Combining Historical Geotechnical and Geophysical Data with Recent Aquares Geophysical Survey Data into a GIS Framework for the Eden Port Development

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Abstract
The Eden Port Development is a $25 million development of new infrastructure assets in Eden, NSW, that is being project managed by NSW Trade and Investments: Crown Lands. The proposed development comprises, the extension of the existing breakwater wharf (including new breasting and mooring dolphins and associated dredging in and around the berth pocket) to accommodate 300m+ LOA vessels, and a feasibility study into a fixed or floating wave attenuator for the protection of smaller recreational and commercial vessels moored in the marina.

To facilitate cost effective acquisition of geotechnical and geophysical data, Crown Lands planned a stepped approach to the ground studies across the entire area, to be undertaken as a single work package. Initially, an Aquares resistivity survey was undertaken to define the geological structures at the site. An Integrated Digital Ground Model (IDGM) was then created that included available geophysical studies and historical geotechnical datasets. Crown Lands utilised this model to plan a targeted geotechnical campaign designed to mitigate latent geological risks specific to the current project, including dredge batter and pile embedment designs. The IDGM was constructed utilising Encom Discover PA 2015 (an interactive 4 dimensional GIS environment) and in the final iteration included newly acquired Aquares data, 21 historical boreholes, 15 vibracores, side scan, magnetometer and reflection datasets. The IDGM also included raw metadata such as run-lines, side scan mosaics and SEG-Y images to assist in comparing unrelated datasets against one another. The IDGM has been utilised to realise an 11% reduction in programmed piling costs and identify $3 million in previously unidentified dredge costs.

The creation of an IDGM is a research project currently being undertaken by OEMG primarily to create robust ground models and to ensure all data formats are digital and compatible with GIS, BIM (Building Information Modelling) and civil design packages such as 12D and AutoCAD. This paper explores the advantages of such an approach and how the work flow and model might be improved in the future.

Keywords: Port Development, Aquares, Qualitative Geophysics, GIS, Ground Modelling, Geotechnical BIM

Introduction

A Federal grant of $10 million was announced in July of 2013 to kick start the re-development of the Port of Eden. With funding now totalling some $25 million and sourced from all levels of government, the re-development of the port is considered essential to revitalising and indeed expanding the local economy. The development comprises two major components, both now managed by NSW Trade and Investments, Crown Lands: the Breakwater Wharf Extension and; improvements to enhance the safety of mooring small vessels in the area. The Breakwater Wharf Extension project is currently in the execution phase and comprises the extension of the existing wharf (including breasting and mooring dolphins) to accommodate 300m+ LOA vessels and dredging of up to 200,000m^3 of material to expand the berthing pocket and approach channel. The project to improve the experience of small vessels is still in definition phase and currently includes a feasibility study into the installation of a fixed or floating wave attenuator. Two separate locations have been identified as potential sited for the new attenuator (Figure 1).

Preliminary engineering reports for the Breakwater Wharf Extension [1] and the safe boating options [9] both recommended the undertaking of further geophysical and geotechnical studies to better understand the geological setting to improve cost estimates. To this end, GBG was contracted to undertake a reflection survey of the Breakwater Wharf Extension area at the end of 2014 [5]. Australian Marine Associates (AMA) was subsequently contracted to undertake geotechnical studies and further geophysical studies, in both the wharf area and the locations identified as being potentially suitable for a wave attenuator.

As part of the contract awarded to AMA, OEMG Global was tasked to undertake an Aquares Resistivity Sub-Bottom Profiling study to create a 3D grid of the sub-bottom throughout the investigation area and collate all available metadata and historical data in the experimental

Integrated Digital Ground Model (IDGM). The purpose of the IDGM was to provide a centralised GIS Framework that would accommodate all spatial data and facilitate the understanding and communication of these complex datasets and, the targeting (or placement) of boreholes within geological structures identified by the Aquares geophysics, to ensure all relevant geological risk areas were sampled [8].

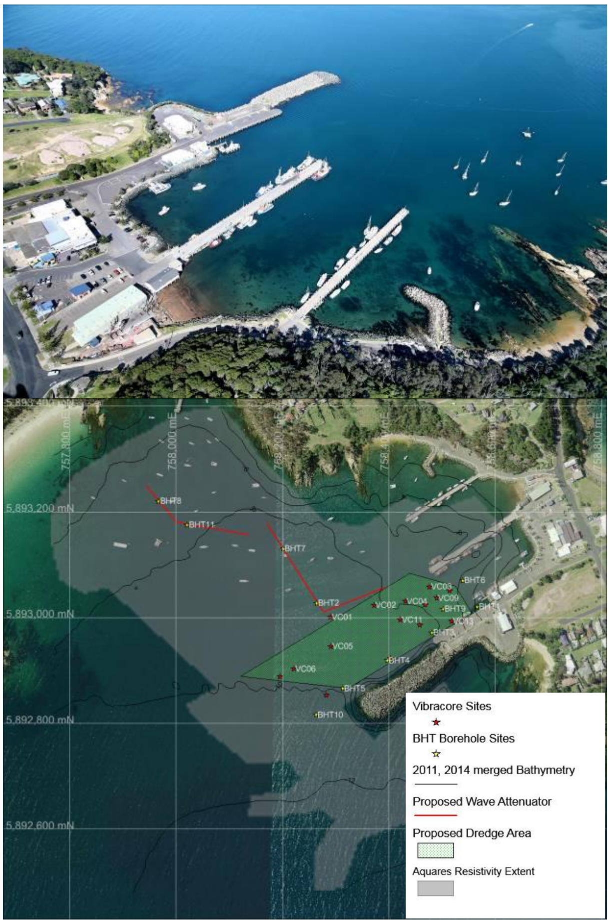

Figure 1 Aerial photo of the proposed Eden Port re-development area. Grid is GDA94, MGA55.

This paper explores the utilisation of the IDGM on this project in the context of its development over the last year. We include examples of how the Aquares system, in conjunction with the IDGM and targeted boreholes, allowed for the visualisation of the complex vertically oriented geology in the area for the first time. We also look at the impact the IDGM had on the proposed designs and cost estimates as well as improvements scheduled for the product as a result of lessons learned during this project.

A New Approach to Ground Modelling

Australian Standards (AS1726, [4]) stipulates the testing of engineering properties in addition to geological variation at a site. The acquisition of engineering data is usually attained through boreholes, however they only provide information about a point in space and cannot provide information about the variation (including stability and extent of geological structures) at a site (Figure 2). Visualisation of geological variation can be acquired utilising qualitative geophysics [3, 4]. Ground modelling for these works varied from traditional methods by utilising geological structures defined by qualitative geophysics to govern the placement (targeting) of boreholes. The IDGM was then utilised to produce a complete and actionable model of the sub-bottom. To achieve this, multiple contractors were engaged by Crown Lands to examine key elements of the geological setting. Crucially, a specialist consultant was engaged to facilitate a stepped approach to the ground modelling and ensure adequate communication between the contractors and ensure agreed data formats and standards are maintained. Adherence to the schedule and data formats was critical to the success of the ground modelling process.

This approach was utilised to mitigate the significant risk and cost implications associated with accepted practice associated with the set out of borehole locations. Commonly, boreholes are set-out on pile locations, gridded or randomly dispersed at a site with no regard for the geological setting. These set-out methods provide no confidence to design and construct contractors that geological structures have been adequately tested for the influence they will exert in the proposed infrastructure.

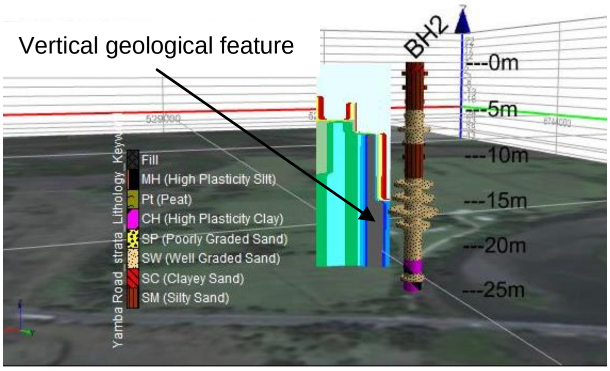

Figure 2 OEMG has been able to utilise Aquares results to identify isolated geological structures that may cause problems during construction. In this figure, an unusually soft vertical structure (dark grey) was found to persist to the limit of vertical detection of the Aquares cable utilised. The area was then tested with a borehole and characterised by very low SPT values and would have been problematic for the Horizontal Directional Drill proposed. Data courtesy Clarence Valley Council.

Additional limitations inherent to ground modelling are that all investigation techniques are remote sensing tools and results (including bore logs) are only approximations requiring corroborating data to support findings. Boreholes can be particularly problematic as the shortcomings of the acquisition process are not widely understood and not always well documented during reporting. They are, for example, a destructive sampling technique and the selection of appropriate sampling methods is critical to both vertical and descriptive accuracies. Therefore the production of a robust ground model is dependent on the appropriate application of each technique to the site, the corroboration of results and the successful communication of the results to all stakeholders.

Aquares Data Acquisition at Eden

For the this Project, OEMG was selected to provide an Aquares survey because of their track record of quickly turning around processed datasets and accurately visualising complex geological structures at a site. Speed and accuracy was critical to produce a model for borehole targeting and to meet established timeframes.

The Aquares system is a resistivity based sub-bottom profiling system that is designed, built and operated by DEMCO and OEMG. The system acquires accurate qualitative and quantitative data and, is particularly suited to the aims of the project and the complex environment at Eden. Aquares has the highest shot rate of any qualitative system available at 1.2Hz (1 shot / 900miliseconds) with analogue to digital conversion occurring during the acquisition process. This facilitates acquisition of a greatly increased number of successful shots and the production of a more robust grid through improved statistical processes, when compares to competing methods such as seismic refraction.

The Aquares sub-bottom profiling spread, including DGPS positioning and echo sounder was mobilised onto a locally based utility vessel, the MV Sherlock (Figure 3). Approximately 16 line kilometres, including approximately 9000 shot points of data, were collected (Figure 4). The entire survey, including mobilisation and demobilisation, was completed over a two day period. Line spacing was largely governed by the distance between moored vessel and the safety of the tow package behind the vessel.

Figure 3 The Aquares spread was mobilised onto the Eden based utility vessel MV Sherlock.

Aquares data was processed over the following two days and the first revision of the ground model created (Figure 4) by uploading all data into the Encom Discover PA environment [8]. This dataset comprised:

- GBG interpreted layers 1, 2 and 3;
- Marine GeoSolutions processed Side Scan data;
- Marine GeoSolutions processed Magnetometer Data;
- AMA vibracores; and
- Historical Boreholes.

From an initial examination of the data it was noted generally that complex high resistivity structures dominate the near surface area to the north and east of the survey area and to the south lower resistivity structures become more prevalent (Figure 4).

Initial Data Review and Borehole Targeting

After consideration of the Aquares data, eight boreholes were proposed by OEMG and Crown Lands. The positions of Boreholes 1, 3, 4, 5 and 6 were provided by the principle and largely based on the position of proposed infrastructure in the area. Boreholes 2, 7 and 8 were proposed by OEMG to verify the Aquares results and to provide useful engineering data for infrastructure proposed at their locations. WorleyParsons then provided peer review of the proposed borehole locations in light of the findings of the IDGM and associated data relating to the site [14].

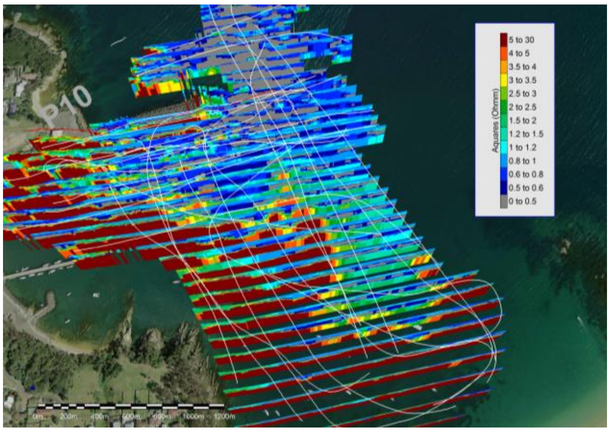

Figure 4 An initial review of the IDGM is made up of 16 line Kilometres and over 9000 shot points of data and sees complex high resistivity structures evident in the shallows to the north and east of the survey site deepening to the south.

The review addressed risks associated with the expected construction activities and included: material (geological) variation in the dredge areas; toe stability of existing structures post dredging; pile drivability; and bearing, sliding stability and settlement of gravity based structures, against known geological conditions. The report utilised the interpreted geological conditions, from a previous study [5] as; loose to dense sand/shelly sand, silt and layers of soft to firm silty clays above bedrock that is variable in height and ranging from less than two meters below the seabed near shore to more than -16m below CD towards the end of the proposed wharf (Figure 5).

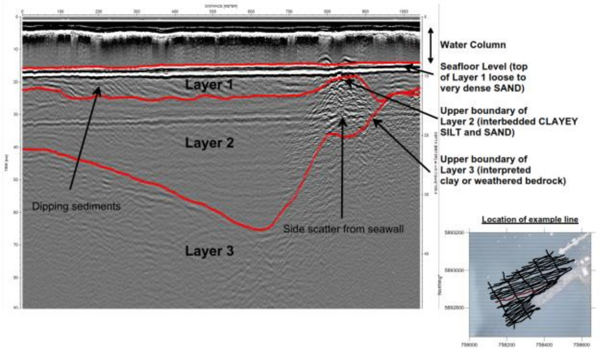

Figure 5 Interpreted reflection results from the 2014 GBG geophysical campaign [5].

Rock strength was noted to vary from weak, to high strength as described by GBG [5]. It is noteworthy that no mention is made of the vertical nature of the rock structures present at the site in this report, though WorleyParsons stated a requirement to test the potential ground variation found in the resistivity results and to assess potential impacts on foundation design. Accordingly, boreholes 9, 10 and 11 were added to the geotechnical campaign.

The Geotechnical Campaign and the IDGM

Following the WorleyParsons review [14] Techtonics undertook the boreholes required over the following 3 months. Their field report [12] described the local geology as comprising structures of the: **Adaminaby Group,** undifferentiated sediments, turbidites, sand stone, mudstone and shale; **Boyd Volcanic Complex,** undifferentiated acid volcanics, basalts, quartzporphyries, and minor sediments; and **Twofold Formation,** fluvial sandstone with mudrock and conglomerate [12]. Volcanic activity associated with the Boyd Volcanic Complex likely caused much of the geological complexities at the site (Figure 4, [12]) and include extrusive rhyolites, metamorphism and steeply dipping (near vertical) strata (Figure 6).

Figure 6 Steeply dipping rock outcrop at the eastern shore of Cattle Bay [5].

To facilitate the successful integration of borehole data into the IDGM, boreholes were accurately located utilising DGPS. In addition, digital delivery of bore log data was required in gINT format along with the uniform descriptions according to AS1726 [11]. Under the direction of AMA, the above criteria were largely adhered to and, the integration of all datasets was relatively straightforward. The combination of historical data with more recent Aquares geophysical information and targeted boreholes presented in Encom PA 2015 provided a geological understanding of the area that was, unprecedented and considered successful.

After analysis of the IDGM [8], all targeted boreholes validated the findings of the Aquares model. Indeed, for the first time the geology (including vertical features) at the site is visualised in 4D with an accuracy that has been utilised to tailor designs and provide real cost-benefit to the project. For the purpose of this paper, we will limit the analyses of the results to the wharf construction along the profile P10 seen in Figure 7.

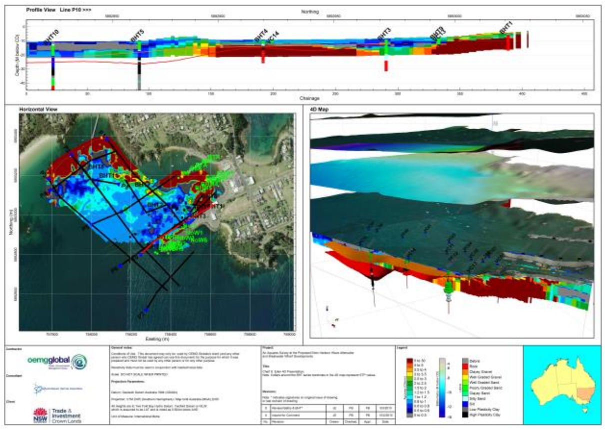

Figure 7 The IDGM is a digital chart delivered to the client with free viewer software. The chart contains a 4D view, a 2D plan view with grids than can be turned on and off as well as vertical sections along agreed flight lines that can be cycled through.

As discussed, earlier, the model (Figure 7) includes interpreted reflection data [5], as well as historical and new, targeted boreholes. Fortunately, GBG provided their interpreted layers as 3D surface grids in Ascii format. Utilising this data the grids were converted to Surfer binaries which could then be imported directly into Encom PA. The 3D surface grids could then be interpreted onto 2D section grids by assigning the grid values under a user defined section line to a GeoSoft Database, via a utility within PA. All historical bore logs were digitised into gINT format by Techtonics, and newly acquired bore logs were created in gINT as part of their normal business practice [13]. The gINT project was converted into a Discover DownHole project utilising the Downhole utility in Mapinfo Discover that could then be imported and visualised in PA. Aquares data is provided as a 3D

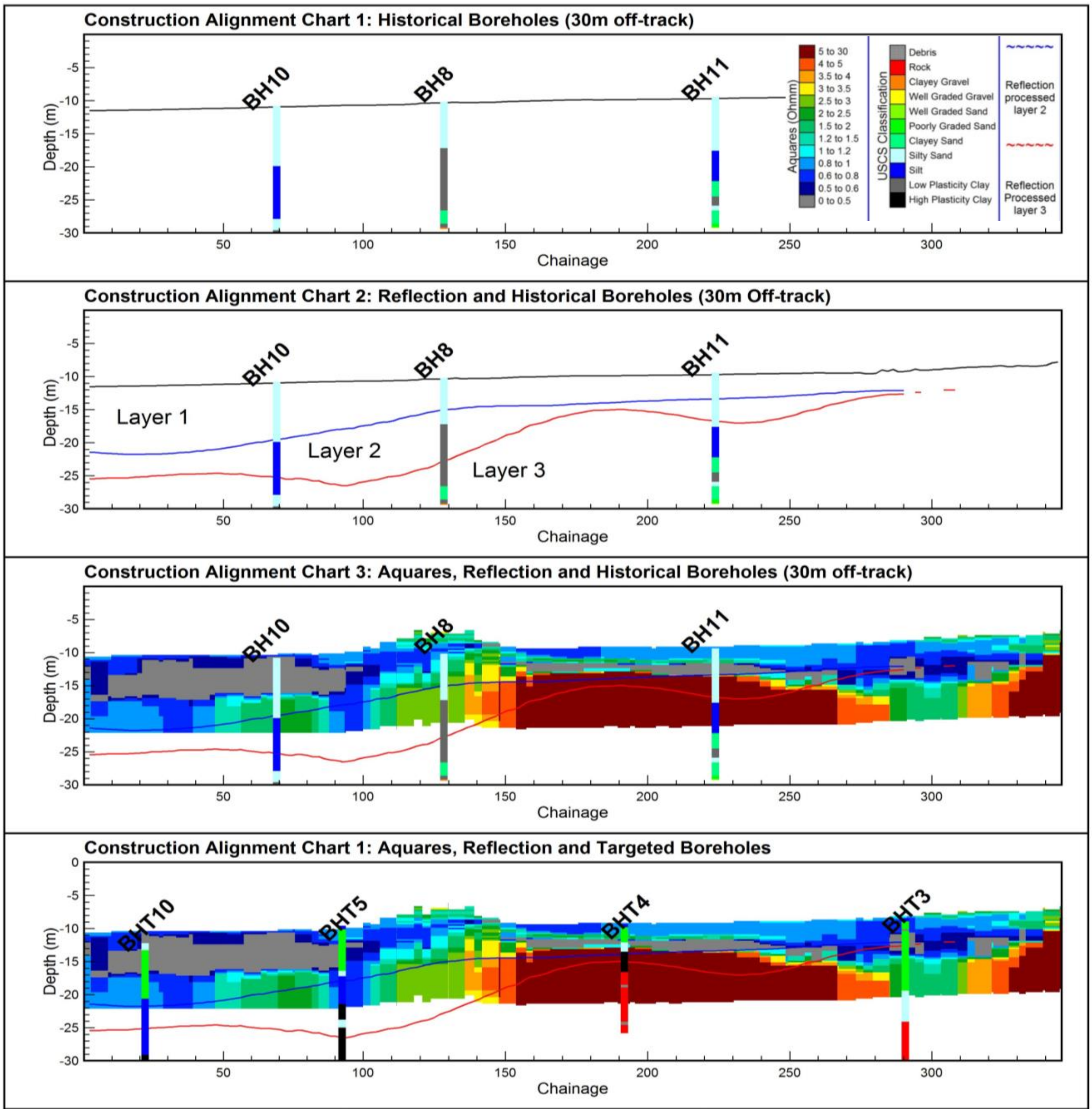

Figure 8 An analysis along section line “P10” looks at the application of different datasets and how they change the interpretation and influence construction.

Ascii grid (x,y,z,d) which can be imported directly into PA and then (utilising a utility in PA) converted into a voxel for visualisation. PA will automatically generate vertical sections along user defined section lines. Once all key datasets were loaded into PA and the IDGM created, it is possible to analyse the site holistically (Figure 7).

Encom Discover PA

We believe that this is the first time Encom PA has been utilised to visualise civil engineering data in this manner. We elected to use PA after reviewing ground modelling practice across industry sectors (including oil and gas) and the many competing software packages. This is because the Aquares system, almost uniquely among near surface (first 50m BSB) sub-bottom profilers, is built from the ground up to collect true 3D data. However, the visualisation of 3D data in 4D space and, the extraction and visualisation of section grids including ancillary data is, in a word, complex.

PA uniquely capable for this application as it is designed for mineral exploration, which routinely requires similar data analysis techniques, albeit at much deeper depths. However, the focus on mineral exploration results in some limitations for near surface ground modelling applications. This is particularly evident with regards to borehole management where it is not yet possible to visualise standard sediment swatches (Uniform Sediment Classification Scheme or AS1726 [5]) or down hole test results such as SPT or Acid Sulphates in vertical sections. With the mechanics, benefits and limitations of PA in mind, it is now possible to review the IDGM and investigate the impacts it will have on the project.

Analysis of Section Line P10

An analysis of section line "P10" is provided in Figure 8 and is representative of the construction footprint of the proposed wharf extension. To illustrate the effect each dataset has on the interpretation of the geological setting and the flow on cost implication for construction, four vertical sections are considered:

- **Chart 1**, Historical Boreholes (BH series) only that are between 30m to 50m off centre;
- **Chart 2**, Processed Reflection data along the construction alignment and Historical boreholes;
- **Chart 3**, Aquares data, Historical Boreholes and Reflection data; and
- **Chart 4**, Aquares data, Reflection data and Targeted Borehole (BHT series) data.

From this data (Figure 8, Chart 1), it can be seen from the historical boreholes that are just 30m off the construction alignment, there is no evidence for the presence of rock. The addition of reflection or indeed Aquares data (Figure 8, Chart 2 and 3) does not assist in the interpretation as reflection Layer 3 is interpreted as clay or weathered bedrock (Figure 5) and is contradictory to other data sets. The complex geological setting is only understood with the addition of targeted borehole data (Figure 8, Chart 4) and the SPT data (not shown). BHT1 and BHT4 both contain rock, respectively sandstone and shale and suggest that resistivities of >3 Ohm.m are indicative of rock. Approximately three meters of high plasticity clay is seen in BHT4 above competent shale however, this is likely to be highly weathered shale. No electrical difference is seen between these two units, likely due to similar silt or clay content. However the layer 3 reflection boundary lines up with this interface and highlights the importance of the utilisation and amalgamation of multiple ground assessment techniques. BHT3 sees poorly sorted sands to -21m Chart Datum (CD) with a marked density contrast at approximately -16m which aligns with the resistivity change (blue to green), likely representing a change in depositional environments [5]. BHT5 and BHT10 follow similar trends with SPT value increasing at this boundary (Figure 8, Chart 4) [13].

Examining reflection layer 3, the extent of useful data reported by GBG is approximately -25m CD (Figure 5 and Figure 8). However, the relevance of layer 3 is not clear at deeper depths when considering the BHT series boreholes (Figure 8, Chart 4). It is possible, that with deeper processing of the reflection data, additional intricacies may be extracted from the raw SEG-Y data, but this would require time and cost that may have been outside the budget of the survey. However, the engineering significance of further processing is at best dubious due to the purely quantitative nature of the method and the complex geology at the site. These results highlight the importance of adequately funding appropriate surveys and corroboration of results utilising supporting data such as bore logs and qualitative geophysics as part of the IDGM.

Initial Cost-Benefit Analysis of the IDGM

Prior to the undertaking of any new geotechnical or geophysical works, a cost analysis of both projects was undertaken by Royal Haskoning [7, 9]. The final option for the wharf construction has yet to be finalised, however capital dredging requirements for all options is consistent and was estimated to cost $1.21 million. After analysis of the geological structures within the IDGM, the cost for the dredging was revised to approximately $4 million. For the proposed fixed wave attenuator sites, only the Snug Cove location (Figure 1) was initially considered for the cost estimate and based on geological findings of Longworth and McKenzie [6]. Cost estimates varied between $32,500/m and $35,000/m and included 320m of pilling. After consideration of the findings of the IDGM, designs were modified to take advantage of favourable geology and costs were revised down to $29,500/m with a requirement for 304m of pilling [10]. Estimates for the wharf development are still ongoing, but the Aquares data is considered important for the design process (Figure 9).

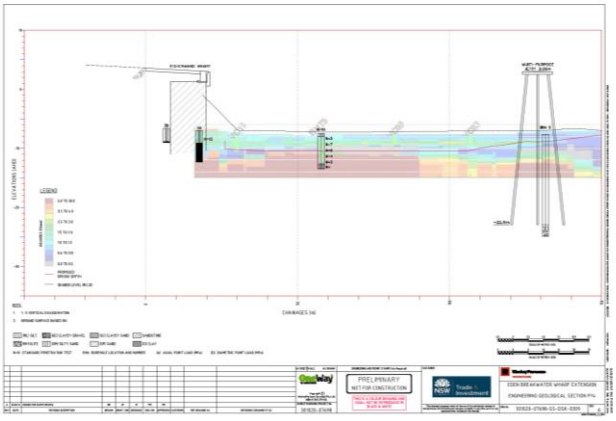

Figure 9 Aquares section data in the 12D environment including proposed wharf structures.

Lessons Learned

The objective of the ground studies for this project was to reduce risk for the design and construct contractors. The results from any one technique proved inadequate and confidence in the ground model was only realised through a stepped approach of targeting boreholes to geological structures identified by qualitative geophysics, as part of the IDGM. Confidence was further amplified by visualising results Encom PA, however the key to the success of the project was the selection of the Aquares geophysical system.

Reflection seismics failed to provide actionable results as it is a quantitative geophysical system that is designed to acquire depth to target data rather than qualitative variation between geological structures. The effect of this trait is exacerbated in the complex geological setting of Eden, where the interface between GBG layers 1 and 2 largely conforms to depositional boundaries rather than structural boundaries (Figure 8). Further, the assumptions made from the reflection data for the interface between Layers 2 and 3 is unpredictable and therefore of little engineering use (Figure 5). While it may be argued that with more time, additional information may be interpreted from the raw reflection data, it is unlikely that, particularly in this complex environment, it would be useful for the effective targeting of boreholes, thereby satisfying the aims of "…assisting in risk management and improving designs" [5].

In contrast the qualitative and quantitative results of the Aquares system provided the resolution required to discern the complex vertical structures and provide borehole targeting data in the time frame required. In addition, the vertical sections extracted from the model were utilised in a BIM setting to improve the sustainability of designs.

Conclusions

The complex geology and the implications for the proposed construction was either unknown or not appreciated until the development of the IDGM based on Aquares technology. Vertical structures mapped throughout the site and particularly along the alignment of the proposed wharf are important geological features that must be taken into account by designers. A pile set too close to the edge of such a structure is at risk of long term instability when considering probability of failure, or skewing off-track during construction. Further the underestimation of the dredge costs by $3 million dollars is significant when considering overall, $25 million budget allocation.

The IDGM has allowed for the first time in the civil engineering space, the opportunity to compare all datasets, including the metadata associated with each datasets (such as run lines) to create a robust and rigorously tested ground model, that provides a cost benefit to the project and allows for sustainable development of the proposed port re-development for the town of Eden.

Disclaimer

The opinions expressed in this paper are the authors' and do not necessarily represent the views of Crown Lands.

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