Adding Value to Projects with Geophysical Ground Investigation: A Review of Three Project Case Histories

Watson M[1], Collins J[1], Sunderland D[2]
[1] *Arup, Toronto, ON, Canada*
[2] *Arup, Perth, WA, Australia*

ABSTRACT
This paper seeks to contribute to the available industry literature on planning geophysical investigations to minimize ground risk and cost while maximizing value for engineering projects. This paper reviews the successes and challenges of three case histories from Hong Kong, Canada and Australia where geophysical ground investigations have been employed on buildings and infrastructure projects. Based on the successes, challenges, and lessons learnt a summary of considerations for planning geophysical investigations to minimize ground risk and cost, while maximizing value, is presented. The authors hope that this paper will encourage practitioners to take a big picture approach when including geophysics in a ground investigation campaign and will result in investigations being targeted, cost-saving and value-adding for projects.

RÉSUMÉ
Cet article cherche à contribuer à la documentation disponible de l'industrie sur les conseils pour la planification des études géophysiques afin de minimiser les risques et les coûts au sol tout en maximisant la valeur pour les projets d'ingénierie. Cet article passe en revue les succès et les défis de trois histoires de cas au Canada, en Australie et à Hong Kong où des études géophysiques au sol ont été utilisées sur des bâtiments et des projets d'infrastructure. Sur la base des succès, des défis et des enseignements tirés, un résumé des recommandations pour la planification des études géophysiques afin de minimiser les risques et les coûts au sol tout en maximisant la valeur est présenté. Les auteurs espèrent que ce document encouragera les praticiens à adopter une approche globale lors de l'inclusion de la géophysique dans une campagne d'investigation au sol et se traduira par des enquêtes ciblées, économiques et à valeur ajoutée pour les projets.

1 INTRODUCTION

Geophysical ground investigation is a class of non-intrusive subsurface investigation that evaluates properties of the earth's subsurface, commonly using seismic and magnetic measurements. While geophysics is not a substitute for boreholes or other intrusive testing, it is a valuable complimentary tool. Geophysics has the potential to optimize time, cost, environmental impact, and ground risk on projects.

This paper comments on the state-of-practice of geophysical ground investigations in the construction industry. The discussion is supported by three case studies from Hong Kong, Canada and Australia spanning across industries and scales. The case studies include a building development, a light rail transit project, and an offshore gas facility and export pipeline. Based on these case studies, the authors present their insights on how geophysical investigations can be effectively planned and executed to add value to projects.

2 BACKGROUND

2.1 A brief history of geophysical ground investigation

Geophysical ground investigation is not new. The science that underpins modern geophysical ground investigation can be traced back around 150 years to studies of elasticity and propagation of waves through solids in the 18th and 19th centuries (Dziewonski and Romanowicz 2015). This fundamental theory was significantly built upon throughout the 20th century. In 1936 Inge Lehmann, a pioneering female scientist and seismologist discovered the existence of the earth's inner core by studying seismograms from the 1929 Murchison Earthquake in New Zealand. Lehmann observed seismic P-waves (primary or compression waves) reflecting off the boundary of the earth's inner core, just as we might observe P-waves reflecting off the surface of bedrock in a modern day geophysical ground investigation (American Museum of Natural History 2020).

In the same year as the Murchison Earthquake, on the opposite side of the world, the first seismic survey for petroleum exploration was being conducted in Alberta, Canada. In the following decades, the invention of computers revolutionized the ability of engineers and scientists to process and interpret the seismic geophysical data (Government of Alberta 2020). The application of geophysical investigation to petroleum exploration transformed the industry by making exploration vastly more efficient than it was previously. An image of a field technician on site for seismic testing for petroleum exploration is pictured in Figure 1 below.

Now, more than 90 years from the first application of geophysics in the petroleum exploration industry, this technique is the default option for exploration surveys.

The mid 1980's marked a turning-point in application of geophysics for construction engineering. The Seismic Refraction method was adapted for widespread use shallower than 30 m (Steeples 2005). Since this time there has been significant uptake of near-surface geophysics investigations to inform engineering designs for our cities major infrastructure.

The application of geophysics on major infrastructure projects is now commonplace. Extensive industry publications on the application of geophysical techniques in construction engineering are available (McClymont et al. 2016).

Figure 1 This photograph of a seismic worker near Taber, Alberta in the 1950s copes with difficult road conditions. (Chevron 2013)

2.2 Why is this discussion important and relevant now?

Considering the significant progress made in the application of geophysics within the construction industry in the last 40 years, it is timely to reflect on how effectively these techniques are being used to add value to projects.

The authors propose that reflection on the current state-of-practice should include two key elements.

Firstly, a review of the available geophysical techniques. This would include evaluating whether available techniques are adequately suited to the needs of the construction industry. As these discussions are more widely covered in industry literature, this will not be the focus of this paper.

Secondly, a review of the processes for planning and implementing geophysics on projects. This would include evaluating whether geophysical investigations are being undertaken at the appropriate time in the project lifecycle to maximize value, whether there is good communication occurring between geophysical specialists and geotechnical practitioners to achieve best use of this technique, and whether the value of geophysical investigations is being effectively communicated to clients. This topic has not been significantly discussed in industry literature and will be the focus of this paper.

2.3 How can geophysics add value to projects?

Geotechnical risk management studies have shown that geotechnical risks tend to be 'wildly random'. As a result, the consequences of inadequately characterizing the ground on a project can be vastly disproportionate to the initial cost of ground investigation (Chapman 2012). Geophysics as a method of ground investigation is uniquely suited to identifying and characterizing ground risks at an early project stage due to the speed of data acquisition, the ability to obtain large amounts of spatially continuous data about the ground and the low cost compared to intrusive investigation such as boreholes (Sirles 2006).

A second impactful way that geophysics can bring value to projects is by providing data on the strain-dependent behaviors of soils. In the present-day, clients and stakeholders expect geotechnical practitioners to evaluate ground movements in the order of millimeters. For assessments of this magnitude and accuracy to be meaningful, consideration of the strain dependent behavior of soils is essential. With increasing strain, soil stiffness reduces non-linearly.

The interpretation of site-specific geophysical testing alongside conventional soil testing allows geotechnical practitioners to understand the strain-dependent behavior of the soils at their unique project site. This results in the estimation of ground movements with greater accuracy. These principles can be used to optimize many serviceability governed geotechnical design solutions.

3 CASE STUDY A: HONG KONG

This case study explores the use of gravimetric geophysical survey to inform the feasibility stage design of a proposed residential development in an area known for its marble bedrock and potential for karst features.

3.1 Project Description

The project is a feasibility study for a proposed residential development including ten high-rise towers up to 40 stories, with multi-level basements. The key purpose of the study from a geotechnical perspective was to identify any ground conditions that may limit the proposed development in any way. The project is located in Yuen Long in the New Territories in the northwestern part of Hong Kong.

3.2 Project Geological Setting

The present-day geological setting of Hong Kong has been shaped over the last 400 million years; largely influenced by regional plate tectonics and changes in depositional environments. The result is a regional bedrock dominated by Mesozoic igneous rock with older isolated areas of sedimentary and metamorphic bedrock. These sedimentary and metamorphic rocks are found primarily within the New Territories of northwest and northeast Hong Kong and include carboniferous marble. An idealized section of Yuen Long Geology is presented in Figure 2.

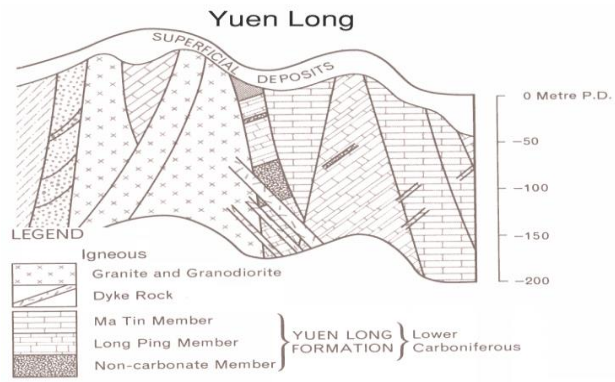

Figure 2 Idealized geological section including Yuen Long (Hong Kong Geological Survey 1992)

The project is located in an area termed Scheduled Area 2, which is defined by the Geotechnical Engineering Office (GEO) of Hong Kong as an area where the presence of marble containing cavities is possible at depth. In the study area, carboniferous marble belonging to the Yuen Long formation is known to be present, forming much of the bedrock locally.

GEO (Geotechnical Engineering Office 1994) notes the presence of an upper zone, 5 m to 15 m thick, consisting of significantly weakened rock mass dissected by dissolution channels. These karst features result in highly variable elevation of rockhead locally, with prominent steep sided peaks and troughs. In addition to the variability of rockhead, the quality and permeability of the rock may be highly variable.

3.3 Summary of Ground Investigation

Gravimetric surveys work by measuring the gravitational field within an area and identifying anomalies. These gravitational anomalies suggest variations in rock density, which can be used to identify potential for faults, karst, or other dissolution features (Geotechnical Engineering Office 2017).

The primary goal of the gravimetric survey was to identify areas of potential concern which would inform future intrusive investigation, initial locations of buildings, and decisions relating to appropriate foundation solutions.

Gravimetric data was collected at point locations in a grid formation. Interpretation of the data is presented in Figure 3.

3.4 Timing of Geophysics Within the Project

The desk study identified a high likelihood of marble and karst within the study area, which prompted use of geophysics during early stages of the project. The gravimetric survey interpretation and reporting was produced during the feasibility stage of the project, prior to the project specific intrusive ground investigation.

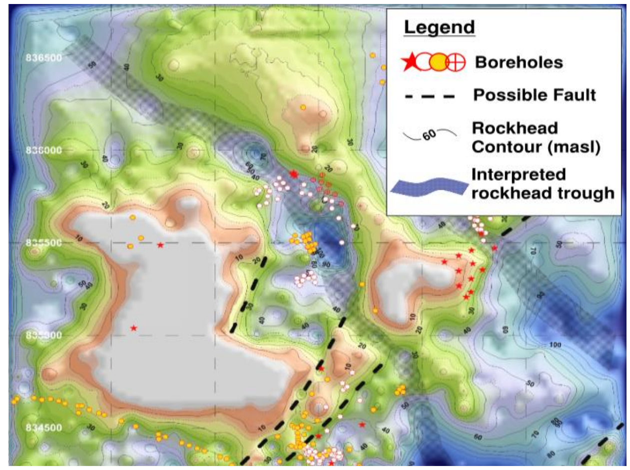

Figure 3 Interpretation of Mass Gravity Survey (Cosine Ltd 2015)

3.5 Key Moments of Communication

3.5.1 Desk Study

Starting the project with a thorough review of the existing information and providing this to the geophysics subconsultant allowed for a good understanding of the likely ground conditions at an early stage, including known areas of marble and deeper rockhead.

3.5.2 Geophysical Reporting

As part of the agreement with the geophysics subconsultant, reporting included an explanation of how the gravimetric data was processed, discussion of all data used (intrusive and geophysical), and an explanation of interpretation procedures. In addition, the agreement included a meeting between the geophysical subconsultant and the engineer to discuss the findings of the report.

3.5.3 Revisiting the Interpretation

As part of the agreement with the geophysics subconsultant, there was an inclusion for revisiting the geophysical interpretation when new ground investigation information became available. This process of “ground-truthing” allowed for verification, and where necessary, updating of the current interpretation.

3.6 Value Gained from the Geophysical Investigation

Based on a desk study, the likelihood of encountering karst and dissolution features within the project site was deemed high. Due to the limitations of the spatial coverage of most intrusive ground investigation techniques, geophysical techniques were deemed advantageous because of their cost effectiveness and ability to cover large spatial areas.

Figure 3 shows areas of higher rockhead in light grey to orange colour in the west and east portions of the study area, and areas of lower rockhead in shades of blue.

Interpretation of the gravimetric survey highlighted several features of importance:

- A central valley/trough passing through the study area.
- A number of potential faults.
- Several localized zones of deeper rockhead.

The geophysical interpretation indicated localized zones of deeper rockhead and possible fault features in areas that were not covered by the existing intrusive ground investigation.

Identification of areas with increased potential for problematic ground conditions gave engineers confidence in providing a realistic site layout early on in the design and allowed for a targeted intrusive ground investigation with the intention of confirming “no-go” or potentially problematic areas.

3.7 Lessons Learnt

The right kind of geophysics can serve as an excellent tool in highlighting areas of potential geological risk that can be used for targeted intrusive ground investigation and early decision-making during design.

During this project potential for geological risk was identified early. This allowed for early communication of the geological risks to the client, which led to early engagement with a geophysical subconsultant. Good communication between the engineer and the geophysical subconsultant was paramount and allowed for discussion of the most suitable geophysical techniques for the ground conditions and characteristics to be investigated.

This project highlights that carrying out a geophysical investigation at an early stage in the project, can be extremely valuable and allow for maximum benefit of the geophysical survey.

4 CASE STUDY B: FINCH WEST LIGHT RAIL

This case study explores the use of geophysical ground investigation to inform the design of a new light rail transit (LRT) project in Toronto, Ontario, Canada.

4.1 Project Description

The Finch West LRT is an 11-kilometre line with 16 stops, two underground stations and a Maintenance and Storage Facility (MSF). Construction is currently underway by Mosaic Transit Constructors (MTC) joint venture and scheduled for completion in 2023.

4.2 Project Geological Setting

The Metropolitan Toronto area has experienced a series of glaciation events during the past 200 000 years, depositing a complex sequence of glacial tills and glacial lake deposits overlying the Georgian Bay Formation shale bedrock. The main geological units encountered on the project are till deposits, peel ponds, glacial lake deposits, modern alluvium, and modern fill.

4.3 Summary of Geophysical Investigation

The geophysical investigation comprised 80 m of downhole seismic (DS) testing in 3 boreholes and 5800 m of multi-channel analysis of surface waves (MASW) along the light-rail project alignment and within the MSF site.

The geophysics served two aims. Firstly, to evaluate the small strain stiffness of soils within the zone of influence of the guideway and key project structures. Secondly, to characterize the top of bedrock surface at the underground western terminal stop, where boreholes indicated shale bedrock may be encountered during installation of the support of excavation piles.

4.4 Key Moments of Communication

4.4.1 Development of scope

In this project the base scope of the geophysical investigation was developed at the bid design stage by the geotechnical designer. This arrangement allowed the designer to align the geophysical testing with their intended design methodologies. Advice was sought from local geophysical specialists on available testing equipment and recommended techniques for local conditions. The scope was provided to the constructor, who procured the geophysical investigation. A secondary geophysical investigation scope was developed in the detailed design stage of the project as uncertainties in the ground conditions became apparent.

4.4.2 Communication of Results

The results of the geophysical investigation were communicated to the designer in the form of an interpretive report prepared by the geophysics subconsultant.

The report provides details of the fieldwork, testing methodology, interpretation methodology, and results. The results included profile drawings showing s-wave velocity with depth, p-wave velocity with depth, low strength soil zones, interpreted groundwater level and interpreted geological contacts.

The raw data of interpreted s-wave velocity and p-wave velocity was also provided to the designer on request in excel format.

4.4.3 Review of the Results

No allowance was made in the scope of the geophysical investigation to review the results based on new intrusive ground investigation. However, review of the geophysics results was undertaken on an as-needed basis when requested by the designer.

4.5 Value Gained from the Geophysical Investigation

In this case study, geophysics provided significant value in both the reduction of ground risk and in the optimization of geotechnical design parameters.

4.5.1 Reduction of Ground Risk

Geophysics was used to manage the risk of encountering unexpected bedrock during installation of piles for the

Humber College Stop station box and portal structure. The station box is 8 m deep and 120 m long. It is connected by a 600 m portal structure to the at-grade guideway.

During the ground investigation for the detailed design, two boreholes in the vicinity of the station box and portal structure found shale bedrock at a critical level, such that rock might or might not be encountered within the depth of the support of excavation piles.

To reduce this uncertainty, which presented a significant schedule and cost risk for the project, the designer proposed MASW geophysics lines both parallel and perpendicular to the station box and portal structures. The geophysical subconsultant calibrated the interpretation of bedrock levels using the two available boreholes. The results allowed the designer to refine the geotechnical model and identify particular areas where rock was likely be within the depth of the support of excavation piles. This informed both the design of the support of excavation piles and the constructor's selection of appropriate construction equipment.

4.5.2 Determination of geotechnical design parameters

In this case study geophysics was used to optimize the selection of project-specific strain-dependant soil stiffness parameters for the detailed geotechnical design.

4.5.2.1 Evaluation of strain dependant stiffness

The design adopted Young's Modulus (E) at 0.02% strain for design of the guideway track slab and 0.2% strain for retaining walls and foundations.

The small strain shear modulus G_{max} was directly obtained from the shear wave velocities (V_s) measured during MASW and DS tests using the relationship $G_{max} = \rho V_s^2$ (Lunne et al. 1991). The large strain stiffness was obtained at a variety of strain levels from laboratory tests (triaxial), in-situ tests (pressuremeter) and by empirical correlation with SPT 'N'.

The stiffness at intermediate strains was interpreted from the shear wave velocities (Vs) measured during MASW and DS tests using relationships by Menq for sands (Menq 2003) and Vardanega for clays (Vardanega and Bolton 2011).

These interpretations of small, intermediate and large strain stiffness were used to develop a project-specific stiffness degradation curve shown in Figure 4. This allowed the selection of realistic stiffness parameters compared with traditional methods such as correlation with SPT 'N'.

4.6 Lessons Learnt and Limitations

4.6.1 Evaluation of boundary between dense glacial till and weathered shale bedrock

At a fundamental level, geophysical investigation detects changes in the physical properties of the earth. Where the physical properties of two materials are similar, it can be challenging to distinguish them with geophysics.

In order to differentiate between units of similar density such as the dense till and weathered shale bedrock, high quality logging of intrusive boreholes used for calibration is essential. In particular, it is critical that the boreholes accurately determine the boundary between overburden and rock. Wherever possible it is beneficial for the designer to supervise keys boreholes to have the greatest chance that the necessary data will be obtained.

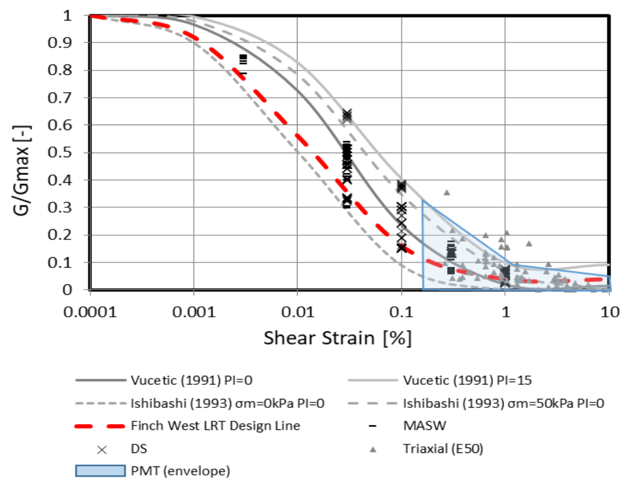

Figure 4 Project specific stiffness degradation curve for till and peel pond formation.

4.6.2 Limitations of interpreting soil design parameters from geophysics

The results of the geophysical investigation were used extensively on this project to refine the selection of geotechnical design parameters. As with the geotechnical parameter derivation in general, significant caution must be used when adopting empirical correlations. It is essential to review the results critically and within the context of all the available geotechnical data.

5 CASE STUDY C: BAROSSA DEVELOPMENT

This case study explores the use of geophysical ground investigation to support the design of an offshore gas field development in the Timor Sea, Australia.

5.1 Project Description

The Barossa Project is located approximately 300 km north of Darwin in the Bonaparte Basin, Timor Sea (Figure 5). The Project is a Joint Venture between Santos Offshore Pty Ltd (the Operator) and SK E&S Australia Pty Ltd. The offshore development includes a floating production storage and offloading (FPSO) facility, Subsea production system (SPS) and a 260 km long gas export pipeline (GEP) connecting to a tie-in point 130 km offshore from Darwin.

5.2 Project Geological Setting

Water depths at the Barossa infield area range between 220 and 300 m with northward dipping seafloor slopes less than 1° towards the Timor Trough. The trough marks the surface expression of a subduction zone approximately 100 to 150 km to the north of the infield area (Figure 5).

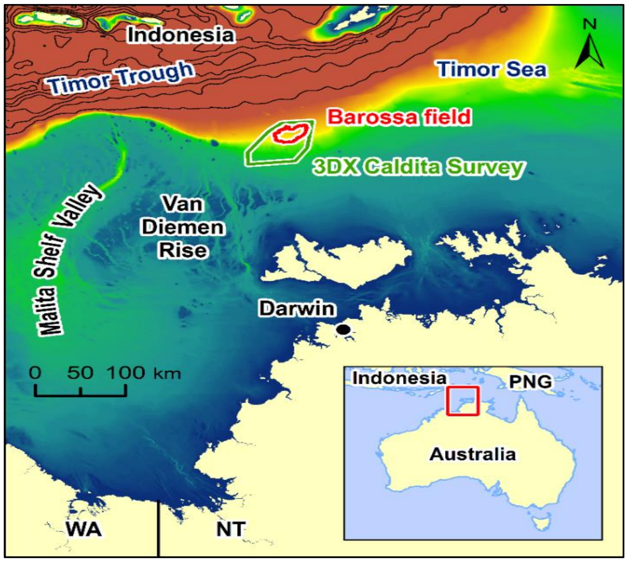

Figure 5 Site Plan of the Barossa field and the 2007 Caldita 3DX seismic survey area (Sunderland and Lane 2017).

As described in Sunderland and Lane the recent geological evolution and patterns of sediment deposition on the Van Diemen Rise have been strongly influenced by glacio-eustatic sea level variations throughout the Pleistocene and Holocene. (Sunderland and Lane 2017) During glacial periods sea-levels were about 125 m lower than present. South-north orientated seafloor valleys to the south and south -east of Barossa would have provided a conduit for sediment sources from terrestrial and shallower water depths as demonstrated by (Bourget et al. 2013).

During the Last Glacial Maximum (LGM) and previous Pleistocene glacial lowstands, the infield Barossa site remained on the Continental Shelf, thus avoiding sub-aerial exposure. Infield sediments are therefore uncemented (calcareous) whilst geological profiles in water depths shallower than 125 m, developed cementation (calcretes).

5.3 Summary of Ground Investigations

Exploration geophysical surveys have been conducted in the Timor Sea for decades, typically penetrating the seabed in the order of 1 to 2 km in search of hydrocarbon resources. A 3D Exploration (3DX) seismic survey covering the Barossa field (an area greater than 4,000 km^2) was conducted in 2006 to 2007 as outlined in Figure 5.

In 2006, shallow offshore geophysical surveys (typically penetrating the seabed up to 100m) were conducted at the Barossa infield area specific to proposed well locations. Survey techniques included multi-beam echo sounding (MBES), side scan sonar (SSS) imaging and sub-bottom profiling techniques.

In 2015, Pre-Front End Engineering Design (Pre-FEED) activities commenced. During this phase, two infield and GEP geophysical surveys were carried out. MBES and SSS were conducted and sub-bottom profiling techniques included surface towed Sparker and Boomer systems and a sub-tow Chirp system. Infield geophysical survey lines spacings were 1 km apart. A Pre-FEED geotechnical survey also obtained Piezo Cone Penetration Test (PCPT) results and samples up to ~100m below seabed..

In April 2018, the Barossa project entered FEED at which time a shallow geophysical and geotechnical survey took place. MBES and SSS were conducted and sub-bottom profiling techniques included Chirp and Sparker. Infield geophysical line spacings were 100 to 200 m apart. Geotechnical investigations targeted engineering locations and included in situ testing and sampling.

5.4 Timing of Geophysics Within the Project

As detailed in Section 5.3, multiple geophysical surveys for the Barossa project occurred between 2006 and 2018. The reason for each survey is specific to the requirements of the project development phase and varied depending on the maturity of the engineering and facility layouts.

5.5 Key Moments of Communication

Given the lengthy durations for offshore projects and the associated costs incurred with survey operations, it is important that the Operator commissioning the surveys understands the associated opportunities and risks of the surveys and the acquired data. Considerations included the timing of surveys in relation to the maturity of project designs and the sensitivities of each technique adopted to external influences such as weather conditions. Open and ongoing communications were maintained between technical and managerial stakeholders before, during and after surveying throughout Pre-FEED and FEED stages between former operator ConocoPhillips, Arup as the Geo-Consultant (or Owners Engineer overseeing the surveys) and various survey Contractors.

5.6 Value Gained from the Geophysical Investigations

Risk reduction from geophysical surveying on the Barossa project included progressing the understanding of ground models as far as possible concurrently with and/or in advance of engineering designs and other activities.

Pre-FEED geophysical surveys covered much larger areas than the FEED survey. Pre-FEED surveys included wide (1 km) line spacings up to 25 km long in the infield area and reconnaissance style surveying on various GEP routes to assess conditions across a variety of possible options. This reflects the project stage whereby engineering layouts for infield facilities and the GEP were not mature. Survey line plans were developed to cover large areas and target geological features of interest such as a buried headscarp around the 220 m seabed contour in the infield area (refer to Figure 6) and north-south orientated palaeo-channels and palaeo-ridges in deeper waters.

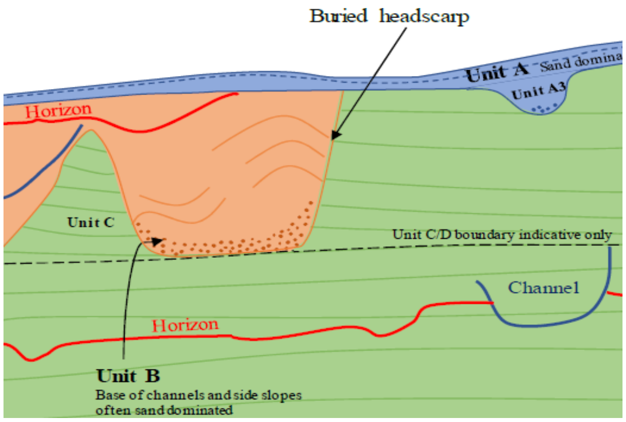

Figure 6 Part of the Barossa infield engineering geological model highlighting selected seabed features (approx. exaggeration, V:70m, H:5km)

The 2015 infield Pre-FEED survey also utilized a re-interpretation of the shallow component of the 3DX data as explained further in Sunderland & Lane (Sunderland and Lane 2017). This allowed a short duration, cost-effective survey to achieve a broad but accurate regional geological model on which to base early project assumptions..

The FEED geophysical survey was conducted with more mature engineering design layouts and foundation concepts with a more targeted coverage. If facility relocations were required, a greater level of confidence in ground conditions could be achieved due to the higher density survey data set. The FEED survey also utilized survey techniques that had been previously proven in earlier surveys for the given ground conditions.

Geophysical survey data could also be 'calibrated' with borehole information, including continuous CPT data thus improving geological and geotechnical models.

5.7 Lessons Learnt

The positive project outcomes experienced can be attributed to industry sector recommendations and experienced personnel who understand and can communicate the benefits and cost savings of geophysics. The wider geological setting was first put in context, narrowing over time with more focus on specific locations. Geophysical techniques trialled in the early phase allowed the most suitable and successful techniques for the given ground conditions to be used in the latter surveys.

Stakeholder communications were coordinated, open and honest. Planning of upcoming stages and activities was developed with combined input from project managers and development engineers, through to geologists, surveyors, geophysicists and geotechnical engineers, all experienced in offshore developments of this nature. Continuity of knowledge was also retained between phases with the same personnel.

Back up plans were also incorporated into the planning, for example, if marginal weather conditions caused significant background 'noise' to data sets, then lines were re-run once the sea state improved or additional post-processing of the data was conducted.

The Owners Engineer who oversaw surveys in the field was also responsible for Geotechnical Interpretive Reporting hence there was a vested interest to achieve a high-quality product from the beginning.

6 KEY INSIGHTS

This section summarises the insights on opportunities for the industry to increase the value gained from geophysical investigations in the construction industry over and above the current standard practice.

6.1 Prevalence of geophysical ground investigation

In building construction projects, the adoption of geophysics is region specific. In regions with significant geological uncertainties, such as the karst formations in Hong Kong presented in Case Study A, geophysics is commonly used. In contrast, within the well-known tills of Toronto, Canada or the well-known residual clays of the Sydney Basin in Australia, geophysical investigations for buildings are much less commonplace. Underutilized opportunities remain, to improve project schedules and reduce cost of ground investigations for small projects in well-known geological conditions using geophysics.

In linear infrastructure projects the use of geophysical investigation techniques is becoming standard practice. Typically, geophysical investigations are completed in targeted areas of the project where there is a specific geological risk or uncertainty to be evaluated. The geophysical investigation usually represents a small fraction of the overall ground investigation scope. In the authors' experience owners and technical advisors often have reservations about utilizing geophysics to reduce the required scope of conventional intrusive investigations such as boreholes with SPT 'N' testing. On these projects, clearly communicating the value of the geophysical investigations and educating clients on the role they play as part of the broader suite of ground investigation techniques remains key in increasing industry acceptance. There is opportunity to utilize geophysical investigation techniques on infrastructure projects more widely, both to reduce the quantity of intrusive testing required and where appropriate to better understand the strain dependent behavior of the soil.

In offshore projects, geophysical investigation is generally well established, outlined in various codes and guidelines and in many circumstances is required for insurance purposes. In offshore hydrocarbon, renewable, and infrastructure industries, geophysical investigations are typically combined with bathymetric or hydrographic surveys and often comprise a significant component of the overall ground investigation. The onshore construction industry can potentially learn from the offshore practice in conducting geophysical ground investigations.

6.2 Purposes of geophysical ground investigation

Geophysical ground investigations are most often used to reduce ground risk on a project. The use of geophysics to inform the selection of project-specific strain-dependent geotechnical design parameters is less common and thus opportunity exists to make greater use of this benefit.

6.3 Communication of value to clients

The value of geophysical ground investigations appears to be communicated to clients, however not all are convinced of its benefit. Sometimes a negative experience may have been encountered in the past e.g. geophysical results that were inconclusive. In such an instance, an incorrect technique for the ground condition may have been adopted, a back-up technique may not have been allowed for or the experience of the parties involved may have been lacking. As industry confidence grows in geophysical techniques, the authors expect geophysical ground investigations will be used more frequently and hence add value in a wider range of circumstances.

6.4 Timing within the project

The ideal timing of geophysical investigations within a project and within a ground investigation campaign depends entirely on the individual circumstances and purpose of the investigation.

Where there is known 'wildly unknown' ground risk such as the karst geology presented in Case Study A, it is essential that the geophysical investigation is done at the beginning of the ground investigation campaign, such that it is followed by confirmatory intrusive ground-truthing.

Where a ground risk becomes known mid-way through a project, such as the critical rock elevation in Case Study B, a geophysical investigation is most impactful when completed swiftly, such that planned intrusive investigation can be used to ground-truth the results.

Where the purpose of a geophysical investigation is to inform the selection of geotechnical design parameters, it still benefits the project to have the investigation done early in the project, but the timing is less critical. A second survey may, on occasion, also be beneficial.

6.5 Communication between stakeholders

The key stakeholders relevant to a geophysical investigation are the client, the geotechnical designer and the geophysical specialist. In each of the examined case studies, open, honest, and collaborative communication occurred between each of the key project stakeholders. This contributed to the success of the geophysical investigations on these projects.

7 CONCLUSION

Geophysical investigation is now commonplace. The adoption of geophysics in the construction industry has grown significantly over the past 40 years. However, in the authors' observation, there remains significant potential for geophysical ground investigation to further transform the geotechnical standard practice and as a result to give more value to clients, owners, and the community at large.

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