Abstract
Getting geophysics right is critical to any port development but to do this, geophysical studies must be undertaken with greater contractor involvement and as a scientific endeavour. Here we propose four key steps that will assist in attaining successful outcomes: Defining a purpose; Designing a data repository; Determining suitable quantitative and qualitative methods; and undertaking a critical review. A successful Geophysical study is useful to all phases of the development including, area evaluation, design, dredge analysis (including quantities and dredgeability), and acceptance studies.

Key questions to consider prior to undertaking a geophysical campaign include: why are the surveys being done; what penetration depth is needed (for foundations, dredging and design, etc.); what is the bottom type; what is the qualitative (e.g. density) assessment tool; what is the quantitative (thickness) assessment tool; and how will ground truthing be done. Special attention need to be applied to ground truthing techniques. Drilling and vibrcoring, while a critical element of the overall study, must be considered a remote sensing technique as the geologist is not at the cutting edge and two geologists will often provide two different results, especially in highly variable sub-bottom environments.

In addition to the collection of data, the storage, accessibility and usability of the data must also be considered. The Seabed Survey Data Model (SSDM), currently in development by the Oil and Gas industry, goes a long way to addressing this problem. A similar model could be adopted by proponents of Port developments, or indeed any infrastructure development, to increase the value of individual data sets and reduce overall risk and uncertainties within a project.

Keywords: Geophysics, Qualitative Assessments, Limitations, Data Sharing, Risk Management.

1. Introduction
Undertaking the geophysics is arguably one of the most important aspects of study of a project. When required, it forms the base data for initial project approvals, design and cost estimates. However, getting geophysics right is a difficult task, and the risks of a poorly thought out and poorly executed campaign are often underestimated by stakeholders. The complexities of a geophysical study are exacerbated by there being no one perfect method. All too often, for various reasons, the initial round of pre-tender geophysical (and Geotechnical) studies do not provide the necessary information to answer key questions that allow contractors to confidently assume risks for latent (or unforeseen) geological conditions.

Applying a rigorous methodology to the acquisition, presentation and review of geophysical and geotechnical data will reduce risks to the overall project. A proposed framework for a rigorous methodology would comprise four key steps:

• Defining the purpose;
• Designing a Data Repository including data formats;
• Determining the preferred Quantitative and Qualitative geophysical techniques to be utilised on a survey; and
• Undertaking a critical review of the acquired data ensuring it meets or exceeds pre-established expectations and standards.

When any of these steps have not been undertaken or satisfied, proceeding with the project under the assumption that any issues can be resolved on the fly, increases risk often leading to project delays and cost overruns. It is a commercial and practical reality that EPC (Engineering, Procurement and Construction) contractors, engineers and estimators can only work with the data they have been given or the latent conditions clauses of their contracts. Further, the efficiency and outcomes of a contractors work will directly depend on the quality of the provided data.

2. Successful Geophysical Programmes
Acquisition, processing and display of geophysical data is a continually evolving field. It is necessarily an expensive and complex undertaking and requires the same rigor that is accorded to any scientific study. A well-executed geophysical study, undertaken in the feasibility stages of a project, will provide all stakeholders with the detailed geological information required to understand geological risks.

As this paper is discussing the development of ports, only the following geophysical acquisition techniques will be examined:

• Reflection sub-bottom profiling;
• Refraction sub-bottom profiling; and
• Resistivity as a sub-bottom profiling tool.
2.1 Defining the Purpose

Prior to undertaking any scientific study the question must be asked; “why is this study being done?” The prime reasons for undertaking a geophysical study can be condensed to the goal of minimising the risk to the proponent. Typically, a modern geophysical study relating to port development can map (qualitatively and quantitatively):

- Fluid muds (to minimise maintenance dredging);
- Solid muds (thickness and extents);
- Calcarenites;
- The bedrock, rock heads and voids; and
- Fill within nominated borrow areas.

Reasonable questions to ask of a geophysical study then might be:

- Are there latent geological risk conditions such as variations in bedrock strength or voids?
- Is there sufficient sediment of suitable quality for the proposed reclamion?
- Can the access channel be aligned to avoid rock dredging?
- How much cutting and / or blasting is required?
- Where should boreholes be placed to cost effectively maximise coverage? or
- How much mud needs to be dredged?

There are obvious economic and environmental gains to be had by pushing the geophysical and geotechnical studies into the early design phases of both complex and simple projects. However, to attain this level of detail and precision, the consultant must have a solid understanding of the application of geophysical techniques and the subsequent management of the acquired data, in the context of the prevailing geology and the questions asked. It must be recognised that all geophysical and geotechnical methods have limitations and it is therefore almost always necessary to utilise multiple techniques on a site.

2.2 Data Management / Repository

Modern geophysical and geotechnical studies will result in the production of large data sets by multiple survey contractors. Further, data produced by one contractor can be critical to the successful completion of works by another contractor. For example a successful comparative analysis between the qualitative and quantitative geophysical studies will give the consultant confidence in the success of both methods. This would then allow for a substantial reduction of the number of boreholes that would be required to complete a representative assay of a site. However, access to available data sets is critical.

The options for data management and sharing have been greatly improved by the (belated) acceptance by the survey industry of Geographical Information Systems (GIS) processes and software. This has largely come about as a result of the Oil and Gas industries development of the Seabed Survey Data Model (SSDM) in Australia and the S-100 standard for open data exchange developed by the IHO. The SSDM adds to the IHO S-100 standard by providing a framework for the collation and sharing of, not only geophysical but geotechnical, geochemical and oceanographic data. For example, It is likely that the early phases of a project would include the collection of grab samples, wave, tide, currents, water and sediment chemistry, bathymetry, sub-bottom data (in 2D and 3D), and boreholes that can be utilised by many different contractors across many specialties for risk reduction. In addition, the data set can be added to during the course of a project, providing not only baseline data, but a mechanism to minimise repetition and recognise change.

With no SSDM, if an EPC contractor is asked to undertake or augment geophysical studies, that additional data may not be received by all stakeholders. In the example below (Figure 2-1) the proponent was able to re-align a pipe-route to remove the requirement for rock dredging in the littoral zone after the assessment of qualitative geophysics. The establishment of a data repository and the correct use of that repository is a critical element in the undertaking of geophysical studies. Requiring a survey contractor to utilise particular formats or data structures is no longer an impost and should it cost extra.

![Figure 2-1 Qualitative and Quantitative geophysical results from the Aquares Resistivity system. Several geological regimes have been identified including a palaeochannel along a beach front. The original pipe alignment (P1) was altered to remove the requirement for rock dredging.](image)

A well implemented SSDM will allow for the fusion of the vast quantity and types of data collected during a modern survey. Key stakeholder decision makers are able to view, interrogate and understand relationships between datasets holistically rather than viewing data as individual or
discrete packets. The goal of the SSDM is to provide a simplified and actionable picture that will add considerable value to traditional standalone data sets.

2.3 Qualitative and Quantitative methods
Geophysical methods are divided into two basic categories, qualitative and quantitative techniques. Quantitative geophysical methods are well understood with reflection sub-bottom profiling being the most commonly used technique (Figure 2-2). Reflection sub-bottom profiling provides thicknesses and depths of geological structures without using a physical parameter to distinguish the quality of each individual structure.

Figure 2-2 A processed vertical section from a boomer survey, courtesy Dr P. Ramsay, Marine Geosolutions.

Qualitative methods can best be described as methods distinguishing different geological structures based on a physical parameter. However these methods do not necessarily provide accurate quantitative data. Refraction and resistivity are the most common qualitative methods. Refraction defines the geology in terms of seismic velocities and resistivity in terms of a units resistivity value (Ohm.m). Qualitative data is provided to the proponent as 2D sections and slices (Figure 2-1) and possibly 3D (volume) grids (Figure 2-3).

Figure 2-3 3D Aquares results in voxel rendering with highlighted sections

3D grids are an exceptionally useful tool especially in the design phase of a project and provide a good understanding of the geological setting. Some advantages would include:

- Understanding voids.
- Qualitative geophysics has evolved to the level that fluid mud may be distinguished from solid mud to provide the nautical depth in a harbour (Section 3.1) or accurately map a contaminated mud layer or unconsolidated plume (Figure 2-4).

Figure 2-4 The fluid mud fraction (yellow) above the solid mud (orange) and the dredge level (red) at the port of Zeebrugge – Data Courtesy THV Nautic.

2.3.1 Limitations
There is no one perfect technique and all quantitative and qualitative methods have shortcomings, some of which are described below. Shortcomings and associated risks of the chosen method(s) will vary with the survey environment and therefore must be examined and understood in the context of the questions asked and on a project by project basis.

Contingency plans, including both time and monetary resources, must be in place for additional works should initial studies not answer the asked questions. The likelihood of a geophysical study failing to answer the questions increases if the geology is not understood prior to selecting a method, or if complex geology is found. In the case that the geology is poorly understood prior to the commencement of a study, a well-qualified (and independent) client representative can be vital to the success of a study. Given the requisite latitude, they can adjust, redirect or alter completely the course of a study, as required. Finally, the findings of a geophysical study (both qualitative and quantitative) must always be tested utilising geo-technical techniques, particularly for engineering studies.

2.3.2 Reflection Sub-bottom Profiling
Seismic reflection is the most widely used quantitative technique [3]. Systems are broken into two basic groups, Very high frequency systems (pinger, chirp or parametric systems) and lower frequency systems, Boomers and Sparkers.

Very high frequency systems operate between 2 to 14 kHz. They allow for very rapid acquisition and processing of high resolution data. In ideal circumstances up to 50m of penetration can be achieved. However, penetration is limited to the depth of the water (i.e. 5m of water = a maximum of 5 meters of penetration) due to excessive noise
created by multiple seabed reflections that is exacerbated if the source and the receiver are mounted together in a transducer.

Lower frequency systems (boomers and sparkers) operate at frequencies of approximately 500Hz to 2 kHz. They utilise a multichannel receiver (hydrophone) array providing a much greater penetration but at a lower resolution. The loss in resolution is offset somewhat by the ability to process out much of the noise (notably in shallow water) due to the multichannel receiver array, often providing excellent results (Figure 2-2). Additional resolution and penetration may be achieved by adding additional channels to the hydrophone array and tweaking the source, however such additions will substantially increase the overall cost, complexity, acquisition and processing times of the survey. The perceived benefits of such a high resolution survey must be carefully weighed against the costs (Table 2-1).

Table 2-1 Quick comparison of shallow seismic reflection techniques

<table>
<thead>
<tr>
<th>Reflection Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Frequency</td>
<td>• Fast and flexible acquisition and processing</td>
<td>• Limited penetration</td>
</tr>
<tr>
<td></td>
<td>• Small equipment footprint</td>
<td>• No data past the seabed multiple</td>
</tr>
<tr>
<td></td>
<td>• High resolution</td>
<td>• Will not penetrate caprock or gaseous muds</td>
</tr>
<tr>
<td>Low Frequency</td>
<td>• Fast</td>
<td>• More equipment / expense</td>
</tr>
<tr>
<td></td>
<td>• Better penetration</td>
<td>• Greater power requirements</td>
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<tr>
<td></td>
<td>• More processing options</td>
<td>• May not penetrate caprock</td>
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<td></td>
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<td>• Will not penetrate gaseous muds</td>
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2.3.3 Refraction Sub-bottom Profiling

Seismic refraction is the most well-known and utilised method for attempting to acquire qualitative data (Figure 2-5). In theory, and when acquired under ideal conditions, refraction may provide acceptable results. However, the risks with refraction must be understood prior to utilising this as a method. Currently refraction will not work or may provide ambiguous results, in the following conditions:

• Gaseous muds;
• Gravels;
• When there is a low velocity layer between two higher velocity layers;
• When the second layer is thin or the third layer has a much faster velocity;
• When there is an undulating interface;
• When there is an offset; or
• When there is calcarenite on the seabed surface.

Additionally, deployments of refraction systems in the marine environment require that the hydrophone array be towed above the seabed in the water column. Uncertainty in the position of each individual hydrophone creates excessive noise and substantially reduces the resolution of acquired data (Figure 2-6). As a result acquisition and processing times can be much longer than comparable techniques.

![Figure 2-5 Principles of seismic refraction Ann Obermann, Geomatrix.co.uk](Image)

![Figure 2-6 Integrated refraction (black lines) and Aquares resistivity data on the Maas River Belgium. The resistivity results (in colour) accurately reflect the sub-vertical geological layering. The interpreted refraction is inconsistent in the harder layers and no returns were acquired in the softer layers.](Image)
equivalence problems. Aquares avoids both predefined layers and finite elements. The improved resolutions attained by Aquares acquisition and processing can be seen in Figure 2-1, Figure 2-3, Figure 2-4 and Figure 2-6. As a consequence, Aquares is currently the preferred marine resistivity technique in dredging markets, internationally.

2.4 Critical Review (Cost / Risk Analyses)

After the completion of the geophysical campaign, the consultant must review both the successes and failures of the survey. It is here that the initial benefits of a SSDM will be evident. In all but the most ideal circumstances, there will be data gaps; a sub-bottom profiling system that has not penetrated to the desired depth, an area too shallow for geotechnical studies, poor coverage that leads to assumptions, etc. A cost / risk analysis must be undertaken prior to deciding to move forward with the acquired data verses acquiring additional data.

During the cost / risk analysis, the initial key questions asked of the study must be re-examined in light of the collected data. For example; has the bedrock been adequately mapped and are there any strength / voids / height variations in the bedrock expected? Are there any mud layers, are they likely to be contaminated and are they mapped adequately? And finally, how many boreholes are required to ensure a representative assay of the geological regimes identified.

Additional questions may then be asked of the design, such as; does the design make the most efficient use of the described natural environment? Can rock dredging or blasting be minimised or eliminated? Can the contaminated muds be avoided and if not, have adequate provisions been made for the expected volume of contaminated spoil? Successfully answering these questions prior to EPC works will substantially reduce overall project risk, costs and environmental impacts.

If questions are not or only partially answered, established contingencies should be utilised to revisit the survey market to find a technique that will work. If questions such as “is blast dredging required” or “what are the mud volumes to be dredged” are not answered fully, these latent geological conditions become uncontrolled risks for the proponent and uncertainties for the contractor. Handing off risks, either, known or unknown, to a contractor is accepting the risk as uncontrolled and will lead to time and cost variations. The critical review of data, especially when that data is in the form of a SSDM, provides a mechanism for the early identification and mitigation of geological risk.

3. Case studies

Two case studies will be reviewed here. The first is the implementation of the Rheocable Method as a tool to map fluid muds above the nautical depth and the second is a comparison of Refraction and Aquares qualitative geophysical techniques. In both studies qualitative techniques have been utilised to further the understanding of the geological setting.

3.1 Rheocable in the Port of Zeebrugge

It has long been recognised that fluid mud is navigable [7]. Risks to navigation increase when there is insufficient keel clearance to the nautical depth. The nautical depth, in the presence of fluid muds, is defined by a significant and sudden increase of viscosity parameters with increasing depth [4]. However, currently applied bathymetric methods, aiming to define the nautical depth, rely on a combination of dual frequency echosounding and density soundings which produce inconsistent results and erroneous bathymetric maps. These uncertainties result in reduced safety and efficiency at the port through loss of time manoeuvring, loss of time at arrival or departure of the vessel (waiting for the tide), extra tug assistance, etc. and even in the nightmare scenario of the vessel completely losing control of speed and course, [5]. These problems undermine the confidence of pilots and shipping companies to sail into Zeebrugge, and indeed other ports with similar fluid mud issues, up to the point that shipping companies would utilise alternate, lower risk ports. So the question was asked, how can the nautical depth be accurately mapped?

The development and commercialisation of the Rheocable method ([1], [2]) (Figure 3-1) in 2008 provided a fast and reliable method of mapping the nautical depth and quantifying the fluid mud above it. The principles of the Rheocable technique are based on pressure measurements acquired on a short resistivity cable towed at the nautical depth. Resistivity measurements are used to verify the cable is actually at the nautical depth and not floating above it.

Figure 3-1 The Rheocable method relies on towing a vented pressure sensor package along the nautical depth. The towed resistivity tail confirms the pressure sensors are on the nautical depth.

The discontinuity seen in the resistivity results from when the resistivity array is on the consolidated mud (nautical depth) and when the array is flying, easily determines the validity of the data (Figure 3-2). The resistivity data is monitored in real time and when the resistivity is low (0.26 Ohmm or less), the operator simply directed the survey vessel to slow until the sensor package drops to the nautical depth and the real-time resistivity
values increase to values of 0.32 Ohmm or greater. It is seen from the results (Figure 2-4) that in large areas in the port there is over 3m of fluid mud above the nautical depth. After the survey in Zeebrugge and a similar survey in the port of Wilmington, Delaware, Rheocable results provided the possibility to significantly reduce maintenance dredging costs, restore confidence of the Pilots and ship owners and increase the efficiency of port operations by clearly and repeatedly defining the nautical depth. The method has recently been accepted in the forthcoming update to the survey manual of the US Army Corps of engineers [6].

3.2 Integrated Refraction and Aquares Data on the Maas River, Belgium

An Aquares survey was undertaken after the failure of a refraction sub-bottom survey in the Maas River in Belgium. The subsurface is known to consist of a sequence of sub-vertically oriented shales and quartzites. In some areas these rock formations are covered with soft mud deposits.

The Refraction and Aquares data have been collated on a single cross-section (Figure 2-6). The resistivity results are presented following the colour code provided with high resistivity values in yellow, low resistivity values in blue and intermediate resistivity values in green and cyan. The high resistivity structures correspond with quartzitic banks while the intermediate and low resistivity structures interbedded with the quartzites correlate with shales. As the shales are softer than the quartzites they are subject to deeper penetrating alteration effects and tend to form clayey depressions on the river bed which subsequently may be covered with soft mud. The resistivity results reflect well all known existing geological information and are confirmed by boreholes and geological maps.

Two different refractors are marked on the section including; a shallow relatively low velocity refractor and; a deeper relatively high velocity refractor. The values of the refractor velocities are marked respectively above and below the sections. The refraction survey seemed to detect refractors only in the quartzitic formations and not in the shaley intercalations. It is difficult to find any correlation with the Aquares results and with any existing geological information. In areas covered with soft mud, no refractors are found at all.

It can be concluded that the Aquares resistivity survey results were very effective in defining, in detail, the main geological structures while the refraction results can only be used to get some idea of the sonic velocities of the harder quartzitic structures.

4. Conclusion

Modern geophysical studies must be treated with the same rigour accorded to any scientific study. It is important to recognise that there is no one perfect technique but a geophysical programme can be developed that is appropriate to the geological setting to be surveyed. Consultants therefore, must have a good understanding of, not only the technology available, but the application of that technology. They must find survey contractors to provide the results they need and not accept results that do not answer the questions asked. However, as is the nature of all scientific studies, the initially selected approach may not work. Contingency must be made for this outcome and additional methods tested as required.

Geophysical studies are expensive and will produce huge quantities of data. The successful management of data will allow the fusion of various data sets that will substantially add to the value of the data as a whole. The benefits of a successful geophysical campaign will percolate throughout all stages of a project allowing the opportunity for overall project cost savings and risk mitigation.

5. References


[3] Institute of Civil Engineers (ICE), Geophysics for Civil Engineers: An Introduction, Institute of Civil Engineers, 1 Great George St London SW1P3AA


