REVIEW OF IMPROVED SUSTAINABILITY OUTCOMES FOR INFRASTRUCTURE PROJECTS GAINED THROUGH THE USE OF MODERN QUALITATIVE GEOPHYSICAL ASSESSMENTS

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Abstract

Undertaking a geological study that includes modern qualitative geophysical collection methods and the dissemination of that data within an Integrated Digital Ground Model, substantially improves sustainability outcomes for infrastructure projects. A robust study, conducted early in the project lifecycle may realise benefits such as:

- Economic benefits: Increased stakeholder confidence through reduced latent geological risks, resulting in lower design and construction costs;
- Environmental benefits: Including designs and construction methods that are tailored to the geological and environmental setting allowing high impact activities such as drill and blast to be minimised or avoided.
- Social benefits: Tailored designs increases infrastructure stability and longevity resulting in reduced public spending and disturbance to amenity.

This paper will explore the improved sustainability outcomes for infrastructure projects by reviewing three recent case studies. For all studies, geophysical data was collected by OEMG global utilising the Aquares Resistivity system, a proven qualitative method, and combined with targeted boreholes. All data was presented in a 4 dimensional GIS environment (Encom Discover PA) to produce an Integrated Digital Ground Model (IDGM). Case studies include the Yamba Ebb Tide Release, the Orara River Underbore, (both for Clarence Valley Council, NSW Public Works) and also the Seal Rocks road slip (for Great Lakes Council).

Key words

Geophysics, Ground modelling, Qualitative Assessments, Sustainability, Infrastructure projects, Aquares resistivity system

Introduction

This paper reviews the improved sustainability outcomes achieved through a modern qualitative geophysical collection method and its dissemination in a GIS environment. First some of the key issues that occur with more commonly utilised ground modelling methodologies are discussed in relation to sources of geological risk and the Australian Standards for geotechnical investigations. An overview is then provided of the Integrated Digital Ground Model (IDGM), an experimental modelling framework under development by OEMG, utilising the Aquares Resistivity sub-bottom profiling system and Encom Discover 3D. Finally, three cases studies that utilise early iterations of the IDGM methodology are provided and actual sustainability outcomes from the projects are discussed.

Sustainable development is development that “meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission for Environment and Development (WCED), 1987, 363). In order to achieve this it is necessary to balance environmental, economic and social objectives and sustainability outcomes are considered for each of these aspects.

Discussion of issues

Understanding and mitigating the risk that existing ground conditions will have on a project is a complex undertaking that will have implications (positive or negative) throughout a project. Baynes (2010) summarises geotechnical risks well (Figure 1) and concludes that between 20% and 50% of projects undertaken will experience failures in the form of cost or time over-runs. While this in itself should be disturbing for project proponents, it is likely not the major concern or source of cost. The real cost will be less direct and measured against sustainability outcomes, for example over-engineering as a result of a poor understanding of the ground, designs not tailored to the existing geology (for example blasting rock in one corner and pouring concrete in another) or inappropriate construction techniques. These issues will also significantly add to the environmental impact of a project and have social implications in regard to public spending costs.

Analysing the geotechnical risks (Figure 1) discussed by Baynes (2010), it is evident that all risks, including "unforeseeable geological details", can be mitigated to varying degrees through better communication of the results of ground studies undertaken, both past and present. The root cause of poor communication of geotechnical data is the tools for characterising the ground are predominantly analogue and very little effort is placed into the digitisation of the results.

Type of Geotechnical Risk		**Hazard**	**Source**
Project management		Poor management of entire geo-engineering process	An *inadequate understanding of the importance of ground conditions* resulting in poor management of the entire geo-engineering process e.g. a decision to submit a tender price with no risk weighting for geotechnical factors.
Contractual		Poor management of site investigation and contract documentation	An *inadequate understanding of the importance of ground conditions* resulting in poor acquisition, understanding and/or communication of site investigation information; this often leads to claims based on contractually unforeseen ground conditions
Technical	Analytical	Unreasonable analytical model chosen	An *inadequate understanding of ground conditions* and analytical methods, resulting in an unreasonable choice of analytical models
	Properties	Unreasonable design values chosen	An *inadequate understanding of ground conditions* and field and laboratory testing, resulting in an unreasonable choice of design values
	Geological	Unforeseeable geological details	*Geological conditions* that are very variable, and because investigation of all geological details is impractical
		Inherently hazardous ground conditions	*Geological conditions and geological processes* that involve hazards such as large ground movements, voids, aggressive chemistry, erosion, etc.
		Unforeseen ground conditions	An inadequate *understanding of geological conditions* resulting in unforeseen ground conditions being encountered during construction, often because of an inadequate site investigation due to poor project management

Figure 1 A summary of sources of geotechnical risk (Baynes 2010)

Project Managers, Environmental scientists, or indeed the public would have difficulty in understanding a bore log let alone relating it in time and space to the project. The effect of this is that geotechnical studies, are often treated as a “tick and flick” exercise and tens to hundreds of thousands of dollars’ worth of studies are shunted to the back of a report, never to be fully utilised or play a significant part in improving the sustainability outcomes of a project.

engineer and the procedures utilised in the field will also have significant bearing on in-situ and laboratory results as well as the cost of the study. Further, as all recovered samples will have undergone some measure of disturbance (Figure 3), a quantitative measure of the projected disturbance of a sample is recommended but rarely undertaken. Therefore due to the subjective nature of undertaking and logging boreholes, it is critical to utilise and compare the results from multiple tools to create a robust understanding of the ground.

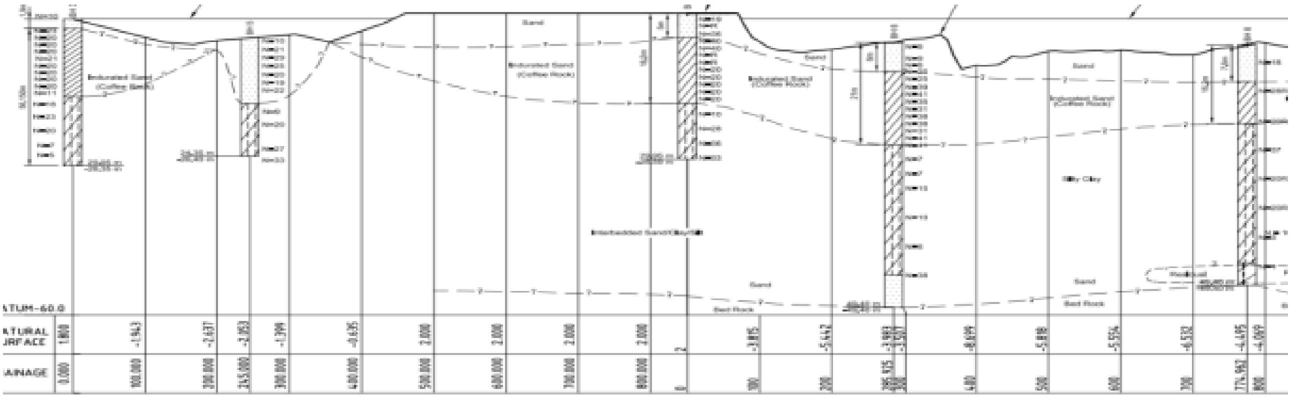

Figure 2. A 2 dimensional geological cross section generated solely by joining similar structures from nearby boreholes often creates more problems than it solves (diagram courtesy Clarence Valley Council).

The relegation of ground studies has resulted in a poor understanding of their importance in effective and sustainable designs. Proponents are thus generally reluctant to adequately fund ground studies and consultants will limit the study to a few boreholes. However, analysing the acquisition process of boreholes the limitations, with particular regard to managing uncertainty, of such a study can easily be seen (Figure 2).

Boreholes represent a very small proportion of the total volume (Baynes, 2010) or a “soda straw” view of the sub-bottom. The typical borehole is approximately 100mm in diameter and sub-samples are typically taken utilising a 75mm diameter tube. Expanding on this, a typical sample tube represents an area of 0.16m^2 so 20 boreholes represents a coverage of 3.14m^2. Then considering coverage in a real sense, if we assume a 50m x 50m site, 20 boreholes represents coverage area of only 0.13% of the total site.

The sampling area of a borehole campaign is one of the inherent uncertainties that are involved with characterising sub-surface conditions. The tools specified by the

Complexities associated with highly variable geology cannot be understood or mitigated by utilising a traditional 2 dimensional analogue presentation of a geological section (Figure 2). Boreholes undertaken in isolation are subjective, prone to physical and interpretative errors and at best, only provide a snap shot of the soil engineering parameters at the site of the hole.

Figure 3. A typical split spoon(disturbed) sample recovered as a result of an Standard Penetration Test.

Australian Standards

The intent of the Australian Standards for Geotechnical Site Investigations: AS1726 (Standards Australia, 1993) is to generate a ground model to test not only the engineering properties of the sub-surface, but also the extent and persistence (heterogeneity) of geological structures present. The standard states "account shall be taken of variations in material properties with time and location, in the area of geotechnical site investigation" (Standards Australia, 1993, section 6.3). While the standard is not specific on the tools that should be utilised to map either the engineering properties of a site or how to characterise the heterogeneity and therefore the underlying geotechnical risks, the wording makes it incumbent on the proponent to justify that adequate sampling of the sub-surface has been undertaken to satisfy both points.

It follows then that a geological cross section (or ground model), that is generated from boreholes undertaken on either a gridded or random pattern, with no regard for the site specific geological structure, will not satisfy the intent of AS1726 or improve risk or sustainability outcomes (Figure 2). Indeed given the inherent uncertainties relating to borehole data and the negative cost-benefit outcomes for large borehole campaigns, alternate methods must be considered for understanding site variability.

Guidance on the set out of a site investigation is provided in the standard. Section 6.1 (Standards Australia, 1993) states "the site investigation methods used shall be chosen on the basis of a preliminary assessment of the relevant site conditions and available geological information and history of the site". The preliminary assessment of a site is almost always a desktop study however, this is unlikely to adequately account for geological heterogeneity and therefore the number or placement of boreholes (gridded or random) required. Given that it is often a small variance in the geological strata (for example, faulting or palaeochannels) that are the root cause of variations, it would be uneconomic to drill sufficient boreholes, or indeed difficult prove that sufficient boreholes have been undertaken, to mitigate such risks. As such Stapledon (1983), Fookes (1997), Fookes *et al* (2000) and Baynes (2010) all advocate a stepped approach to ground studies. Appropriate qualitative geophysics is often the most economic tool for continuously mapping the geological structures (Figure 4) as part of the "preliminary" site assessment.

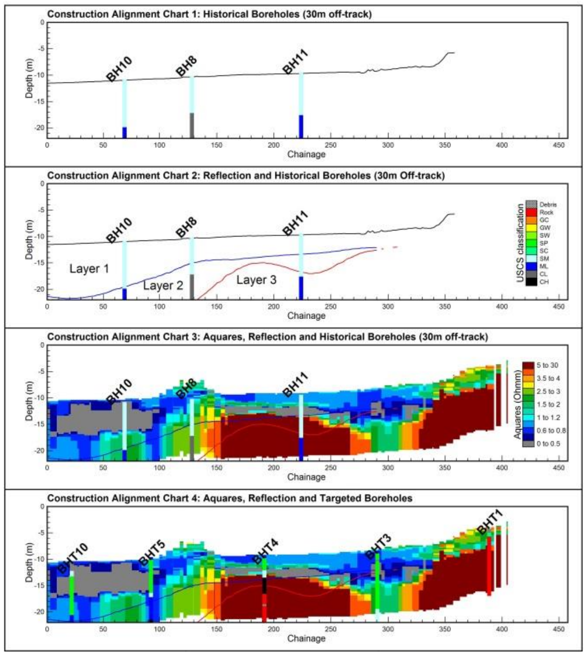

Figure 4. Here is an analysis of cross sections of boreholes and boreholes combined with two and three dimensional geophysics. In the top diagram three historical boreholes are seen that are up to 40m off track, no rock is evident. In the middle diagram, two dimensional quantitative geophysics is added, again, no rock is obvious. In the lower diagram, three dimensional Aquares geophysics is added and a high resistivity structure is seen that is subsequently drilled and found to be rock.

Once the geological structures at a site are understood, a reduced number of targeted boreholes can be undertaken creating a cost effective study that satisfies the requirement of the AS1726, to test both the heterogeneity and engineering properties of geological structures at a site. A failure to understand the implications of site heterogeneity is likely to have major negative downstream effects on objectives including sustainability outcomes and risk

The downstream effects of poor ground modelling are highlighted in (Figure 5). Here, a project was paused as geophysical and geotechnical studies failed to answer key questions that would reasonably allow the project to proceed. It was not until an Aquares study reliably mapped the variation in quality across the site, that risk could be understood and reasonable decisions regarding the viability of the project made.

The failure was directly attributed to two key factors:

1. Not staggering the ground studies to allow the geological structures to be mapped prior to geotechnical studies; and

2. A poor choice of geophysical tools in the first instance.

The ground model is therefore a key element of the project management of infrastructure development. A sufficiently funded study comprising elements to map the geological structures, their heterogeneity and the engineering characteristics is critical. If such a study undertaken early in the lifecycle of a project and effectively communicated to the project team, the proponent can judge the viability of the project at the chosen site and therefore the overall sustainability including the design and construct techniques. However, it is the ability to compare and then successfully communicate the results amongst the project team that is the hallmark of a robust ground model.

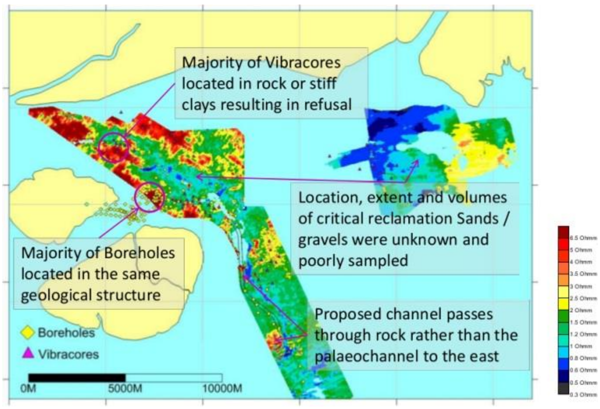

Figure 5. In this study, a geotechnical campaign was undertaken to map the geological structures. A subsequent Aquares study determined that the layout of geotechnical sampling sites did not cover the geological structures present. Failure to do this early in the project, resulted in millions of dollars of geotechnical studies that did not satisfy project aims, significant lost time and many millions of dollars in potential cost over-runs.

IDGM Methodology Overview

The Integrated Digital Ground Model (IDGM) is an ongoing project driven by OEMG with the assistance of Pitney Bowes, which aims to combine all geophysical, geotechnical and environmental data into a single GIS framework. It aims to improve the accessibility of (particularly) geological datasets and subsequent decision making processes. Fundamentally however, the integration of multiple datasets such as boreholes and geophysical studies into a 4 dimensional environment, allows for otherwise unrelated data to be compared and contributes to a robust understanding of the ground that can be utilised and added to throughout the lifecycle of a project. The IDGM stems from the underlying ground modelling process (Errey and Brabers 2013), namely to:

1. Define a purpose of the study based on the cost and risk of the project

2. Create a data repository

3. Define the qualitative and quantitative geophysical method

4. Undertake a critical review of the geophysics; and

5. Undertake a targeted geotechnical campaign based on the geological structures defined by the geophysical study.

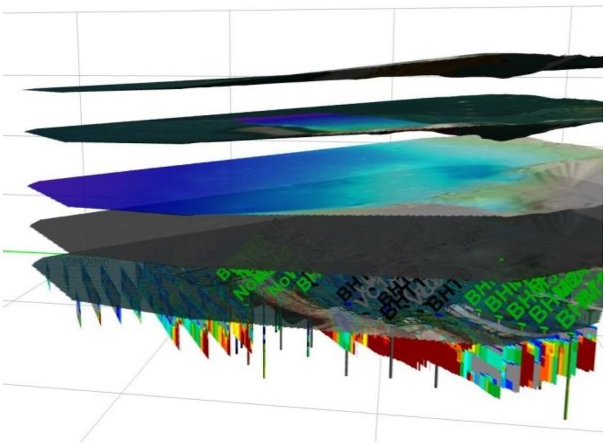

Figure 6. A 4 dimensional ground model in a GIS framework that includes: Aquares; Historical Boreholes; new targeted boreholes; vibracores; bathymetry; Magnetometer; reflection and sidescan sonar data. In this model, the continuous Aquares data provides the base structural data that is supported by a limited number of targeted boreholes and the findings of the historical datasets.

Data integration utilising GIS framework, is not a new concept. Indeed Oloufa *et al* (1994) discussed the potential benefits very early in the development of the graphical user interface of Windows 3.1. However, the effectiveness was limited by the computer processors of the time. Today, utilising programs such as Discover PA combined with high quality 3 dimensional Aquares sub-bottom profiling, the advantages of such an approach are clear, even for small to medium infrastructure projects (Figure 6).

The Aquares resistivity system is unique and particularly suited to the IDGM. Aquares is a geophysical method designed from the ground up as a 3 dimensional acquisition system that can be used on land or in marine environments. It collects accurate quantitative (thickness and depth) and qualitative (quality) data about the sub-bottom, and most importantly, the dataset is digital and therefore GIS ready.

The successful application of OEMGs ground modelling technique, including Aquares and early iterations of data residing in a GIS framework (IDGM) is examined via three different case studies.

Case Study 1: Yamba ebb-tide release

A qualitative geophysical assessment was undertaken for Clarence Valley Council as part of the conception stage of the Yamba ebb-tide release where NSW Public works is the project manager. Lessons learned from a similar project in Iluka were utilised to improve the methodology for the Yamba project. It should be noted that this project is currently in the design phase.

Lessons learned from Iluka project

The Iluka ebb-tide release utilised simple geotechnical techniques for creating a ground model. Various historical boreholes were available and traditional desktop interpretations were conducted to create a rudimentary model of the geology (Figure 2). This model proved to be inadequate leading to variations during the construction stage of the project. Specifically, the ground model failed to identify weak spots in the indurated sands (coffee rock) leading to delays as a result of hole collapses in larger gravel pockets.

Project Methodology

The Yamba ebb-tide release improved on the methodology used for previous projects and included an Early Tenderer Involvement (ETI) process. A need for robust ground model was also identified and an early form of OEMG's IDGM was utilised. This ground model combined results from an Aquares geophysical survey with historical borehole data (Figure 7). The IDGM was then presented to design and construct contractors as part of the ETI process prior to tenders being submitted, allowing geological risk to be established at a detailed level. Results were presented in such a way that they were also able to be interpreted by people without a background in geophysics.

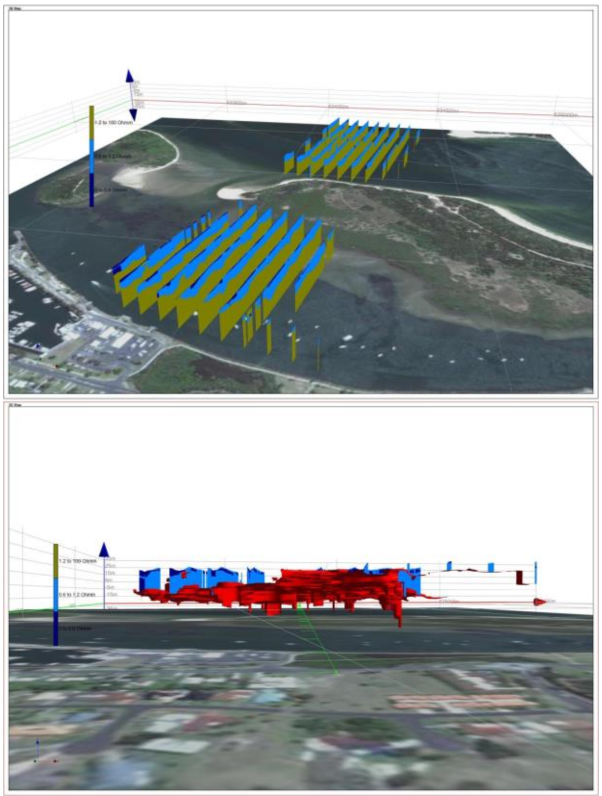

Figure 7. For these works 14 line kms of data was collected comprising approximately 14,000 shot points over two days. The very large volume of data points allowed the creation of an accurate 4 dimensional ground model. Generally, loose sediments are seen above indurated sands. An Iso-surface along the top of the indurated sands was created (below) and the data below excluded. This then highlighted any weak areas extending past the target depth of the under-bore and the design group was able to project an ideal path for the pipe.

Of interest, the historical boreholes GH5 and GH7 appear to not conform with the findings of the Aquares model (Figure 8). However, after reviewing the borelogs, and inparticular, the Standard Penetration Test (SPT) results, it was possible to re-interpret the findings of the boreholes to conform to the Aquares model. This highlights the benefit of multiple and unrelated ground modelling tools, the IDGM and that boreholes are a remote sensing tool and subject interpretation.

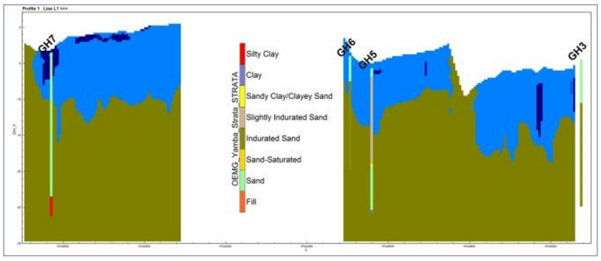

Figure 8. It can be seen from a cross section along the centre line that boreholes GH6 and 3 conform to the predictions of the Aquares model, but GH5 and 7 do not. However, after reviewing the original borelogs and in particular the SPT values, the client was able to re-interpret the findings of the boreholes to conform to those of the Aquares model.

Sustainability outcomes

Despite the project being in the design phase, the improved ground model has already provided tangible benefits to the project. Probably the most important was the reduced risk levels for contractors as weak spots in the “Coffee rock” were identified up front with a high degree of confidence and the findings of the ground model could be effectively communicated through the use of the IDGM to all parties. This gave NSW Public works and Clarence Valley Council confidence to assume the risk for potential variations as a result of latent geological conditions. Results complemented the ETI process very well, giving surety to contractors for their designs.

A number of sustainability outcomes were achieved due to the geophysical collection methods and associated ground model including:

- **Environmental benefits**: Due to the confidence in the geophysics acquisition and modelling, it was possible to rely on historical boreholes as these aligned extremely well with the data collected. Therefore environmental impact was reduced as there was no need for additional overwater sampling activities.
- **Economic benefits:** The tender responses received for the works were considered competitive by the principle, and were in line with government projections. A competitive market, the ETI process and the IDGM are all considered factors in this. A “lessons learned” exercise is planned after the completion of the works and an attempt will be made to analyse the additional benefit of the IDGM.
- **Social benefits**: Data was acquired more quickly and earlier than is normal, without need for additional over water borehole investigations. Therefore there was very little interruption to a working port with little or no inconvenience to port users. The potential cost savings due to fast turnaround times and lower risk also reduces pressure on public funds.

Case Study 2: Orara River under bore

A qualitative geophysical assessment was undertaken for Clarence Valley Council as part of the conception stage for an under bore in the Orara river.

Due to steep terrain and pristine water conditions, no boreholes could be undertaken in the riverbed. Potential complex issues were identified by boreholes undertaken for the project on top of the riverbank (100m away from river on either side) that suggested the area was unsuitable for under-boring. Contractors were therefore reluctant to provide a costing for the under bore due to unknown geological risk.

Aquares for land data was collected at the site including river banks and river bed. When combined with the boreholes in a ground model, it demonstrated the continuation of the complex geological risks under the river bed proving the under bore would be complex and expensive.

Council elected to undertake alternate methods for crossing the river. Without the ground model, the project would likely have gone ahead at high cost due to risks, particularly frack-outs or excessive leakage of drilling muds to the environment.

Sustainability outcomes

Sustainability outcomes for this project include:

- **Environmental benefits**: A potentially high risk project was not undertaken that could have created damage/ issues in the Orara River.
- **Economic benefits**: If the project had gone ahead, cost overruns for the project were likely to be significant.
- **Social benefits**: Protection of the waterways and cost savings also provide social benefits.

Case Study 3: Seal rocks road slip

An Aquares geophysical survey was undertaken for Great Lakes Council to assess the cause of a major road slip near Seal Rocks (Figure 9). The root cause of the slip was unknown and the nature of the terrain meant the repair would be costly so it was important to get it right.

Figure 9. Aquares for land was utilised to investigate the root cause of a road slip in Seal Rocks, NSW.

An Aquares for land survey was undertaken on both sides of the road and a ground model produced (Figure 10). The ground model highlighted a thin (30cm) saturated clay layer between the road base and the rock and this was later confirmed in boreholes. Due to the very thin and subtle nature of the clay layer it most likely would have been missed during the course of a normal borehole study. However, because the layer was identified during the geophysical study, it was successfully targeted and sampled by the drillers.

Any subsequent fix of the road would likely require pinning through the road base and well into the rock to prevent further slips. If only drilling had been done and the clay layer wasn't detected then a less suitable repair method may have been adopted. This could have led to further road failures in the future. The ground model also highlighted risks either side of the slip that need to be addressed.

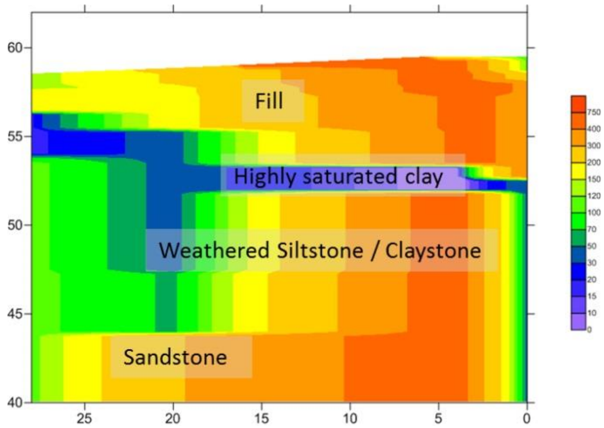

Figure 10. A thin, highly saturated clay layer is seen in the cross section of the slip region. Findings were later confirmed utilising boreholes and the clay layer was detected as the geologist was looking for the layer.

Sustainability Outcomes

Sustainability outcomes for this project include:

- **Environmental benefits**: Assist with preventing further slips. Reduced resource and energy use required for rework.
- **Economic benefits**: Cost savings as adequate repair of the road able to be conducted properly and repeat work unlikely to be required.
- **Social**: Improve safety in the area of the slip due to good understanding of the causes of the failure and ability to put appropriate prevention measures in place.

Conclusion

Ground modelling is a complex but often underrated part of infrastructure development. However, a failure to undertake appropriate studies to map the geological engineering properties and heterogeneity, combined with failure to successfully communicate the results to stakeholders, significantly increases ground related risk. In addition, poor ground modelling has led to many sustainability issues including unnecessary environmental impacts, cost and time overruns and social costs e.g. misuse of public funds.

OEMG's IDGM methodology presents an alternative to traditional ground modelling techniques. It is a stepped approach that utilises the Aquares resistivity system to identify the geological structures at a site and test the heterogeneity. A targeted borehole campaign is then undertaken to understand the engineering properties of the various geological structures at a site. All datasets, including geophysical, geotechnical and environmental, are then integrated into a GIS Framework.

The result is a cost effective and robust ground model that can be readily understood by anyone. It will provide certainty to proponents of underlying geological structures that will impact the infrastructure development. In addition, digital data can be easily integrated into design packages such as 12D and CAD, improving quality and saving time.

Case studies demonstrate that the IDGM methodology can significantly improve on sustainability outcomes for infrastructure projects.

Environmental impact is reduced as less boreholes are required which can reduce need for overwater investigations. Accurately mapping the geological structures can also minimise variations from project objectives which, in turn reduces resource and energy use. High impact activities such as blasting and drilling, required if unexpected geological structures are encountered, can be mitigated or avoided. In addition, in some cases, project designs that may have had a significant environmental impact, such as horizontal drilling in sub-surface conditions which could have resulted in frack out, can be avoided altogether.

Economic benefits of the IDGM are significant with the major contributing factor being that uncertainty of geological structures is reduced, allowing the proponent confidence to assume a greater proportion of risk and therefore reducing the cost of vendor bids. An accurate ground model can lead to lower variation rates and lower costs and rework for projects overall. In addition, accurate ground modelling helps to prevent otherwise costly projects (or project options) from going ahead.

Social benefits stem from both the environmental impacts being reduced as well as economic benefits due to cost savings, which can reduce pressure on public funds. The quick turnaround of the IDGM methodology also minimises impact to existing infrastructure use e.g. ports, roads etc. and an accurate ground model can also improve safety by identifying and mitigating possible hazards.

The importance of robust ground modelling that complies with AS1726 and can be communicated and utilised by the project team cannot be understated. It is incumbent on contractors, consultants and proponents to work together to highlight any deficiencies in the ground model and insist that these be rectified. Without such actions, many projects will continue to suffer cost or time overruns, in addition to poor sustainability outcomes. This is a statistic that will only change if improved ground modelling techniques are adopted.

Disclaimer

The opinions expressed in this paper are the authors' and do not necessarily represent the views of Clarence Valley Council, Great Lakes Council or NSW Public Works.

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