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Use of geophysics for site investigations and earthworks assessments

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Abstract Site investigations for various infrastructure is traditionally done using boreholes drilled through various strata, logging of boreholes, sampling of strata and laboratory testing to assess engineering properties and infer behaviour of slopes, soft soils, embankments and foundations. Geophysics is still not used as a standard tool by most engineers due to the perception that it is not well-established science or that the results are unreliable. This paper outlines how Engineering and Geophysics can be integrated by having a well-balanced team with all the team members understand the fundamentals of each area. This is demonstrated by case histories for site investigations and earthworks quality assessment. The variety of geophysical methods available for site investigations, their applications, interpretations are presented. The paper describes how cost of investigations can be reduced and the risk of ground variations can be reduced by applying geophysics in geotechnical investigations.

1. Introduction

In typical infrastructure projects such as roads, airports, pipelines etc. the cost of underground works can be between 20% to 40% of the project cost. However, world over the main cause of cost and time disputes is the fact that the ground conditions were found to be different to what was presented in the tender using limited number of boreholes for site investigations.

The use of geophysical investigations supplemented with selective intrusive investigations at critical locations offer an economical means of obtaining an assessment of the subsoil strata. Echo sounding, seismic wave measurements, electromagnetics and microgravity are some techniques that have been used with success as they can provide indication of soft sediments and hard layer profiles. The data obtained from intrusive investigations such as boreholes and Cone Penetration tests are typically used to relate geophysical data with observed engineering properties of the ground. These are used to develop a 2-D and 3-D model of the subsoil profile to show the variable distribution of the various subsoil layers.

2. Geophysical techniques

Geophysical method applies the principle of physics, which is used in studying the earth. Some of the geophysical methods that are commonly used are resistivity, seismic, gravity, magnet and electromagnet. According to [1], geophysical technique offers the chance to overcome some problem inherent in more conventional ground investigation techniques. In most equipment testing, the geophysical methods apply a non-destructive testing which can reduce cost and time of the project [4].

There are several other specialised geophysical techniques, but all of these are not covered in this paper.



An endemic issue in the civil engineering industry is that Civil Engineers are not trained in the principles of geophysics or even possess in-depth knowledge of geology. The similar applies to geologists and geophysicists whereby their disciplines do not adequately cover the type of challenges civil and geotechnical engineers face in projects. Hence these disciplines tend to work in silos with in dequeue appreciation of how each expertise area can contribute to solving their challenges.

2.1 Seismic techniques

Seismic techniques utilise the ways in which vibrations travel through materials. The surface wave techniques measure the density of the materials below the surface, irrespective of any strength inversions. The Multi-Channel analysis of surface waves (MASW) technique as in Figure 1 measures the surface waves generated from a source, such as sledge hammer. The user measures the propagation velocities of those surface waves with an array of geophones, and then finally deduces shear-wave velocity (V_s) variations below the surveyed area that is most responsible for the analysed propagation velocity pattern of surface waves [2] as in Figure 1. Shear-wave velocity (V_s) is one of the elastic constants and closely related to Young's modulus and therefore is beneficial to geotechnical engineers [3] as in Table 1. Under most circumstances, V_s is a direct indicator of the ground strength (stiffness) and therefore is commonly used to derive load-bearing capacity [2].



Figure 1. Data acquisition at site using MASW technique

Other techniques that make use of surface waves are the CSWS (Continuous surface wave system) [5] and SASW (Spectral analysis of surface waves) [6]. These techniques both produce 1D profiles using a small array of geophones with the CSWS having the advantage of the ability to control the wave frequency through a vibrating plate. This element of control allows the operator to focus measurements on certain depths, such as depths that might correspond to a bedrock interface and gain a higher resolution of data.

Table 1. Relationship between geological material and shear wave velocity (V_s) based on SASW measurement

Classification of Geological material	Shear wave velocity, V_s (m/s)
Very Soft	84 – 107
Soft Soil	107 – 137
Moderately soft soil	137 – 183
Hard Soil	183 – 274
Very hard/stiff soil	274 – 366
Highly weathered rock	366 – 610
Slightly / moderately weathered rock	610 – 2743

2.2 Resistivity techniques

This technique also known as electrical imaging as in Figure 2 which aim to build up a picture of the electrical properties of the subsurface by passing an electrical current along many different paths and measuring the associated voltage [7]. From these measurement, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as mineral and fluid content, porosity and degree of water saturation. Sedimentary rocks are usually more porous and have higher water content, thus they normally have lower resistivity values compared to igneous and metamorphic rocks as in Figure 3. Unconsolidated sediments (overburden) generally have even lower resistivity values than sedimentary rocks, the resistivity value is dependent on the porosity as well as the clay content.

**Figure 2.** Data acquisition at site using Resistivity technique

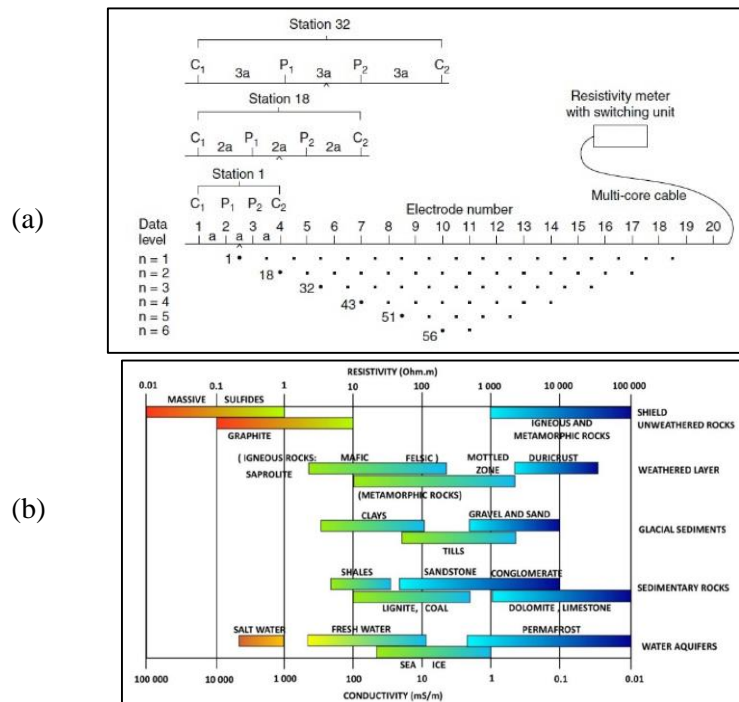


Figure 3. (a) The arrangement of the electrode for 2-D electrical survey and the sequence of measurements used to build up a pseudo section, (b) Resistivity and conductivity values for some of the earth materials. (after Palacky, 1987)

2.3 Gravity techniques

Gravity survey as in Figure 4 is a measurement of the gravitational potential field in a series of different locations. The objective of this survey is to relate the density differences to anomalous gravity changes [8]. The gravity anomaly depends on densities, density relates volume to mass and the variation can cause different in mass and gravity acceleration as in Figure 5. Any geological condition that results in a horizontal variation in density will cause a horizontal variation in gravity. The anomaly gravity changes show horizontal density differences of subsurface rocks or materials and could be used to determine the subsurface structure [9].



Figure 4. Data acquisition at site using gravitometer

In engineering and geotechnical applications, gravity surveying is used to locate natural cavities (such as caves, caverns) and man-made subterranean openings such as abandoned mines, tunnels). Natural cavities may be air-filled, water-filled, soft-sediment filled or partially filled.

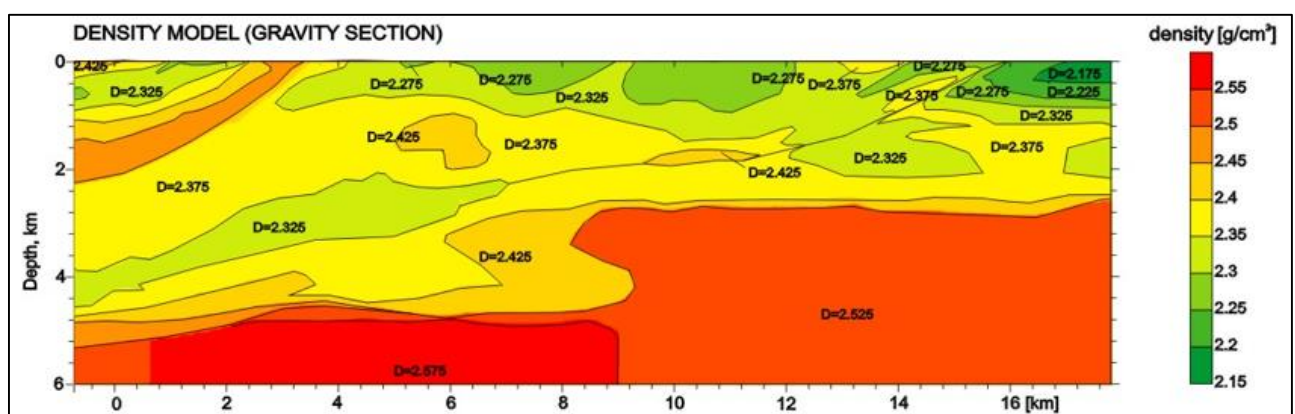


Figure 5. Shown below is an example of a study using gravity measurements for a residential development to check for cavities.

2.4 Borehole geophysics

Downhole geophysical logging is a technique used to determine the physical properties and distribution of soil and rock surrounding a borehole annulus. These measurements record naturally occurring physical phenomena or they may use an artificial physical source such as electrical, nuclear and acoustic, to excite the medium and measure the response to the excitation. Borehole geophysics can be used to obtain valuable data including information on geological conditions and in-situ physical parameters in drill holes. The amount and benefit of this information is determined by logging suite, borehole conditions, geological parameters, interpreter's experience and application of current technology as in Figure 6.

The choice of appropriate geophysical methods requires an understanding of the geological environment and the borehole conditions. Very seldom can a geological property be identified from a single geophysical log (BS7022, 1988). It usually involves a combination of methods to identify each property of interest.

Information required	Nuclear				Electrical						Acoustic	Seismic wave	Structure	Electro-magnetic		
	Log measurement	Natural Gamma	Gamma Spectroscopy	Gamma Gamma	Neutron-Neutron	Focused Electrode	Focused Induction	Dipmeter	Non Focused Electrode	Single Point Resistance (SPR)	Spontaneous Potential (SP)	Acoustic Borehole Televiewer	Suspension PS	Downhole Seismic	Caliper (3-arm or 4-arm)	Ground Penetrating Radar
Bulk Density			A													
Correlation	A	A	A	A	B D	B & P	B D					B D	B D			B & P
Diameter / Hole Volume											B D				B	
Elastic Properties			A									B D	B D			
Fluid Flow																
Formation Dip and Direction							B D				B D					
Formation Fluid Quality					B D	B & P		B D		B D						
Formation Resistivity					B D	B & P		B D								
Fractures							B D				B D	B D	B D			B & P
Lithology	A	A	A	A	B D	B & P		B D		B D		B D	B D	B D		B & P
Permeable Zones						B & P		B D		B D					B	
Porosity			A	A	B D							B D	B D	B D		
Shale Content	A	A		A						B D						
Uranium /Thorium /Potassium	A	A														
Water Level					B D				B D							

LEGEND :

A

No restrictions on hole

B

Open hole

B & P

Open hole or with plastic casing

D

Fluid filled hole

LEGEND :

A	No restrictions on hole
B	Open hole
B & P	Open hole or with plastic casing
D	Fluid filled hole

Figure 6. The applicability and limitation of relevant methods.

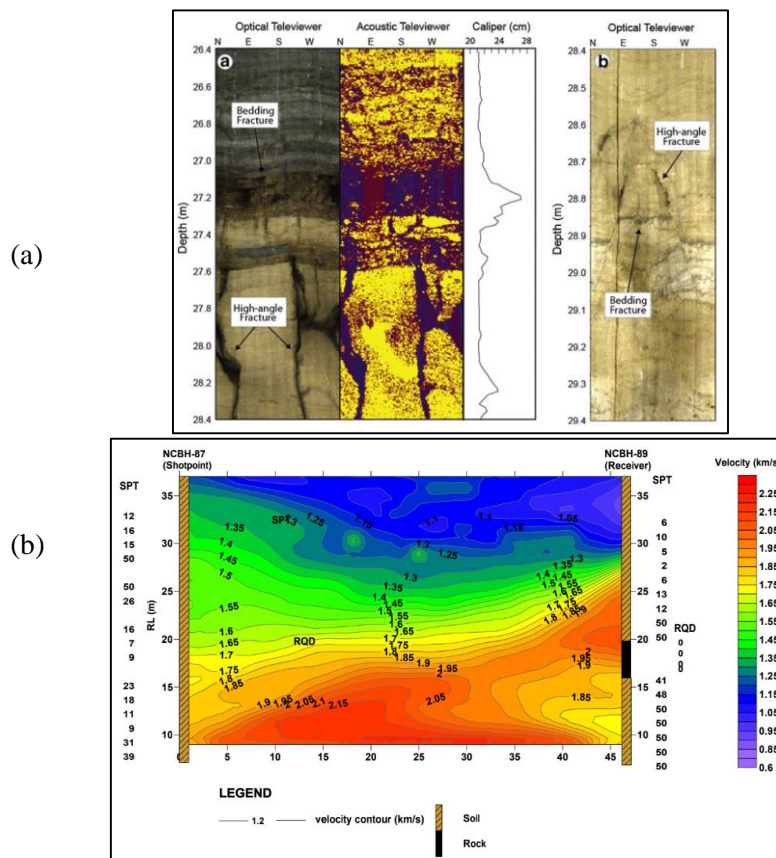


Figure 7. (a) Acoustic Televiwer was used in determine discontinuities and rock quality design [12], (b) Cross hole seismic was used in mapping subsurface geological information.

3. Applications in infrastructure projects

Civil and Geotechnical Engineers need to understand the basic principles associated with data acquisition, data processing and interpretation for engineering parameters. This will enable the proper selection of the appropriate method for the specific situation to be investigated. Due to the lack of this understanding there is a perception of geophysics as an unreliable approach. This can be overcome by the Civil designer, Geotechnical Engineer, Geophysicist and Geologist working to gather as a team with mutual understanding of each other's capabilities and expertise to derive best value in terms of reducing ground variation related issues on projects.

3.1 Rollinson Road, North Coogee, Australia

The area was planned for development, at the south of Fremantle. The land surface was partly been compacted by impact roller. The MASW processing scoped is to address the effect of compaction, competence of the ground and information about subsurface condition. Three lines (156m each) were proposed as in Figure 8. The data along one of the lines were recorded in the opposite direction to others.



Figure 8. Location of survey line at site

The S-wave velocity sections as in Figure 9 show the S-wave velocity is generally over 250m/s from the surface. There is hardly any area where the S-wave velocity is slower than 250m/s. Therefore, the ground is quite competent with Young's Modulus over 300MPa.

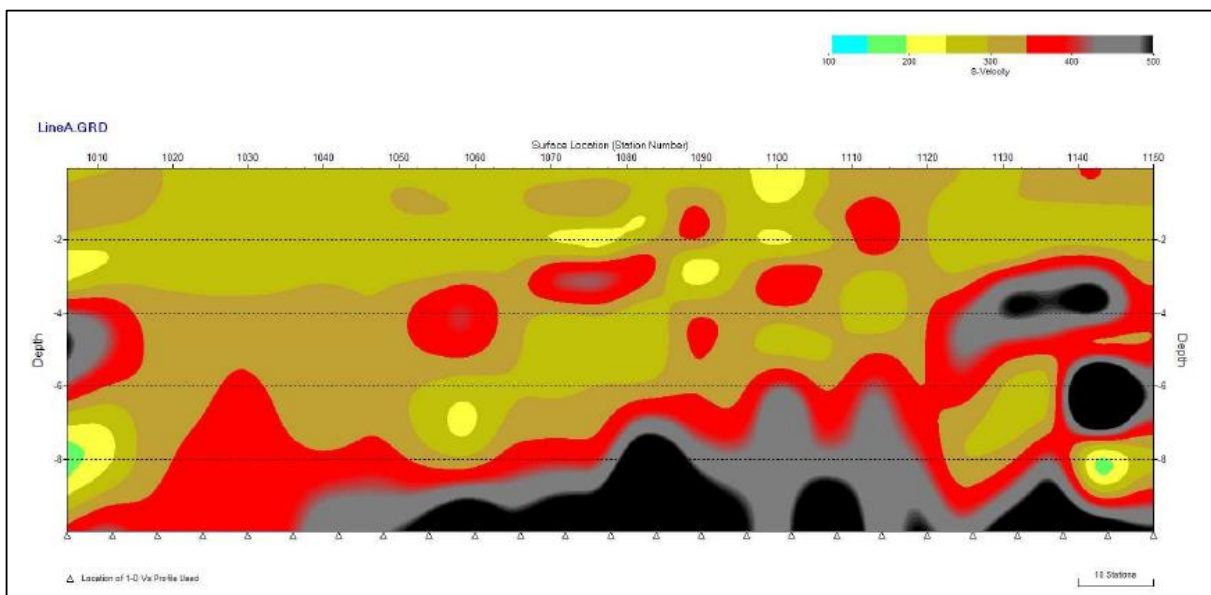


Figure 9. MASW data from site investigation

3.2 Mount Magnet Leinster road, Western Australia

This 180km road was to be constructed as a 2-lane single carriageway sealed road. There were several cuttings and valley fills. The site as in Figure 10 had weathered residual soils but there were also cemented layers that might require hard digging, ripping or even blasting. If this is not captured adequately in each cutting the chances of cost and time overruns due to encountering hard materials would be very high. Similarly, if each valley floor is not assessed adequately for loose or soft deposits then the fill embankments could settle. The site investigation would normally require at least 360

boreholes to obtain a good assessment of each cutting and valley section. The site investigation consisted of 180km of seismic refraction and 50 bore holes. The seismic velocity profiles were interpreted for hard layers, rippability and blasting and presented as colour coded long sections. This enabled the civil designers to have a more accurate calculation of common excavation, ripping excavation and excavation requiring blasting.

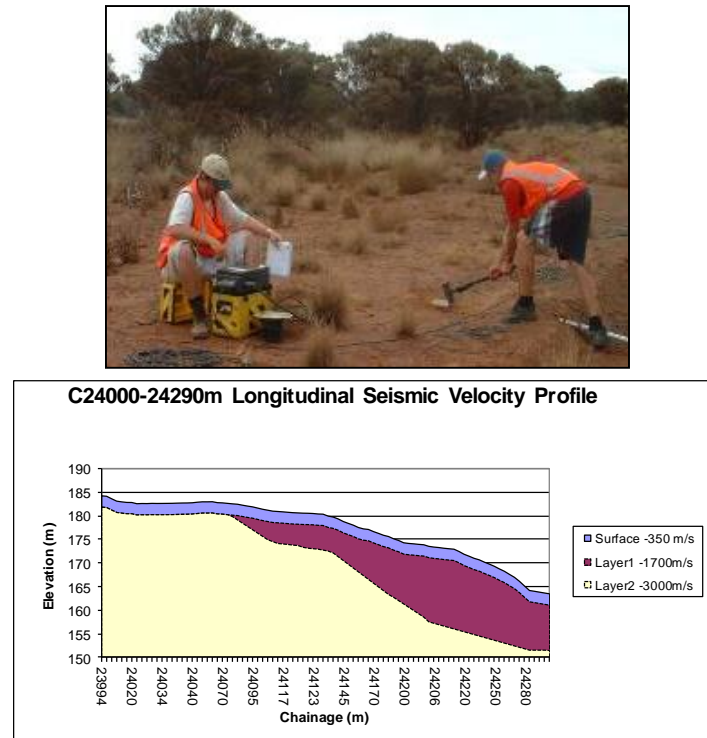


Figure 10. Data acquisition and geological profile from seismic survey

3.3 Pulau Pangkor, Perak, Malaysia.

The project consisted of the construction of a network of underground sewer pipes and a regional sewerage treatment plant along Jalan Pasir Bogak [10]. The depth to inert level of the proposed sewer pipes are designed to be as deep as 15m over the valley of Pangkor Island. The estimated length of the sewer pipe network is approximately 4.5 km. The proposed alignment traverses along existing road alignments, road shoulders, crossing existing buildings, culverts and other existing infrastructure facilities. The project objective was to recognize boulders in the subsurface in the specific area and the identification of the weathered and fresh bedrock interface in each section of the alignment. To achieve this objective, 3 methods were used that is Continuous Wave Surface System (CSWS) as in Figure 11, resistivity as in Figure 12 and Ground penetrating radar (GPR). Based on this, locations of boulders were mapped to reduce the tunnelling uncertainties.

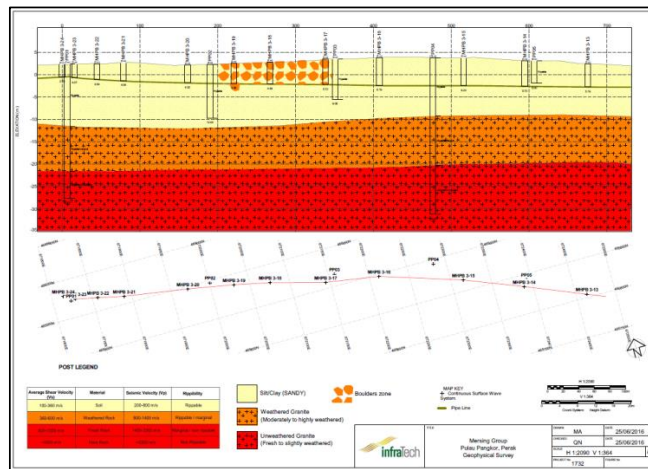


Figure 11. Final finding and location of boulder and bedrock depth.

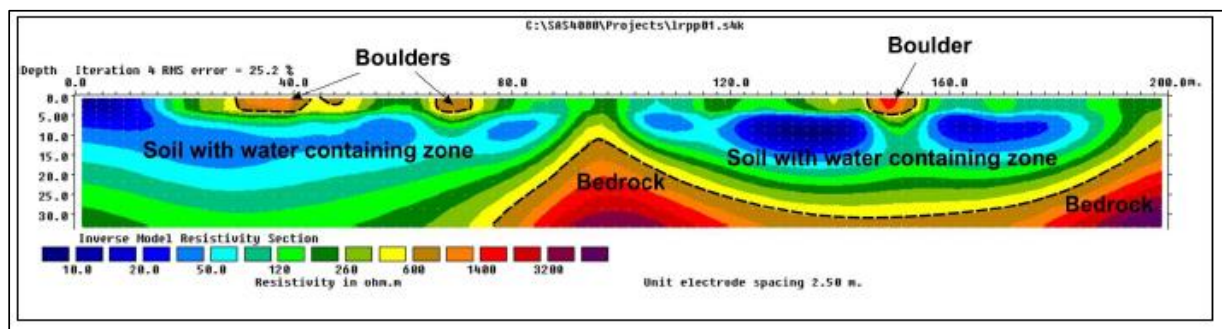


Figure 12. Resistivity survey along alignment to detect the boulder location

3.4 Jalan Chan Sow Lin, Sungai Besi, Kuala Lumpur, Malaysia.

The site is located along Jalan Chan Sow Lin, occupying a plan area of 2.1 acres. The site was planned for the development of 2 blocks of 40-storey residential towers with a podium and a 1-level basement. This Geological Formation mainly consists of limestone with possible presence of cavity and pinnacle structures. The initial plan was to drill at least one borehole at each column location. This was perceived as the only way to ensure cavities can be detected. Later MASW scanning was proposed along all column grids as shown in the scanning layout plan for 22 scan lines as in Figure 12. This was followed by drilling 5 numbers of boreholes. This integrated technique could identify features like cavity and pinnacles that could easily have been missed with traditional investigation only as in Figure 14. Overall findings showed that the area have shallow rock head between 4m – 7m. Potential cavities were also detected at some locations. This finding was correlated well with the existing boreholes.

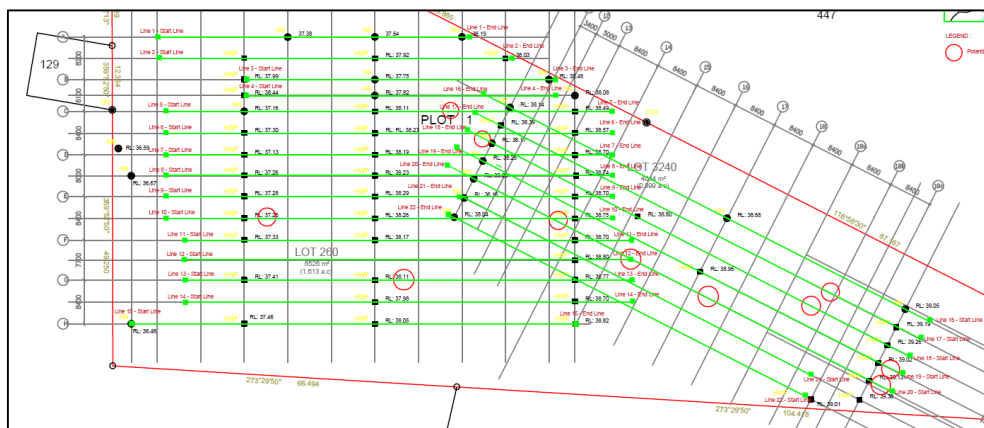


Figure 13. Scan line location plan

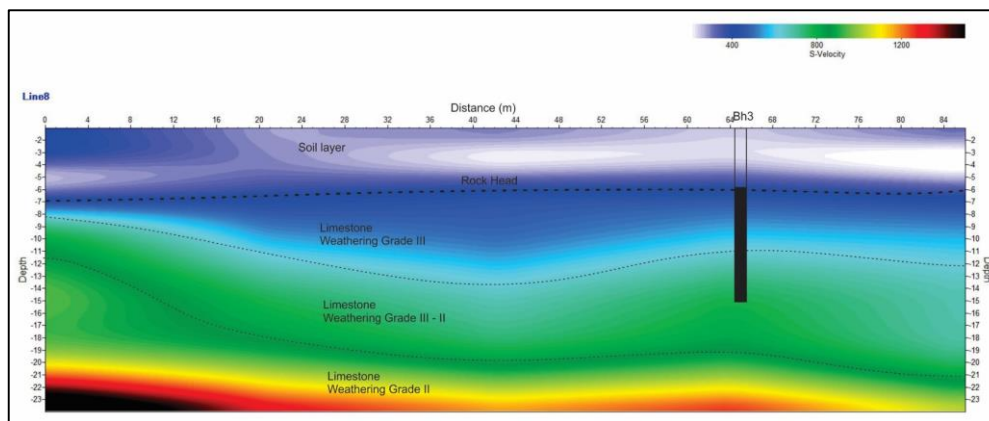


Figure 14. Correlation between MASW result & borehole

3.5 Bagan Datuk, Perak, Malaysia.

This project initially covering a plain area of approximately 900 acres. Area of Bagan Datuk is covered by quaternary sediment. The geology of the area consisted generally depositions of clay and silt. It also known as soft soil area. Since the site was a former meander plain of the nearby Sg Perak deep buried channels were expected with high variation of the soft soil layer depths. The challenge faced was to capture the ground variation with many boreholes (450 bore holes based on a one bore hole per 2 acres) which would be costly and time consuming. To reduce cost and time for investigation while reducing the risk of missing out on large ground variations, an integrated approach was adopted. This integrated approach included Boreholes and Geophysical methods. The objective was to identify soft soil depth variation and geotechnical properties. 20 nos. of borehole were done with 40 nos. of resistivity survey line [11]. This approach provides adequate information to assess the depth of ground improvement required, depth of piling in various parts of the site. Figure 15 shows the typical outputs from this approach.

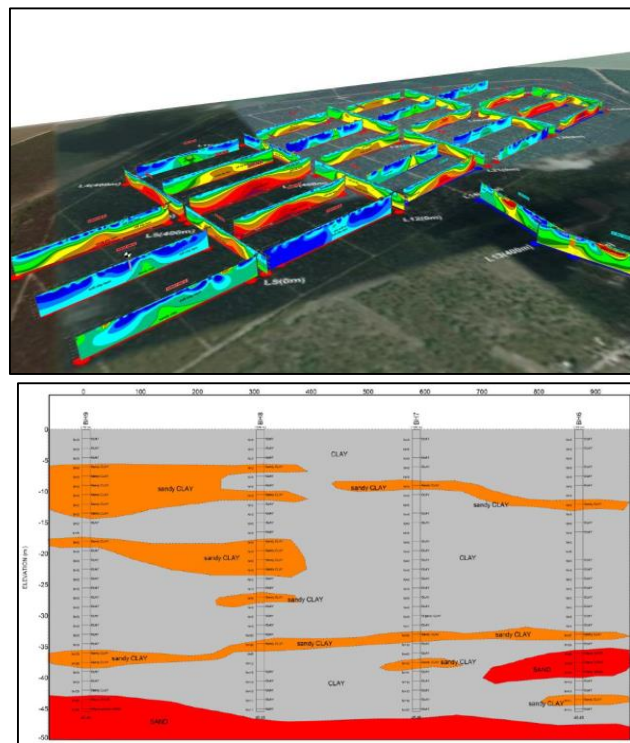


Figure 15. ER line survey (400m each) at of Bagan Datuk, Perak and subsurface cross-section profile showing the lithological variations based on correlation of borehole and geophysics investigation.

4. Advantages and limitations of geophysical methods

The advantages of this technique are fast, low cost, and covers a large area intensively. It is the best way to capture ground variation which is practically not possible by traditional bored holes. Another advantage is a good correlation between engineering properties and geophysical parameter (Resistance, Vs etc). However sometime correlations are not fully explored and established for all types of soils. Furthermore, each technique has its resolution issue and depth limitations. These limitations must be understood to enable the selection of the appropriate technique.

5. Summary

The use of geophysics in geotechnical and geo environmental site investigations requires a multi-disciplinary approach between Civil and Structural designers, Geotechnical Engineers, Geophysicists and Geologists. If carried out with an in-depth understanding of the applications and limitations of each methods to what the engineers required to assess, then effective results can be obtained. This eventually leads to reduced ground variation risk while saving time and cost. Consequently, will also increase the quality of the site investigation. Intrusive boreholes must be used in correlation with the findings. With appropriate geophysical scanning of sites, the number of boreholes reduced, and the variation risk can also be greatly reduced.

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