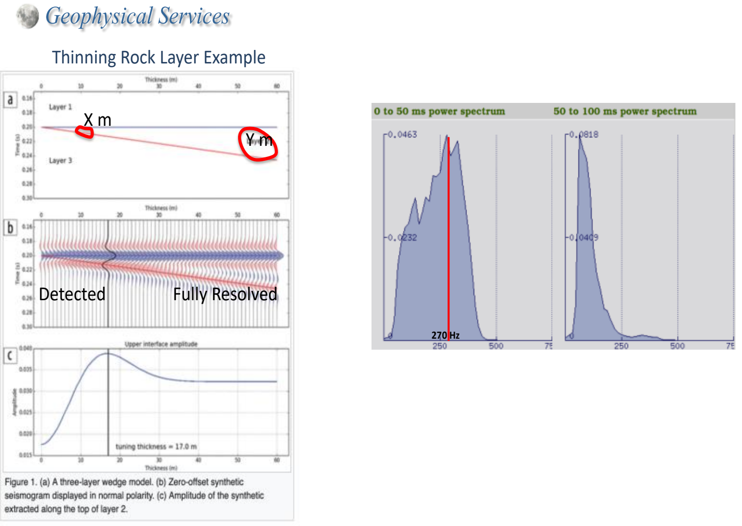

Figure 9. Data Resolution.

GSL City Seismic

A good seismic signal is observed down to at least -50 meters HKPD. This is well below the base of the zone of interest, which is roughly -1 to -7 m HKPD. The "Rockhead" granite is observed at -40 to -50 m HKPD. In high-resolution seismic surveying for Civil Engineering, understanding the limits of resolvability vs detection is critical. In general, seismic data can resolve the top and base of an event or feature, such as a boulder bed, if the feature is >=λ/4, where Lambda is the dominant wavelength. To calculate Lambda, use λ= v/f where v = velocity of feature to be resolved, and f is the dominant frequency. Figure 9 shows the calculated frequency spectra in the data. The dominant frequency is 270 Hz. A wedge model often used to explain resolution and detection is also displayed. Given a peak frequency of 270 Hz, cobbles or boulders of hazardous size are assumed to be resolvable in the tunnel path.

5.4 Seismic Attributes

The interpretation methodology uses seismic attributes. The following is a discussion of some of the attributes used (Tanner et al.). Seismic attributes are measurable properties of seismic data such as amplitude, dip, frequency, phase and polarity. Attributes can be measured at one instant in time or over a window of data. They can be calculated on a single seismic trace (one x, y, z data point), a set of paths, or on a seismic surface (geological event) interpreted on the seismic data. Seismic attributes reveal features, relationships and patterns in seismic data that may otherwise not be noticed.

The instantaneous phase attribute is a physical attribute and can be effectively used as a discriminator for geometrical shape classifications, such as lateral continuity, sequence boundaries, bedding configuration and edges. The instantaneous amplitude measures the reflectivity strength, which is proportional to the square root of the total energy of the seismic signal at an instant of time.

It is a measure of reflection strength and can be used to identify lithological contrasts, bedding continuity, bed spacing (thickness), and gross porosity.

The instantaneous frequency is a seismic attribute, which is defined to be the time rate of change of the instantaneous phase. Instantaneous frequencies relate to the wave propagation and depositional environment; hence they are physical attributes and can be used as effective discriminators such as seismic character correlation in the lateral direction, Indication of the edges of low impedance thin beds, fracture zone indicator; they may appear as lower frequency zones, Chaotic reflection zone indicator, due to excessive scatters, bed thickness indicator. Higher frequencies indicate sharp interfaces or thin bedding; lower frequencies indicate thicker bedding. Sweetness is calculated by dividing the instantaneous amplitude (amplitude envelope) by the square root of the instantaneous frequency. The Sweetness attribute reduces the contribution of the higher frequencies. And is useful for the identification of thicker, hard rock units (such as boulders or cobble zones), which will be seen as high amplitude/low-frequency values (DUG Insight software (v.5.1, 2021).

6 Seismic Events Identified, Horizons Mapped and layers Described

In Figure 7, the key surfaces were identified. These are Base Fill (orange), Intra Alluvium C (brown), Intra Alluvium B (dark red), Intra Alluvium A (olive), Granite GV/Base Alluvium (yellow) and Granite Grade GIV/GIII (purple). The ground level is o displayed as dark brown. The ground level surface was derived from the surveying operation undertaken for the 3D shot/receiver layout.

Figure 10

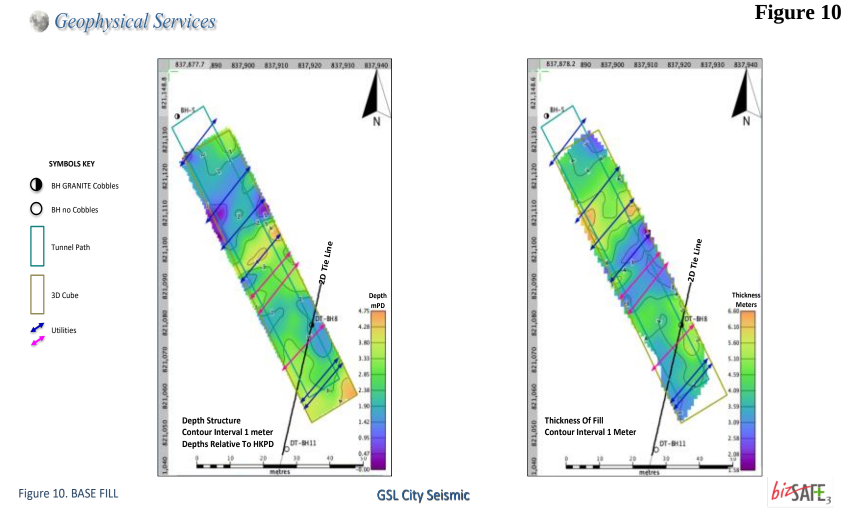

Figure 10. BASE FILL

The Base Fill map (Figure 10) defines the bottom of the Fill layer. The surface is fairly flat but slightly undulating. The depth ranges from 0 mPD to almost 5 mPD. The Fill comprises rock and concrete

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fragments, some asphalt and clayey SAND, silty SAND and gravels. It varies from 1.6 to 6.6 meters in thickness. Cobbles of rock fragments cemented with concrete are mentioned in BH-8.

The upper portion of the fill layer will comprise concrete and asphalt road materials in the PERE area of the survey. Additionally, many utilities, including electricity cables, water and other pipes, are present in the FILL. These utilities can be seen in Figure 6b. No attempt to resolve these utilities was attempted.

6.1 The Alluvium Layers

Alluvium is described as consisting of unconsolidated detrital rock material deposited in stream beds or on a flood plain (K. W. Lai.). Three depositional layers are recognised in the outcrop. These are Middle Pleistocene, Late Pleistocene, and Holocene.

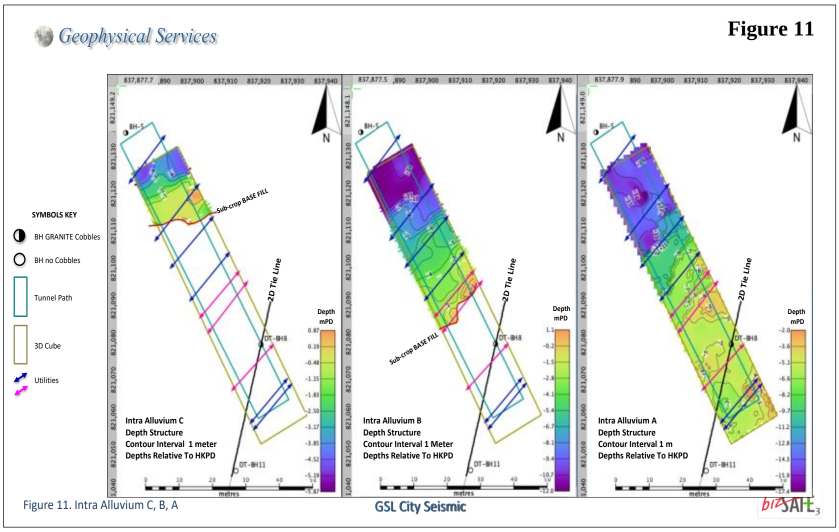

Figure 11. Intra Alluvium C, B, A

The alluvium can be sub-divided into three layers based on seismic data interpretation. This corresponds with what is observed in the outcrop. We have defined these layers as A, B and C from base to top (Figure 7). Layer A, which is considered to correspond to the Middle Pleistocene outcrop, is present throughout the survey area, while Layers B, Late Pleistocene and C Holocene, sub-crop the Base Fill (Figure 11).

The alluvium ranges from 16 to 31 meters (Figure 12) and thickens and plunges towards the NW. The depth ranges from -28 to -33 mPD.

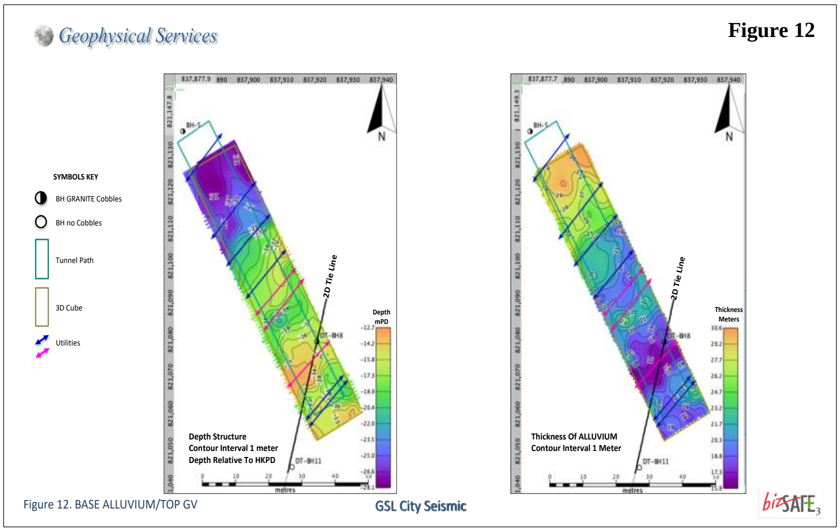

Figure 12. BASE ALLUVIUM/TOP GV

The alluvium, as described in outcrop and boreholes, is comprised of mixed sand, gravel, clayey sand and silty sand. Detailed descriptions of outcrop are found in K. W. Lai.

6.2 Weathered Granite

The GV weathered granite is between 18 and 36 meters thick (Figure 13). It is the thinnest in the centre of the survey. The granite is described in BH-8 as extremely weak, reddish yellow to dark brown-grey to spotted white, and medium-grained. Cobbles and boulders are present.

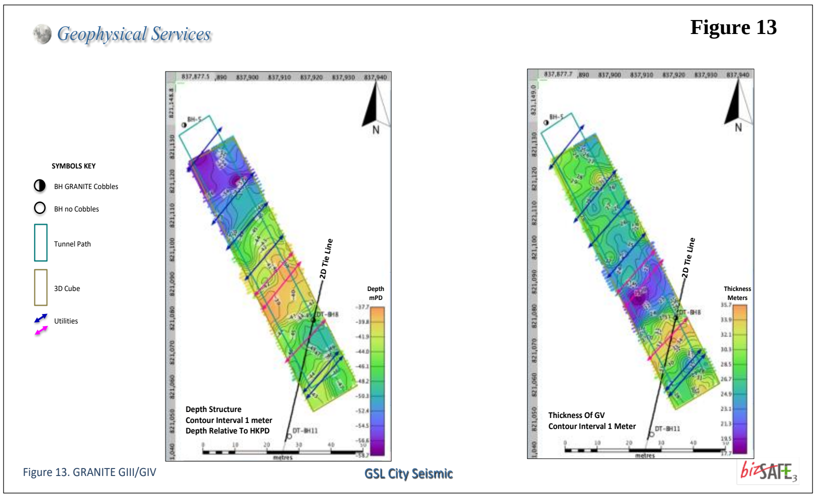

Figure 13. GRANITE GIII/GIV

6.3 Granite

The granite GIII/IV) is mapped at between -38 and – 59 mPD. It is at its shallowest in the survey centre, where it rises to -37.7 mPD. The GRANITE is described as pink to spotted white and black, moderately strong to strong. Jointing and fractures are observed. While the granite GIII/GIV does rise into a dome in the survey centre, it never reaches heights that could impact the tunnel boring (Figure 13).

7 Discussion of Results

7.1 Known and Unknown Potential Hazards

Known hazards in the area include water and electrical utilities pipelines, as seen in Figure 7b. Utilities are known to be much shallower than the top tunnel and do not impact the tunnelling project. The alluvium will be comprised of eroded and weathered GRANITE from the Mt Butler and Kowloon GRANITE suites. Cobbles and boulders, although not identified in boreholes, could be present in the tunnel path. The presence of these could present problems for the tunnelling project. It has already been determined that granite pinnacles are not present in the survey area. The following analysis aims to determine the probable presence of alluvial boulders.

7.2 Discussion of Objectives and Process

The survey's main objective was to analyse the presence of and location of potential hazards. The analysis has shown that granite is too deep to be a concern, and no granite pinnacles have been identified. The utilities are all in the artificial fill layer and are too shallow to be of concern. Of remaining concern is the presence of large cobbles or boulders. Once the basic interpretation and identification of the key surfaces are completed, a set of attribute volumes are created or extracted from the Fullstack 3D Depth high-frequency amplitude volume of the 3D data. DUG Insight software (v.5.1, 2021) was used for seismic visualisation, interpretation and analysis. The attributes calculated, and referred to previously in the Seismic Attributes section, include Sweetness, Instantaneous Amplitude, Instantaneous Phase and Instantaneous Frequency.

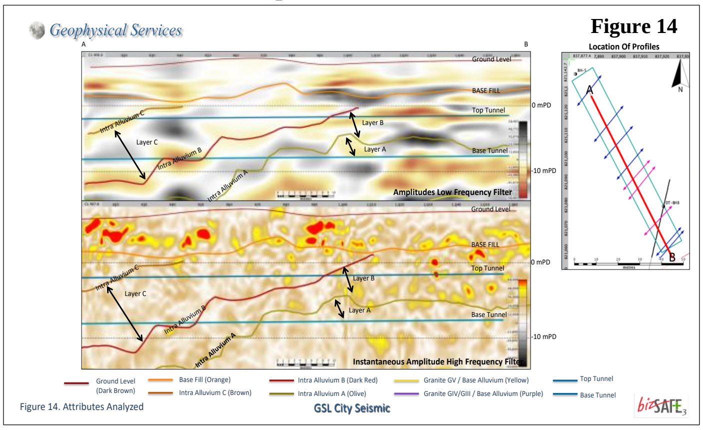

Figure 14. Attributes Analyzed

Figures 14 through 16 are examples of the attributes used in the analysis. In all attribute extractions, the hot colours green to red are higher values. The Amplitude and Sweetness attribute can be equated with higher relative densities. For the Frequency attribute, this indicates higher frequency.

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In Figure 14, the upper section is an Amplitude section taken from the low frequency filtered data cube. The lower section is an Instantaneous Amplitude section derived from the high frequency filtered data cube. Within the tunnel pathway (shown by the two cyan coloured lines), three distinct layers of alluvium can be identified. This fits closely with the alluvium as described in K. W. Lai.

The attribute analysis was windowed around these layers and examined Layer A, which is from the base tunnel to Intra Alluvium A, Layer B, which is from Intra Alluvium A to Intra Alluvium B and clipped at the top tunnel and Layer C, which is from Intra Alluvium B to top tunnel.

Figure 15

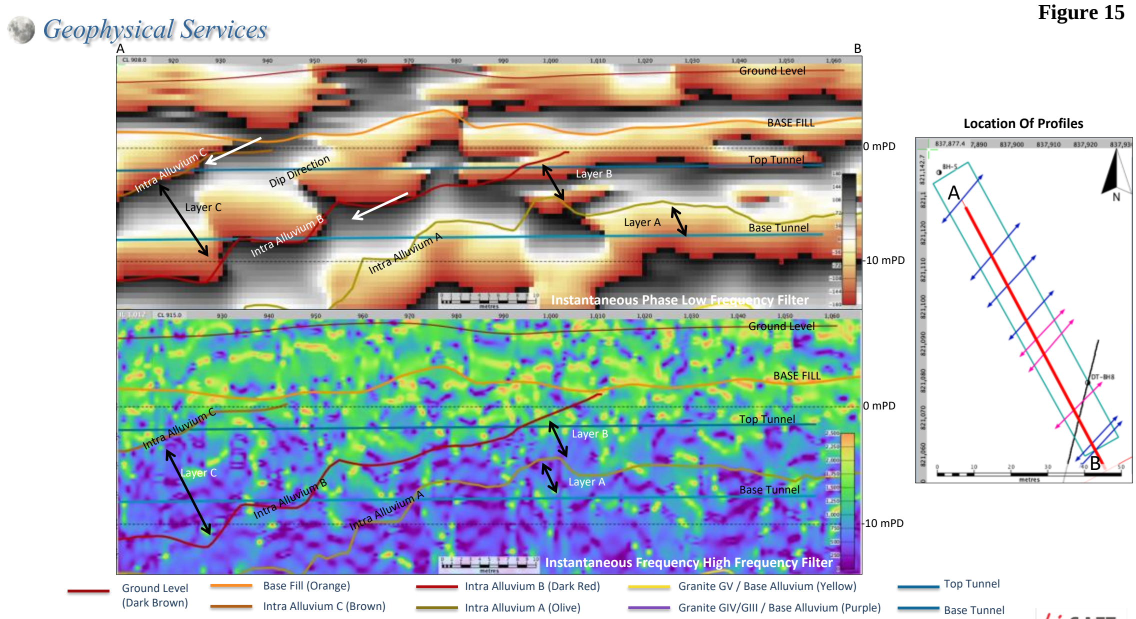

Figure 15. Attributes Analyzed

Figure 15 has an Instantaneous Phase section, which was derived from the low-frequency 3D cube and an Instantaneous Frequency section derived from the high-frequency 3D cube. Figure 16 contains a Sweetness section from the high-frequency 3D cube and an Interval Velocity section.

Figure 16

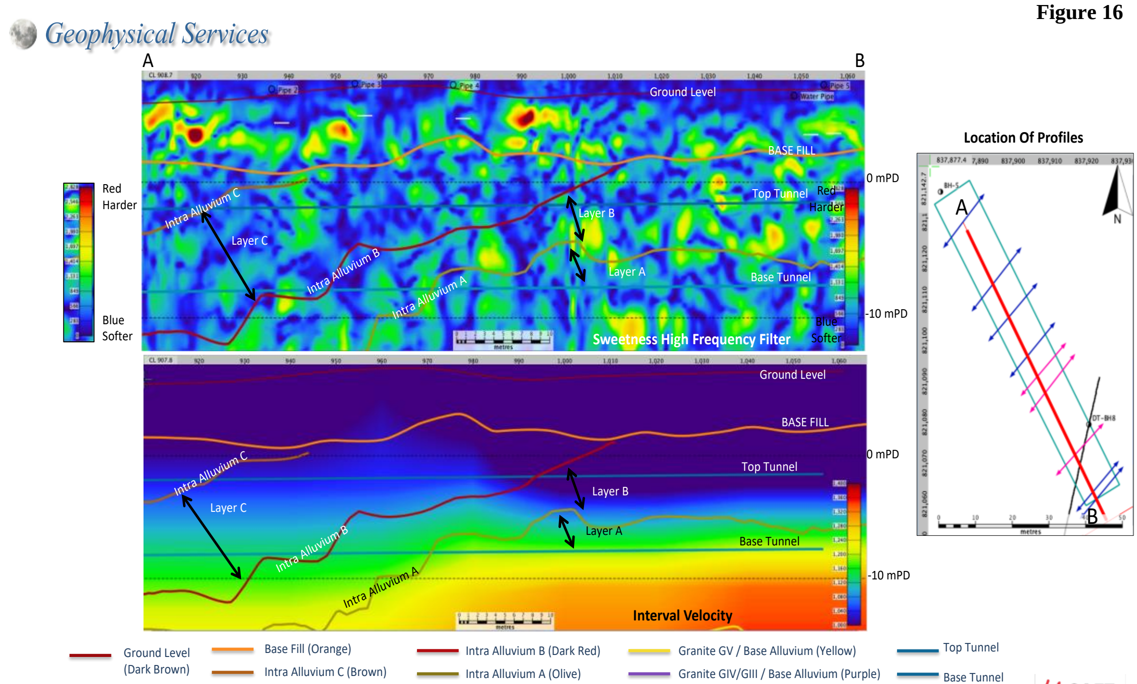

Figure 16. Attributes Analyzed

Figures 17 through 19 display extracted attributes for Layers A, B and C. Windowed depth slices of each attribute are calculated for layers A through C. Layer A is calculated from Base Tunnel to Intra Alluvium A, Layer B is calculated from Intra Alluvium A to Intra Alluvium B and clipped at Top Tunnel, Layer C is calculated from Intra Alluvium B to Top Tunnel (Figures 17 to 19). Intra Alluvium C to Top Tunnel is included in Layer C as the area is extremely small. These attributes are subsequently analysed for subtle discrete anomalies. The Instantaneous Phase attribute is used here for structural measures of dip and strike.

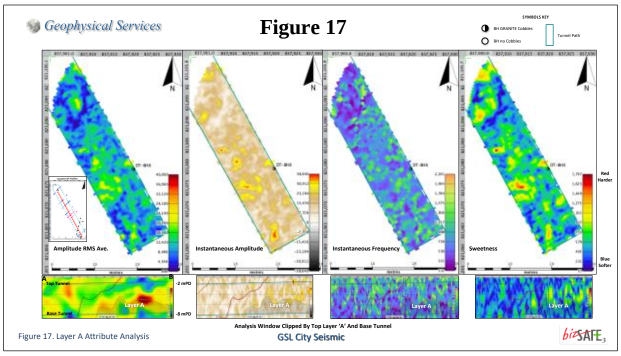

Figure 17. Layer A Attribute Analysis

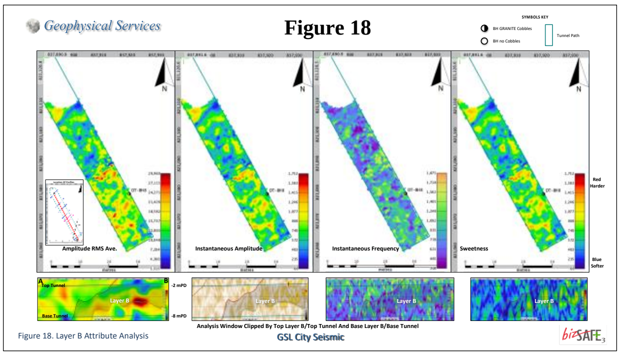

Figure 18. Layer B Attribute Analysis

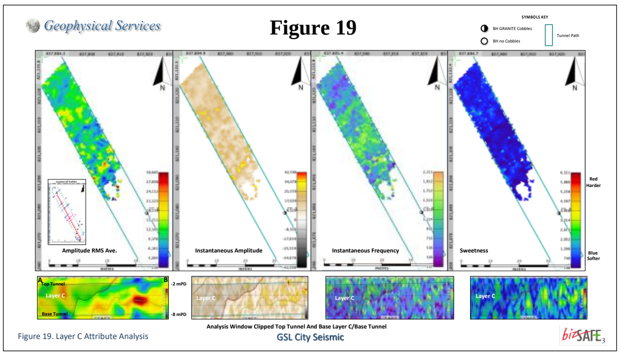

Figure 19. Layer C Attribute Analysis

7.2.1 Correlation of attributes to surface and borehole descriptions

Knowledge of outcrop geology is directly applicable to the understanding of subsurface geology. Outcrop analogues and borehole descriptions are used to provide a qualitative check on the subsurface model. Outcrop data coupled with borehole descriptions provide a good source of information on structural and sedimentological geometries at sub-seismic scales. K. W. Lai described in detail the Alluvial and Colluvial deposits of Hong Kong. Three layers or periods of deposition have been described.

Layer A, Middle Pleistocene, is described at Lam Tsuen River. Age Range 157,500 +/- 36,500 years BP. Layer B, Late Pleistocene, is described northwest of Yuen Long. Age Range 30,400+/- 8,000 to 81,000 +/- 13,500 years BP. Layer C, Holocene. Age Range 520 +/- 112 to 6,700 +/-700 years BP.

Holocene alluvium occurs mainly along narrow stream courses incised into fluvial terraces. The Holocene deposits are yellowish-brown clayey, silty sand with thin layers of organics. The outcrop data describe thin cobbley and boulder zones with cobbles ranging from 20 to 170 mm. These sized cobbles and boulders are beneath the desired resolution size of 250 mm and are below seismic resolution with a peak frequency of 270 Hz.

No cobbles or boulders are described in boreholes 5, 8, 9, 10 and 11. These are the nearest boreholes to the survey area. It is unlikely that cobbles or boulders are distributed as individuals. It is more likely that cobbles and boulders are confined to specific beds. Such as identified in Figure 4. K. W. Lai describes the cobbles as generally 20 to 170 mm. Cobbles of this size range are too small to detect, even with a peak frequency of 270 Hz.

Given that the alluvium has been described as layered and outcrop evidence points to cobbley intervals, it is likely that the denser Layer B could contain such cobble beds. An interval of up to 60-70% cobbles or boulders could provide enough of an impedance contrast to result in the layered intervals seen.

No cobbles or boulders are described in boreholes 5, 8, 9, 10 and 11. These are the nearest boreholes to the survey area.

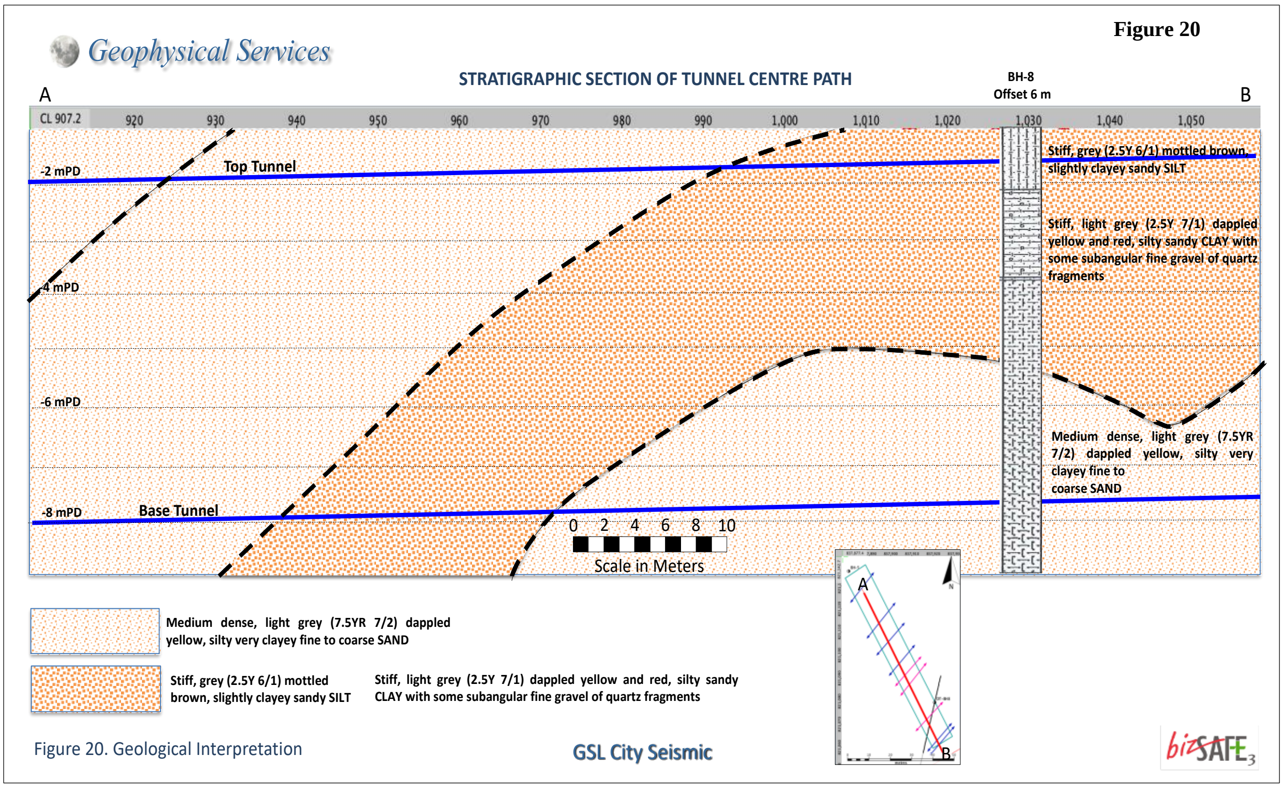

Figure 20

Figure 20. Geological Interpretation

Integration of outcrop analogues, borehole data and attributes allows a geological interpretation to be made. Figure 20 is a geological interpretation of the analysis. The profile is taken from the survey centre and runs from NW on the left to SE on the right. It has been smoothed to simplify the interpretation. Three distinct layers are identified. These correlate to surface geology and borehole descriptions as Layer A, Middle Pleistocene, Layer B, Late Pleistocene and Layer C, Holocene.

From the Instantaneous Phase section and general structural mapping, the dip and strike are derived. The dip is to the NW, and the strike is NE-SW. Analysis of the other attributes, Instantaneous Frequency, Instantaneous Amplitude and Sweetness, of both vertical and interval extractions indicate that Layer A and Layer C contain lower attribute values than the middle Layer B. This suggests that these layers are less dense than the intermediate Layer B.

The horizontal depth slices also support the interpretation of denser material in the SE. All displays indicate high attribute value and higher relative density in this area.

8 Effectiveness of Method

The data quality of the 3D volumes and 2D seismic profile is good to very good. The seismic data ties to boreholes with little or no shift required. Six surfaces have been identified and mapped across the 3D volume. Mapping the Granite GIII/GIV indicates a dome in the centre of the survey, but the Granite does not reach high enough to impact the tunnelling. The Alluvium is layered. Three distinct layers are seen through the tunnel path.

The middle Layer B appears to be denser and may have cobble beds. However, outcrop mapping suggests alluvial cobbles to be in the range of 20 to 170 mm. These are too small to detect as individual items. No individual cobbles or boulders of a size greater than 250 mm have been identified in the zone of interest. This analysis suggests that the tunnel path will pass through lower density sediments in the NW, pass through a higher density interval in the middle where cobble layers could be encountered, and then pass into a zone of higher density sediments over lower density sediments in the SE. This method is unique because it can deliver a complete geological profile in 3-Dimensions in areas where access is either severely limited or denied. This is particularly useful in Hong Kong urban development, where existing structures may obstruct the areas of interest.

For the subject project, the findings and conclusion in the report are adopted for the RTBM design in the selection of cutterhead, cutting tools and screw conveyor to suit the geological character of the existing ground. The application of this technology can benefit other substructures construction projects, such as basement and piling, in which the complete mapping results can supplement the discrete site investigation findings to allow both designer/contractor to have a complete picture of the variation of ground condition, thus minimising the potential dispute of the project and avoid the potential hazard in geology complex location.

9 Publisher's Note

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LIST OF ABBREVIATIONS FOUND IN THIS REPORT:

AOI:	Area of Interest
BH:	Borehole
CMP:	Common Mid-Point
GIBR:	Geological Interpretive Baseline Report
GEOPHONE ARRAY:	An assembly of Geophones arranged in symmetrical or asymmetrical form
HSE:	Health, Safety, Environment
i-SEIS:	i-Seis digital data acquisition system
NMO:	Normal Move Out
PATCH:	An area containing geophone and source points. (i.e. 15 * 50 meters)
PERE:	Prince Edward Road East
PSS-100:	Portable Seismic Source 100
RECORDING SENSORS:	Geophones, Hydrophones
ROLLING:	The moving or leapfrogging of a geophone or energy array from one location to a new location.
SOURCE:	Seismic Energy Source
SUB-ARRAY:	A smaller array of Geophones or source points. Several of which form a FULL ARRAY

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