Case study of geophysical surveys for profiling soil / rock interface in Singapore

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ABSTRACT: Profiling soil / rock interface is an important task in geotechnical site investigation. Instead of drilling limited boreholes, geophysical surveys are sometimes needed due to various objectives and challenges case by case. Although the selection of an appropriate type of geophysical surveys would be the foundation of project success, it might be still a common puzzle to geotechnical engineers who may not have the geophysical background. This paper shares an interesting case history where we have conducted 3 different types of geophysical surveys at the same site for profiling soil / rock interface. From the survey results and the nearby boreholes, it is shown that the seismic survey performs better as it has the least differences and the closest profile trend, followed by gravity. The resistivity survey does not show convincing result as the differences at each reference borehole location are rather large and the general trend does not match the possible real one. Hence, the resistivity survey is found as the least suitable one in this case study.

Keywords: gravity survey, seismic imaging, soil / rock interface, Singapore geology, resistivity survey

1. Introduction

This paper shares a case history of three different types of geophysical surveys carried out at the same site in Singapore. We introduce the key methodology and results for each type. We also make remarks and discussion by comparing across all these three surveys.

1.1. Background

For a city to be a compact, efficient and livable one, effective land use is essential. In many cities, such as Singapore, major public infrastructures (e.g., transportation and service utilities) have been already placed underground. Unforeseen underground condition due to heterogeneous or existing obstacles is a critical uncertainty encountered in underground space development. Risks associated with construction safety, cost and project management inversely correspond to the knowledge of ground conditions. Profiling and/or mapping of soil / rock interface can provide essential information for various geotechnical and underground construction projects, and not limited to:

(a) Design the foundation type (shallow and deep foundation)
(b) Estimate appropriate budget and project duration
(c) Select suitable equipment type and numbers
(d) Evaluate and select appropriate tunnel alignment

Thus, based on reliable underground mapping technology, appropriate subterranean space creation methods (e.g., excavation or tunnelling) and actual construction approach can be determined with reasonable engineering design.

Most site investigation practices have been conducted based on conventional borehole programs which involve traditional drilling, sampling, and laboratory testing. In Singapore, several case studies [1-3] reported that the boreholes are drilled in about 50m to 200m spacing along with the proposed underground developments, with the depths up to 50 to 60m. Drilling a borehole requires a vacant land which can be accessible to place the drilling equipment. The actual drilling of a 50m deep borehole may take from 3 days to one week or even longer, depending on the ground condition, e.g., depth to the stiff soil or rock. Adding the preparation and reinstatement works, the entire duration per borehole may take 1 to 2 weeks.

Concerning the limitations of current site investigation approaches, it should be noted that bedrock depths in Singapore have been estimated via the traditional borehole logging method which is rather time-consuming and cost-intensive. In terms of the considerable cost saving, it is strongly recommended to consider complementary geophysical and geotechnical test programs. For fast, economical, and efficient soil / rock interface survey, geophysical methods can be employed together with conventional approaches or even as possible alternatives.

Based on early pioneers [4-6] in the exploration geophysics, the geophysical survey has been introduced for near-surface site investigation in the industry of geotechnical and earthquake engineering since 1960 [7]. With the advantage of 1) easier implementation, 2) shorter duration, 3) fewer expenses, and 4) less intrusive or non-intrusive, geophysical survey becomes more attractive and promising as an alternative to the conventional site investigation.

There are several different types of geophysical surveys developed. US National Research Council [8] summarized several salient points for them: 1) gravity survey assesses variations in density and is used to determine localized features. 2) magnetic survey detects the differences in the magnetic field which may be primarily applied to locate metal deposits. 3) resistivity survey detects variation in electrical resistivity that is related to changes in pore fluid of soil. It can be used for mapping the geological profile, water table, etc. 4) seismic survey uses the propagation of elastic waves to measure the velocities in different material. It is most widely used in near-surface site investigation with its various types and relatively higher resolution characteristics.

1.2. Singapore Geology

The upper surface of Singapore is almost covered by residual soils from both Igneous and Sedimentary geological formations, locally namely as Bukit Timah Granite Formation and Jurong Formation, respectively. Table 1 summarises the geological and geotechnical charactersitics of these two major formations of Singapore geology. For Bukit Timah Granite Formation, it poses spatial variability with different grades of weathering and uneven soil / rock interfaces. Given the potential sudden change of soil / rock interface within a short distance, it is rather criticle for geotechnical site investigation to capture such sharp change to minimise the uncertainties due to unforeseen ground condnition.

The site of this case study is in central area of Singapore, which is within Bukit Timah Granite Formation. Bukit Timah Granite Formation is one of the oldest geological formation in Singapore, back traced since middle Triassic age (250 – 235 myr). Based on the weathering classification of different grades of granite rock (as listed in BS 5930[9]), it divideds as 6 weathering grades. As mentioned the upper subsurface is almost covered by residual soil, which is Grade VI, followed by completedly weathered granite as Grade V. Grade VI and Grade V are soils. The rocks are from Grade VI towards Grade I from slightly weathered to intact granite. It is noted that the the Grade VI is not commonly widely existed. Generally, the the soil / rock interfaces refers to the interfaces between Grade VI/V and Grade III. Such interfance is normally clearly defined as the material properties between soil and rock are well distinguished.

Table 1. Geological and geotechnical characteristics of Bukit Timah Granite and Jurong sedimentary formations [1]

Bukit Timah Granite	Jurong Sedimentary Formation
• Weathering is extensive, mainly decomposition. • Depth varies between a few to 80 m. • Undulating bedrock surface with a sharp change from residual soil to granite. • The granite rock mass is mostly of good (and above) quality but varies from locations.	• Most of the rocks of the Jurong formation are weak. • Rock mass quality is generally below good, e.g., mostly fair to poor, due to intensive fracturing and low strength. • Rock type and quality can vary rapidly, due to folded rock layers. • Relatively high permeability due to fractures.

2. Field Testing Overview

In Singapore, seismic imaging, gravity and resistivity surveys have been carried out at the same site. In the subsequent sections, each survey and its result will be elaborated separately, followed by a discussion comparing the three surveys across. It would be a useful case study to compare three different types of geophysical surveys.

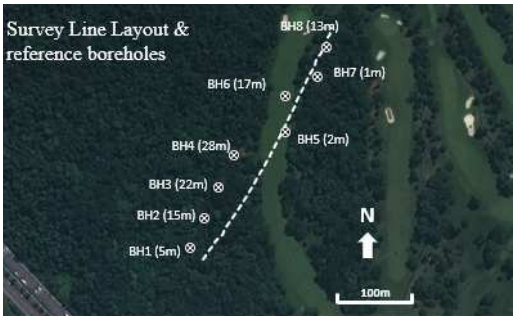

Figure 1. Layout Plan: survey line shown as a white dash line and reference boreholes layout with the offset shown in brackets.

Figure 1 shows the layout plan of the survey line and reference boreholes. There are eight reference boreholes on site. The distance to the survey line is shown in the bracket for each borehole in Figure 1. BH5 and BH7 are the nearest ones. The boreholes are then used for comparison and benchmarks to appraise the accuracy.

3. Seismic *Survey*

3.1. Background

Based on the mechanical wave type, the seismic survey can be distinguished as body wave and surface wave test. Seismic reflection and refraction are based on the P-wave. Seismic reflection is one of the oldest and common methods well documented in numerous textbooks [10-12]. As the current state of the art, the passive seismic survey is mainly utilizing ambient noise to approximate the Green's function of surface waves, based on which to establish the S-wave profile or tomography [13-17]. Compared with the studies of passive seismic using surface wave, P-wave based passive seismic studies are relatively less reported and rare [16]. Since the objective of this study is to mitigate the uncertainties between available boreholes, amongst the above mentioned, seismic imaging can be the most appropriate option as it directly reflects the layering information.

Seismic reflection is using the body reflections occurred at each boundary of underground strata layers. The seismic waves can be triggered by an artificial source on the ground surface. The seismic reflections can be recorded during a certain period with a series of receivers placed on the ground surface. The typical receiver used in ground seismic survey is geophone, a portable device which converts ground motion into an analogue electrical signal.

Each seismic source is triggered at a different location. With the moving of the seismic triggered source, the body wave reflections pass across a distance. The recorded signal can be processed to infer the various underground strata layering boundary based on the body waves reflections. The evolving signal processing techniques can help remove a certain level of noise and increase resolution. With modern computing technology, we can also afford to process large amount of seismic signals wherever necessary.

3.2. Field Acquisition

Two lines of 3 Hz geophones have been configured on-site about 30m apart from each other. They are evenly separated with the common middle points (CMP) in line with the target survey line (as shown as a white dash line in Figure 1). Geophone interval is 2.5m. One survey line consists of a total of 108 geophones. The source is an accelerated weight drop, which has been triggered for each geophone location. In this study, we use the offline gather to derive the image. It is different from the common practice in which the source and receivers are in the same line. It is because we found that the inline shot gathers are much contaminated by surface waves. It is rather challenging to find out P-wave from the inline shot gather. The situation is not bad in the offline gather, where we can visualize the P-wave reflection. We can also separate the P-wave reflection from the surface wave. It offers a good opportunity for profiling the soil / rock interface.

3.3. Seismic Image

Through static correction, grid regularization, 1st reflector separation and migration, a seismic image is derived as shown in Figure 2. Based on a smooth window, an interpreted soil / rock interface is marked in a blue line. The soil / rock interface depths from the reference boreholes are also shown as blue dots, except for BH 5 and BH7 shown in pink.

In the image shown in Figure 2, the x-axis is horizontal offset, also known as the midpoint, starts around BH1 location. The y-axis is the elevation based on a Singapore local survey datum, namely reduced level (mRL). A classic post-stack time migration [19-21] is applied to produce the image. We also compared other migration algorithms. It is found that the migrated images are quite similar, showing almost identical trend with close interprated soil / rock interface. Due to the page limit, we do not show other images. Based on the image, it is clear to see the soil / rock interface, which fluctuates from 105 mRL to 90 mRL over the 260m cross-section. Since BH5 and BH7 are the nearst boreholes, they are almost in line with the image. The other 6 boreholes are with certain offsets to the survey line, therefore there are relatively larger differences at those locations, which is also expected. Nevertheless, the trend of soil / rock interface follows quite well with the seismic image. However, due to the limitation of the seismic survey which is associated with the wavelength of the P-wave, the resolution cannot be as fine as a few meters. This is reflected as the white band shown in the image. The width of the white band profile is up to approximately 10m plus. Due to this limitation on seismic wavelength, it is rather challenging to achieve the required accuracy in geotechnical site investigation, which is in a few meters. Bearing this in mind, it is always advisable to have a few reference boreholes for local calibration. For this case, BH7 is used to fine-tune the image. BH5 is then referred to calibrate the smooth windowed interpreted soil / rock interface shown in blue. This is a practical and feasible way to counter the limitation of the seismic survey.

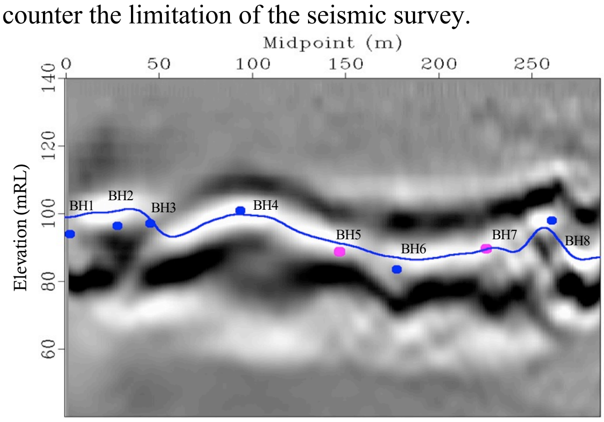

Figure 2. Seismic image of the first reflection, and interpreted soil / rock interface shown in the blue curve; soil / rock interface depths based on reference boreholes are shown as dots, for BH5 and BH7 which are the two nearest are highlighted in pink.

4. Gravity Survey

4.1. Background

The microgravity technique in the context of civil engineering consists of measuring variations in the gravitational pull of the earth and interpreting the presence of voids and cavities from these readings.

Microgravity survey has been developed considerably over the last ten years [22-25]. The method is becoming widely used in geotechnical investigations to detect natural and man-made cavities and has the significant advantage of leaving the ground completely undisturbed. The value of the Earth's gravity is generally between about 9.78 and 9.83 m/s^2. The unit is too large to be appropriate for measuring the changes in gravity described above and instead a unit called the gal (after Galileo) which is 1/100 of 1 m/s^2 is commonly used. Most of the Earth' gravitational variations are measured appropriately in these units but the scale of variations which are encountered in the search for voids and cavities is much smaller again and a unit called the microGal which is 1/1,000,000 of a gal is used.

The term 'Anomaly' is used commonly in the gravity data processing. Fundamentally it refers to the departure of the value of measured gravity from the value that conceptually would obtain for a laterally uniform and geologically layered Earth at the same place. The theoretical value can be computed. The differences and distributions of the anomaly are indicative of the degree of geological inhomogeneity. The principle of gravity survey is simple. If there are some materials below the ground having density difference from surrounding ground, the gravity shows a relatively low anomaly and vice versa.

4.2. Field Acquisition

The reading resolution is 1 microGal with a standard deviation of less than 5 microGal. The gravity responsive acquisition system consists of a spring and a proof mass. Microgravity data are obtained within a survey grid around the survey line shown in Figure 1 and 3. For this survey, a 15m square spacing grid is used. Two gravity meters are used. Measurement at the base station is taken before commencement of the gravity survey. At each station, three measurements have been taken to ensure repeatability. For every 2 to 3 hours, the reading at the base station has been taken again to monitor the drift of the gravity meters.

4.3. Result

Before interpreting the soil / rock interface, several processing and corrections are needed with the survey data. Terrain corrections for variable terrain have been conducted. It is to compensate for the lateral gravitational effect of variable topography around each gravity data measurement point relative to its elevation. We also consider the desnity correlation based on the soil and rock samples collected from nearby boreholes. The sample derived the density contrast of ±747 kg/m^3. The final effective mean density contrast adopted to achieve the optimum correlation is determined as −950 kg/m^3. The residual anomaly of the total gravity field is shown in Figure 3. This is the basis thereafter in the inversion of the soil / rock interface profile. The contour data are expressed on a regular grid at 5m interval. The output on the regular grid therefore effectively represents the depth of the rock head, based on the density anomaly.

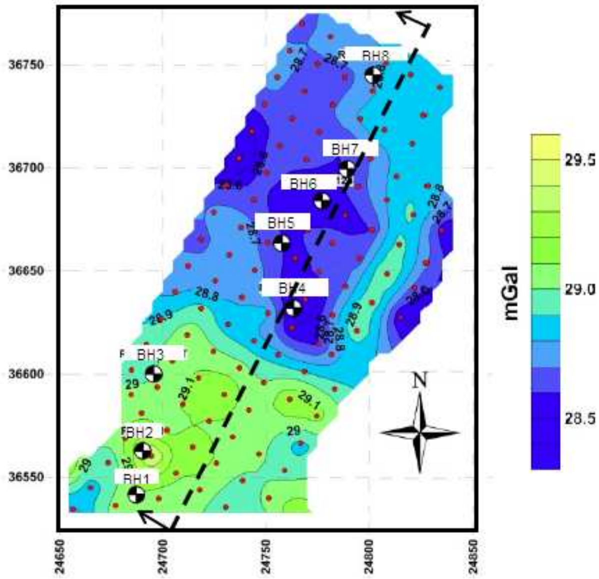

Figure 3. Gravity data distribution contour and the boreholes. (Unit mGal is microGal)

With the cross-section along the line shown in Figure 3, the inverted soil / rock interface is shown in Figure 4. The soil material is shown in brown and the rock material shown in granite-look texture. Similarly, the reference boreholes are shown together as dots. Generally, it appears the soil / rock interface follows the interpreted result from gravity survey. However, at BH5 location where the borehole is nearer the cross-section, the predicted depth rather deviates. Whereas it seems a better match at BH7, another nearer borehole along the section. The trend seems generally matched, though it may not be the real case due to larger offset.

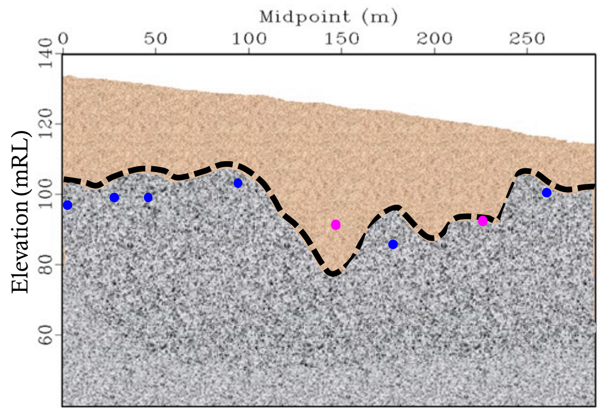

Figure 4. Gravity survey result and reference boreholes are shown as dots, for BH5 and BH7 which are the two nearest are highlighted in pink.

The discrepancy is tabulated in Table 2 and discussed in Section 6. In short, there is a moderate scatter of the differences based on the results shown in Figure 4, except BH5. For this case, some areas show that greater variations can be attributed to the strong irregularity of the soil / rock interface surface and the gravity variation.

5. Electrical Resistivity Survey

5.1. Background

Resistivity is a fundamental parameter of material related to the flow of electric current. It is also applicable to geomaterials. It determines the surface resistivity distribution by making measurements on the ground surface. Ground resistivity is related to various geological parameters such as mineral content, fluid content, porosity, degree of water saturation, etc. It is deemed suitable to detect soil / rock interface, fault zones or significant discontinuities in the rock [26-28].

Generally, there are two types: surface resistivity test and downhole type resistivity test. The common practice of field acquisition is to apply an electrical direct current (DC) from one electrode to another, which are normally installed in the ground. Generally, the potential electrodes are along with the current electrodes, though theoretically, they can be anywhere. The electricity can be either normal DC or AC of low frequency (say normally about 20Hz). However, the analyses and interpretation are normally carried out based on DC input. The potential distribution can be related to indicate the distribution of ground resistivities. For instance, if a vertical fault with a sharp spike or a vertical valley, the boundary could be very distinct, and the resistivity across the boundary may be relatively distinguished. For such a case where the medium is homogenous and the boundary is clear, the magnitude of resistivity can be representative. Nevertheless, for other kinds of scenarios where the boundary and resistivity contrasts are less significant, the interpretation can be carried out by qualitative comparison. This can be compared with a hypothetical model or on some basis of empirical methods.

5.2. Field Acquisition

Input voltage is up to 500 V with 0.5 μV sensitivity. The field acquisition has been carried out using the pole-pole array. The actual survey is configured as one single line as shown in Figure 1.

To make the resistivity values to be meaningful to differentiate various geological materials. We adopt the site-specific calibration for the resistivity result, with the help of nearest borehole. This procedure is undertaken as a confirmation measure in establishing a better result.

5.3. Result

The resistivity is inverted from the measured current. The interpreted soil / rock interface profile along the survey line is shown in Figure 5. The color towards yellow means higher resistivity, whereas the color towards green is lower. The soil / rock interface is interpreted and shown as the dashed line.

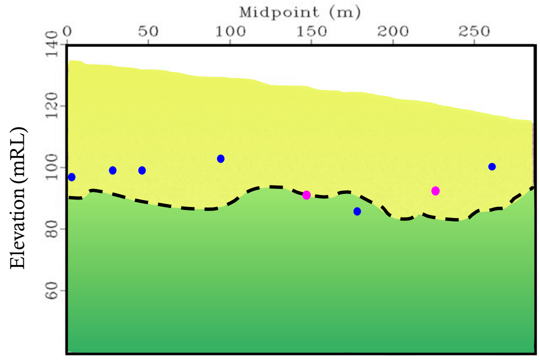

Figure 5. Resistivity survey result and reference boreholes are shown as dots, for BH5 and BH7 which are the two nearest are highlighted in pink.

For the soil / rock interface, generally, with the presence of the blue dots and pink dots, the resistivity survey presents larger differences, except at BH5 and BH6. The interpreted trend of the soil / rock interface generally goes flat. However, it doesn't look similar to the reference boreholes. The site consists of residual soils and weathered granite. Since the bedrock is not competent rock (normal condition), site-specific calibration might be needed. In this case, the resistivity survey is quite sensitive to variations in electrical conductivity of subsurface materials, which tallies the findings from Beauvais et al. [29] and Zhou et al. [30]. We concur the same finding with Coulouma et al. [31] that the efficiency of the resistivity survey is decreased when bedrock exhibited poor resistivity contrasts with the upper soil layers.

6. Summary

The interpreted soil / rock interface profiles are produced by three different types of geophysical surveys for the same cross-section. The results are presented together with reference boreholes. A qualitative look and brief discussion are made in earlier sections.

In this section, we summarize and quantify all the three profiles together. Figure 6 shows the three profiles and the eight reference boreholes altogether. The black profile produced by seismic survey follows well with the reference boreholes. The red profile by gravity survey is also generally following the trend. However, it has more and larger bumps and hikes that may not be representative and realistic. The blue profile produced by resistivity survey appears to provide the least matched result, not only based on the trend, but also from the eight reference borehole locations.

Figure 6 qualitatively compares the accuracy across the three geophysical surveys. To quantitatively appraise these three methods, we tabulate the differences from the prediction against the factual information in Table 2. We also put the offset between the borehole and the survey line in the table. It is quantitatively indicating that the seismic survey returns the most accurate results with a maximum difference up to 4m. Since BH7 is used for adjusting the velocity model and BH5 for adjusting smooth window, the differences at these two locations are almost negligible. Even though, for other locations, the differences are not substantial and acceptable in practice.

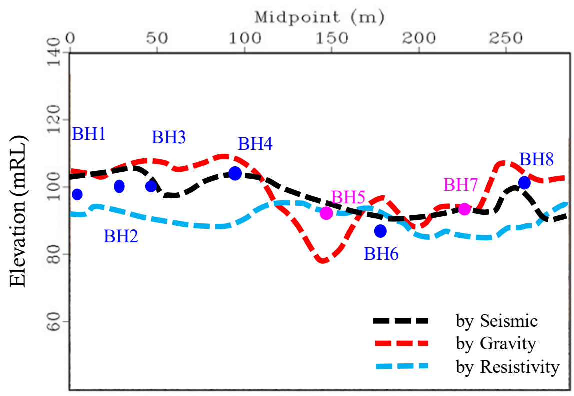

Figure 6. Comparison of the interpreted soil / rock interface by seismic, gravity and resistivity surveys. Soil / rock interface depths from reference boreholes are shown.

Gravity survey generally estimates the soil / rock interface shallower than its actual depths. However, it shall be noted that at BH5 and BH7 locations, the differences are -14 and 1 meter respectively. Such contrasting results downgrades its confidence level for the application. Other than this contrasting prediction errors at BH5 and BH7, the general trend somehow appears not too far away from the other reference boreholes.

Resistivity survey generally estimates the soil / rock interface deeper than its actual depths. The differences are onerous amongst the three methods. The errors are generally more than 6m and even worse up to 13 to 15m, such as BH4 and BH8. Furthermore, the general trend of the interpreted soil / rock profile is rather flat, which is not realistic based on the eight reference boreholes.

Table 2. Differences of interpretation vs factual and offsets of each reference borehole

No.	Offset (m)	Difference* (m)		
		Seismic	Gravity	Resistivity
BH1	5	4	7	-6
BH2	15	4	5	-7
BH3	22	1	7	-9
BH4	28	-2	4	-13
BH5	2	2	-14	1
BH6	17	3	12	6
BH7	1	0	1	-9
BH8	13	-4	4	-15

*: positive means overprediction, while negative is underprediction.

7. Conclusion

Three geophysical surveys (seismic, gravity and resistivity) have been carried out at the same site. We aim to identify the suitability of various geophysical techniques for profiling the soil / rock interface in Bukit Timah Granite formation. The survey line is about 260m long. The inferred soil / rock interfaces are compared across. The seismic survey provides the best results in terms of smaller differences and closer match on the trend. Gravity survey returns a less matched trend profile, with larger hikes and bumps, as well as slightly larger difference. Resistivity survey appears to give the least accurate interpreted profile with large differences up to more than 10 m. The resistivity survey result also does not reflect the actual possible soil / rock interface profile based on the eight reference boreholes. It could be attributed to the less apparent resistivity contrast between the completely weathered granite and the moderately weathered granite. Thus, for similar ground conditions, the seismic survey would be recommended as the first choice. Gravity survey can be also considered with cautions. Based on the comparison, resistivity survey is not advisable to be conducted to map the soil / rock interface in such environments.

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