# GEOPHYSICAL SOLUTIONS TO ENGINEERING PROBLEMS

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## ABSTRACT

Amongst the geotechnical community there is a mixed appreciation of the benefits of geophysics to geotechnical investigations. It seems many engineers have lost confidence in geophysics usually as a result of: insufficient communication of the capabilities, limitations and precision of the geophysical approach; poorly planned investigations; or lack of data integration. With good communications and planning, geophysics surveys can be used together with borehole and excavation data to provide greater certainty of site characteristics. The cost of a geophysical investigation is often paid for many times over by the reduction in the cost of engineering designs, which may otherwise be over specified to account for a wider range of possible site conditions. This paper presents three case studies of geophysical investigations that were carried to assist with geotechnical assessment and design. The case studies illustrate how geophysical data integrated with drillhole data can provide important geological interpretation that could not be achieved by interpretation from drilling results alone.

## 1. INTRODUCTION

With the difficulties associated with mapping the subsurface using borehole data alone, geophysical investigations have been known to assist with geological interpretation and geotechnical design (Fitzallen, 2010; Gul, 2011). The requirements of the engineer (i.e. mapping basement, calculating shear wave velocities to assist with dynamic modulus calculations, etc.) determine the type of geophysical technology that is employed to assist with the engineering investigation. Engineers, geologists and engineering geophysicists each interpret the use of geophysics in a different light (Whiteley, 1988; Stapledon, 1988; Fell, 1988), hence there is paramount importance in the clear communication of investigation objectives, site conditions, access issues and geophysical technology limitations.

The following case studies provide indications of the engineering problem and the geophysical solution that was employed in order to achieve the engineer's objective. Technologies included within the case studies are Multichannel Analysis of Surface Waves (MASW), seismic refraction, Electrical Resistivity Imaging (ERI) and Airborne Electromagnetics (AEM).

The case studies illustrate the positive results that can be achieved with good communication, planning and interpretation between engineers and geophysicists.

## 2. CASE STUDY 1 - MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW)

A field case study is presented from a Multichannel Analysis of Surface Waves (MASW) investigation carried out at a proposed port infrastructure site in Western Australia. The objective of the geophysical investigation was to determine the 3D shear-wave velocity structure of the subsurface which, when combined with material density, could assist engineers with dynamic shear modulus calculations.

The geophysical technology that was deemed the most suitable was MASW. MASW is a seismic method that uses the dispersion of seismic surface-waves to evaluate variation in the subsurface shear-wave velocity as function of depth (Park et al., 1999). MASW is a non-destructive technology, which involves using a seismic source (e.g. sledgehammer, drop-weight) to produce seismic surface waves and measuring the speed at which these waves travel across the surface using an array of geophones (or vibration sensors). The dispersion curves of the seismic shot records are then analysed and inverted to calculate the shear-wave velocity (Vs) as a function of depth. It is possible to then correlate calculated shear-wave velocities (Vs) with borehole data (Table 1).

The field set-up consisted of six parallel MASW lines in a north-south orientation, approximately 120 m long with 5 m station spacing and 3 m from the source to the nearest receiver. The MASW lines were spaced approximately 10 m apart. From the results it was possible to produce 2D shear-wave velocity profiles to a depth of 20 m and illustrate a simple three layer model. An example of two MASW sections with their nearest boreholes is shown in Figure 1.

| Shear-Wave Velocity, Vs (m/s) | Lithology |
|---|---|
| <50 | peat |
| 50-150 | soft clay/silt |
| 150-250 | stiff clay or unconsolidated silt/sand |
| 250-500 | stiff silt/sand or gravel |
| 500-1000 | cemented/compacted sand/gravel or fractured/weathered rock |
| >1000 | crystalline rock |

Table 1: General Table of Comparison for Vs and Lithology

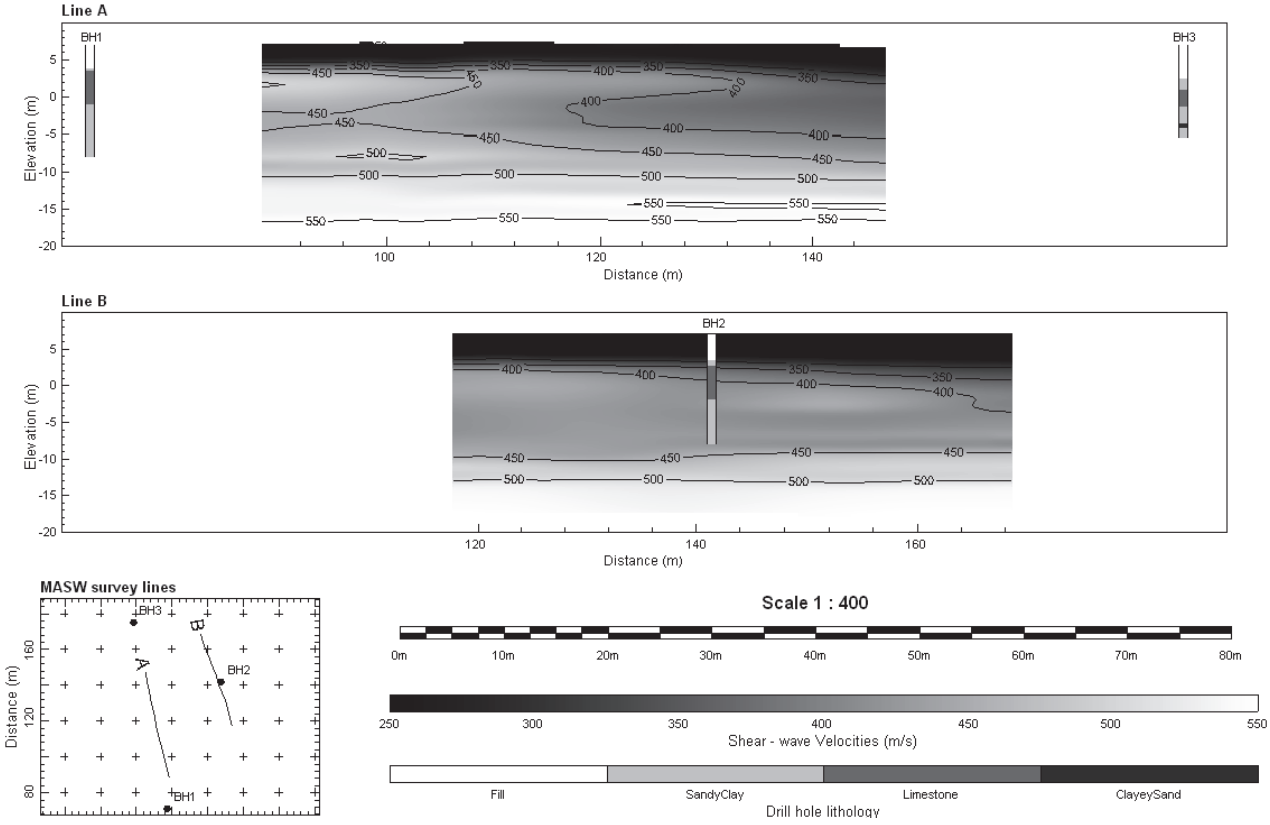



Figure 1: 2D MASW Sections with associated boreholes

Based on the MASW profiles and the borehole data a 3-layer model of the subsurface was interpreted (Table 2).

| Layer | Shear-Wave Velocity, Vs (m/s) | Lithology |
|---|---|---|
| 1 | < 350 | Dry, fine to coarse unconsolidated sand and gravels |
| 2 | 350 – 500 | Sandy clay and soft, weathered limestone |
| 3 | 500+ | Cemented/compacted sand/gravel or fractured/weathered rock |

Table 2: Summary of MASW results with interpreted lithology

Layer 1 compares directly to the fill observed in the drillhole logs matching Vs of 250 – 275 m/s. The drillhole logs observe this lithology as being dry, fine to coarse sand and gravels. Layer 2 exhibited regions of velocity inversions (high velocity layer overlying a lower velocity layer); the higher velocity regions of Layer 2 were interpreted to represent regions of extremely weathered limestone. Regions in the northern end of the site illustrated thicker cover of softer materials (low Vs).

The geophysics was able to delineate a “step” feature in the geology between boreholes, which was observed across a few of the MASW lines (shown in Line A – Figure 1); this assisted in providing a 3D interpretation of the geology. The step feature in the basement would otherwise have been lost by geological extrapolation between boreholes alone.

## 3. CASE STUDY 2 – MAGNETICS, SEISMIC REFRACTION AND ELECTRICAL RESISTIVITY IMAGING (ERI)

A geophysical investigation was commissioned to assist with geotechnical assessments regarding an extension of an existing dam site in Western Australia. The objectives of the investigation were to map the depth to bedrock and variations in bedrock hardness and composition. Previous drilling had shown the presence of a dolerite dyke, so another objective was to map possible dolerite dykes and their orientation; the knowledge of their location is important as the presence of dolerite dykes could introduce leakage or dam failure (decomposed dolerite dykes would be less permeable than the surrounding granite). The geophysical technologies that were used for the investigation were ground magnetics, seismic refraction and Electrical Resistivity Imaging (ERI).

Magnetics (ground magnetics) measures the natural magnetic field of the earth, which can be locally influenced by magnetic materials such as hematite (Stanley et al. 1990). At this investigation site magnetics was used to define the location of the dolerite dyke due to the presence of magnetic minerals in the dolerite. Magnetics data were acquired in a grid of lines at 25 m spacing over the survey area.

To provide information regarding the stiffness of the rock and the depth of interest (25+ m), seismic refraction was deemed the most suitable of the seismic technologies. Seismic refraction (land) consists of a linear array of geophones, coupled to the ground, with a series of shots (source e.g. sledgehammer, drop weight, explosives etc.) initiated through the array and from offset (off-end) positions (Redpath 1973). The recorded first arrival of the seismic signal provides information of how long the seismic wave takes to reach the geophone after leaving the source and travelling through the geology; this makes it possible to calculate the approximate P-wave velocity (Vp) of the earth material. Vp correlates well with the material strength (see for example Caterpillar rippability charts (Caterpillar, 2008)). Two parallel seismic refraction lines were recorded (290 m and 332 m in length). Geophones were spaced at 5 m with approximately 9 shots per spread (including offset shots). The seismic source was explosives (75 g for in-spread shots, 185 g boosters for offset shots).

ERI is a non-destructive technology that involves injecting a current in the ground and measuring the resulting voltages through a series of electrodes coupled with the ground (Samouelian et al. 2005). ERI is strongly correlated with porosity and water content; this is particularly useful in mapping groundwater, cavities, clay layers or geological strata and structure. ERI was chosen as a geophysical technology for this investigation to assist with delineating weathered clay material (electrically conductive) and granitic bedrock (electrically resistive). ERI data was acquired in a grid of eight lines over the investigation area, with an electrode spacing of 5 m. A non-standard array of a combined dipole-dipole and Schlumberger array were used to optimise vertical and lateral resolution.

The results from the Total Magnetic Intensity (TMI) showed regions of high TMI amplitude (59650 – 59700 nT), which were interpreted to indicate the presence of near-surface dolerites; areas of moderate TMI amplitude (59300 to 59500 nT), which were interpreted to indicate the presence of deeper dolerite and areas of low TMI amplitude (59700 – 59200 nT) which were interpreted to be areas of granitic bedrock. Drill holes that intersected dolerite were all located in regions of moderate to high TMI (> 59300 nT).

The two seismic refraction lines illustrated a consistent velocity structure: an upper low velocity layer (~350 m/s) interpreted as soft, unconsolidated sediments; an intermediate layer (500 – 1500 m/s) interpreted to be consolidated sediments or potentially weathered bedrock (in areas of larger Vp) and a lower basement unit of high velocity (> 5000 m/s) interpreted as competent bedrock. The drilling showed good correlation with seismic data (Figure 2). No obvious correlation could be seen between lateral changes in Vp and large magnetic units. This indicated that the velocity of the dolerite unit did not differ significantly from the surrounding granitic host material.

The general electrical structure of the investigation area showed an intermittent resistive surface layer (> 1000 Ωm) interpreted as resistive surficial sediments, a moderately conductive second layer (< 500 Ωm) coming to surface where the surface layer disappears - this was interpreted as more conductive sediments and weathered bedrock - and a highly resistive basement layer (> 2000 Ωm) interpreted to be bedrock. The results from the drillhole data indicate fresh bedrock was closely correlated with the ERI results (Figure 2). There was also a close correlation between the ERI and seismic results (Figure 2) – the 2500 Ohm.m contour and 2000 m/s contour boundaries, which could be interpreted as the top of the bedrock boundary, show a similar trend across the section.

Overall the ERI and refraction provided continuous profiles of the depth of bedrock and the magnetics showed the important locations of the dykes, neither of which could be achieved by drilling alone.

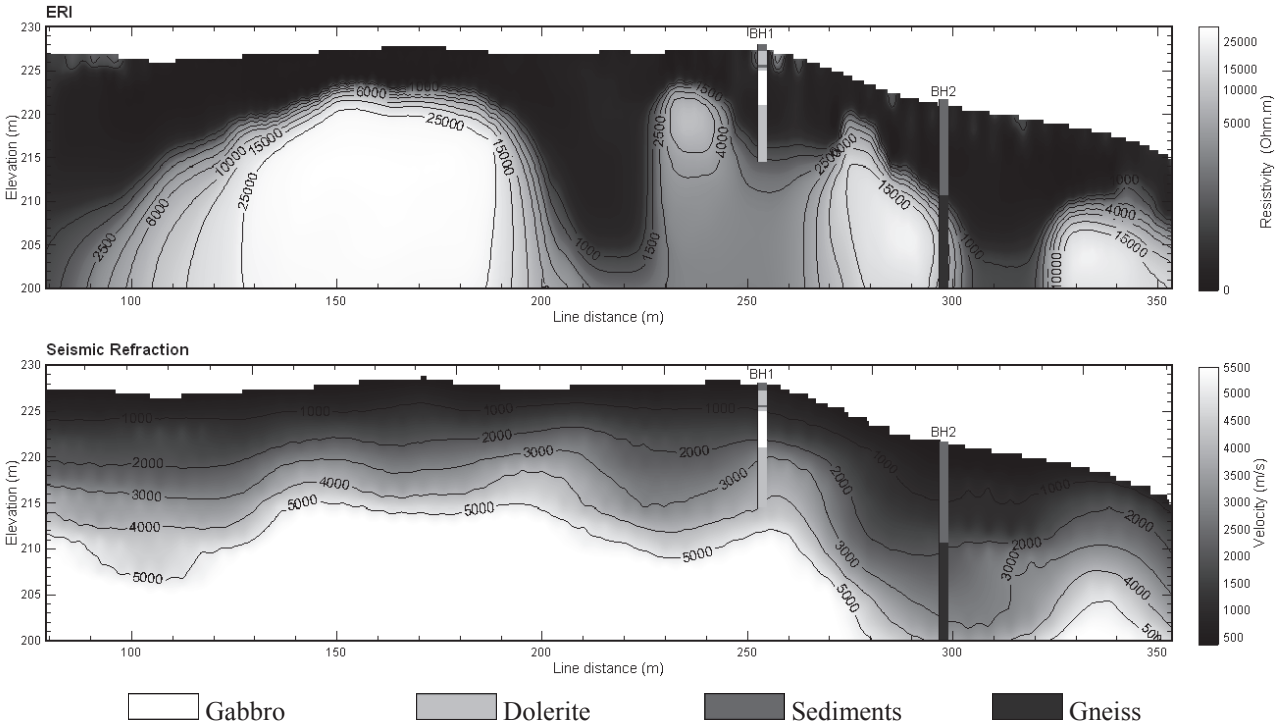



Figure 2: 2D ERI and Seismic Refraction Sections with associated boreholes

## 4. CASE STUDY 3 – AIRBORNE ELECTROMAGNETICS (AEM)

Increasingly airborne electromagnetics (AEM) is being used for a wide range of geotechnical purposes, including pollution mapping, geotechnical assessment on road and freeway alignments, assessment for major infrastructure such as pipelines, railways and tunnels, bathymetry and depth to bedrock (Christensen & Reid, 2012). AEM surveys can reduce planning risk by predicting likely near-surface ground conditions ahead of construction. In the case of oil and gas pipelines, these are often buried at a depth of a few metres and the cost of construction depends critically on whether the subsurface is composed of soft easily-excavated sediments and weathered bedrock (typically conductive) or hard rock formations (typically resistive) which require much heavier equipment and in some cases blasting.

A field case study is presented from a SkyTEM AEM survey conducted in 2011 along a proposed >500 km gas pipeline alignment in eastern Australia (Christensen & Reid, 2012). Here a gas pipeline was to be buried, requiring excavation to a depth of 3 m. The geology along the alignment was highly variable, ranging from thick sedimentary sequences to exposed crystalline basement. Areas of near-surface crystalline basement are the most problematic for excavation. The AEM survey objective was to identify areas of shallow basement along the profile – areas which were likely to require specialized excavation machinery and/or blasting (Christensen & Reid, 2012).

Figure 3 and Figure 4 display two example model sections from the survey. Figure 3 shows fairly low resistivities suggesting softer materials, whereas Figure 4 displays higher resistivities indicating the possible presence of harder rock. A statistical analysis of a set of equivalence models (i.e. a set of models that all match the data) was applied to assess the likelihood of encountering sediment or hard rock – this is shown as a black line in Figure 3 and Figure 4 (Christensen & Reid, 2012). In Figure 3 the estimated depth to hard rock is large, showing two minor zones where there is high resistivity near to the surface. The zone near 461700 m is surficial and may represent dry clay-free sediments rather than genuine shallow bedrock, however the zone near 465000 m extends to depth and may represent a genuine bedrock high (Christensen & Reid, 2012). The latter zone represents the greatest excavation risk on this section of the gas pipe alignment. Figure 4 shows a 9 km section over an area of thin unconsolidated sediments over crystalline bedrock, where drilling has shown the depth to bedrock is very variable, ranging from ~1 m to >10 m (Christensen & Reid, 2012). It would be difficult to predict bedrock depth along the parts of this section where there is no drillhole data. This is where AEM provided the information to fill the gaps. The bedrock interface determined from the statistical approach (as shown in black) is at >3 m depth along the entire section of line, and is consistent with all drillholes except the one drillhole to the far right of Figure 4. This mismatch may be due to weathered or fractured, and thus conductive, bedrock here (Christensen & Reid, 2012). The bedrock depth estimated from AEM shows very good agreement with the

drillhole at 402000 m which hit crystalline bedrock, and generally shows resistivities of <60 Ωm associated with unconsolidated sediments (Christensen & Reid, 2012).

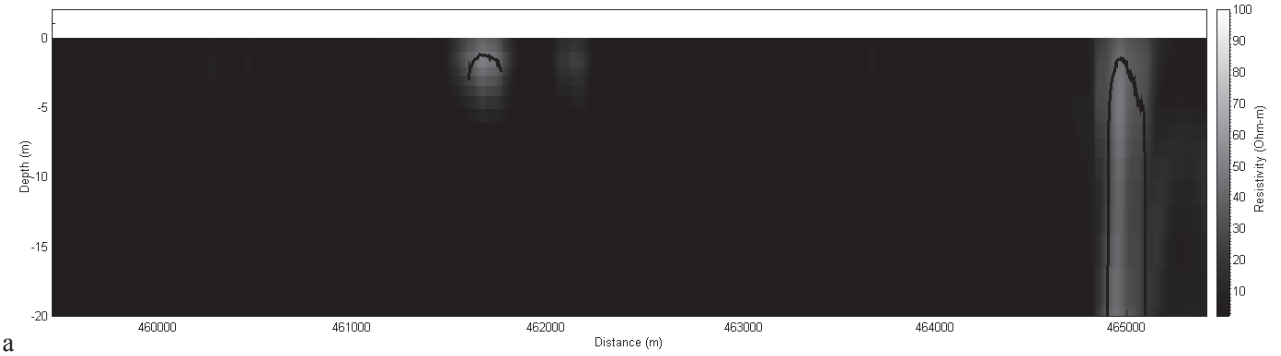



Figure 3: Resistivity cross-section along a section of the proposed pipeline alignment. Depth to bedrock estimated using the statistical approach is shown as a black line. This ~6 km section of line is generally very conductive and is likely to present few obstacles to excavation. (Christensen & Reid, 2012, Figure 2)

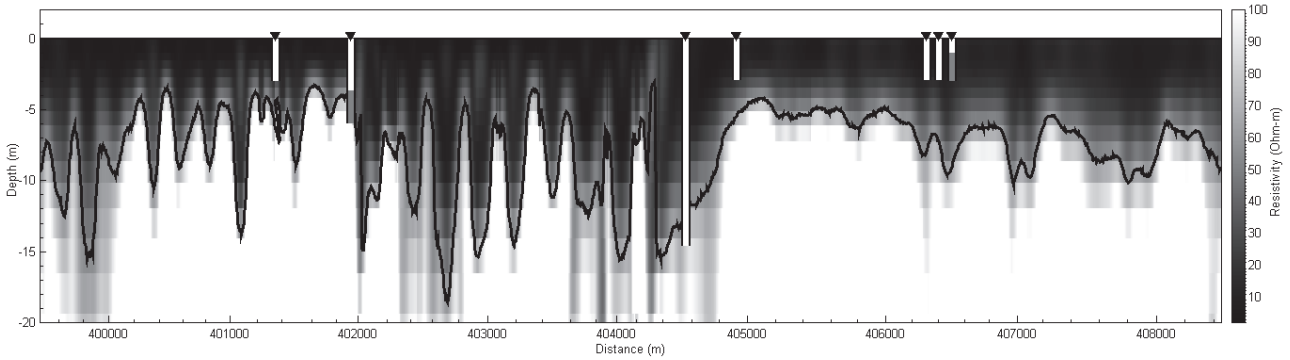



Figure 4: Resistivity cross-section along a section of the proposed pipeline alignment. Depth to bedrock estimated using the statistical approach is shown as a black line. Drillhole lithology logs show unconsolidated sediments as white and crystalline bedrock as grey. This ~9 km section shows the AEM-derived depth to bedrock is generally consistent with drilling results and suggests material above 3 m depth will generally be able to be excavated. (Christensen & Reid, 2012, Figure 3).

The AEM method successfully delineated the possible occurrence of hard formations in this case study and shows reasonable correlation with available drillholes (Christensen & Reid, 2012). AEM was rapid and cost effective and provided a very good early indication of areas which may be difficult to excavate over extensive areas where ground access was difficult.

## 5. CONCLUSIONS

Case studies have been presented in this paper that demonstrate that geophysics is a tool that can assist geotechnical engineering investigations. Case Study 1 assisted in providing a 3D interpretation of site geology which would otherwise have been lost by geological extrapolation between boreholes alone. Case Study 2 illustrated that the use of multiple geophysical technologies integrated with drilling results assisted with providing interpreted basement boundaries and interpreted locations of magnetic dykes, while Case Study 3 showed that airborne geophysics correlated with drilling results provided a rapid and cost effective interpretation of areas that may be difficult to excavate and/or access.

Geophysics is a tool that assists with engineering design and adds value to the final design product. Geophysics is not a tool that is independent of geotechnical and geological assessment; they are tools to be used together, to complement each other. Geophysics can reduce the costs of drilling programs by targeting drill locations and also assist with “filling in the blanks” between existing drillhole data. Where drilling access and ground disturbance is a problem, geophysics can offer a much more cost effective solution.

## 6. ACKNOWLEDGEMENTS

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