S8D3 P127

Integrating Geophysical and Geotechnical Technologies for Improved Site Assessment of Ports and Harbours

Dr Bob WHITELEY
Senior Principal Coffey Geosciences Pty. Ltd. NSW, Australia.
bob_whiteley@coffey.com.au)

Abstract

Population pressures, a new generation of larger vessels and the achievement of waterfront efficiencies with improved technologies is accelerating development in Australian ports and harbours. To more effectively support tender processes and marine civil construction this, in turn, has forced an evolution of site characterisation methodologies aimed at providing more accurate geotechnical models. Modern geotechnical practice for ports and harbours now includes a range of technologies , principally marine seismic reflection, underwater seismic refraction, targeted drilling and seismic tomographic imaging.

A case study from Port Kembla demonstrates how underwater seismic refraction may be applied to assist material classification in variable sub-bottom conditions. A further study involving review of Port Hedland dredging campaign carried out in the mid-1980's demonstrates the consequences of an inaccurate geotechnical model. A third study shows the application of overwater seismic tomography to a tunnel project in Sydney's Middle Harbour and shows the value of this new technology to near-shore or harbour crossing geotechnical investigation.

When these technologies are well integrated, geotechnical risks are substantially reduced for both large and small civil projects in ports and harbours.

Introduction

Most contracts for Port and Harbour works follow Conditions of Contract (International) for Works of Civil Engineering Construction prepared by FIDC (Federation Internationale des Ingenieurs-Conseils) and FIEC (Federation European de la Construction) and are approved by many international construction associations. These are supported, for example, by the ICE (Institution of Civil Engineers) Conditions of Contract for Ground Investigations (Cottington and Akenhead, 1984) and , for marine navigable channels, guidelines from PIANC (Permanent International Association of Navigation Congresses).

Typically, such contracts recognise that not all geological/geotechnical conditions can be completely specified i.e. there are elements of geotechnical risk in these projects. These contracts will normally contain provisions (e.g. clause 12 of the International Contract) to the effect that, when physical conditions are present that could not be reasonably forseen by an experienced contractor and the contractor has incurred additional expense, he can claim for the additional amount from the Principal.

Extensive experience from civil construction on land has shown that there is a strong relationship between the quality of site information provided to contractors and the contractural outcome. Table 1 (from Stewart et al., 1997) was prepared by a large Australian organisation (Roads and Traffic Authority of NSW) concerned with major road construction to cover a 20 year period. Excavation was a major component of this construction. In this case, the cost of a site investigation program is less than 1% of the project value.

Table 1: Information provided to contractors and typical claim values.

Type of Information provided to contractors	AverageClaimValue/ Contract Value
Minimal information (e.g. drillers logs)	15 – 25%
Sparse information (1980's standard), limited interpretative content	10 – 12%
Comprehensive investigation/design information, limited interpretative comment	2 – 2.5%
Comprehensive investigation/design information, extensive interpretative comment	< 0.1%

Table 1 clearly shows that claims for additional payment can be significantly reduced if comprehensive geotechnical/design information is provided at the tendering stage. This allows contractors to gain a realistic appreciation actual site conditions and associated geotechnical risks. It also permits earlier recognition of genuine unforeseen conditions that can be treated by variation clauses in the contract rather than by contractural dispute.

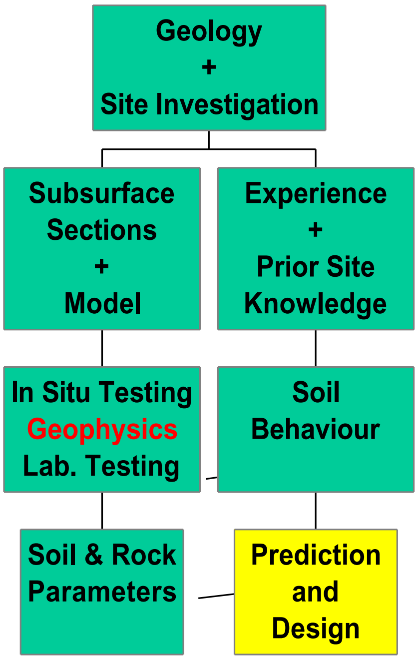
In the opinion of these authors most savings are achieved by integrating site characterisation, design and specification throughout the life of the project. With this approach site investigation is not seen as an end in itself but as a vital input to the both the design and construction phases of the project.

The Geological/Geotechnical Model

An essential part of reducing geotechnical risk is the provision of an appropriate geological/geotechnical model for the site. This model should be independent of any proposed structure or excavation method (Stapledon, 1983) and must accurately reflect the sea floor and sub-bottom conditions. Inevitably the presence of the water layer adds to the cost of developing this model when compared with the onshore environment and places greater pressure on marine geophysical interpretations as one input to model development. Each input component to the model must be viewed independently without any attempt to adjust or "harmonize", for example, the geophysical interpretation with drilling information or from inferences derived by observating of present-day coastal processes. Often apparent discrepancies or inconsistencies between different data sets lead to insights and highlight deficiencies in the available information that is used to construct the model. Major problems can occur when one part of the input data is used to control the rest and contradictions are simply assigned to errors in data or interpretation.

The approach taken to geotechnical model construction is shown schematically in Fig. 1. This proceeds along two arms whose outputs combine to provide the model embodying the prediction of site conditions and design parameters required for site assessment. The major supporting disciplines involved in site characterisation are shown in Fig. 2. In recent years, environmental engineering and geophysics have assumed an increasing importance in modern marine site investigation programs.

Figure 1 Procedures for geotechnical model construction



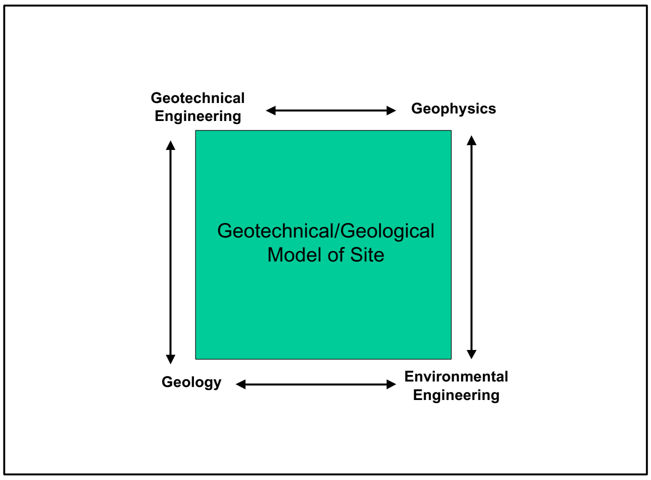


Figure 2 Supporting technical disciplines.

Site characterisation in the Marine Environment

The essential approach to site characterisation program is by systematic application of experience and site specific testing using geotechnical and geophysical technologies. There are two components of site characterisation i.e. exploration/hazard identification and material parameter specification. In all site characterisation processes the information that is available or acquired can never be complete, i.e. geotechnical risk can never be eliminated entirely regardless of how much effort is expended some uncertainty will remain. This uncertainly arises from two sources, incomplete data and errors in the data. Incomplete data results from our inability to measure the natural spatial variability of soil and rock materials and their engineering properties. This comes as some surprise to many engineers dealing with materials made to specification. Table 2 illustrates the issues by comparing the range of variability in different material properties.

Table 2 Variability of material properties

Type	Property	Order of Magnitude Variation
Geotechnical	Stiffness/strength	6
	Permeability	13
	Density	<1
Geophysical	Electrical conductivity	6
	Seismic velocity	1
	Seismic wave attenuation	4
Structural	Made to Specification (e.g. steel)	<<1

For example, steel, exhibits a variation much less than one order of magnitude, while the strength of earth materials can vary by as much as 6 orders of magnitude as can electrical resistivity. In contrast, nature has provided us with comparatively well-controlled geophysical parameters such as seismic velocity and density. These are also well correlated for a wide range of materials including sediments and rocks (Fig. 3). Seismic velocity may also be correlated with other parameters such as sediment porosity and strength, if calibrated correctly, and more indirectly with lithology.

Figure 3 Correlation of Seismic Velocity with density for a wide range of materials

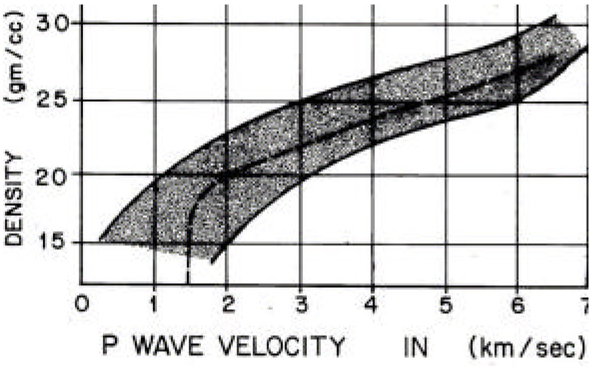


Table 3, for example, lists the typical range of seismic velocities obtained in the marine environment for a wide range of materials and conditions. Tables such as this provide guidance when other information is not available or is limited.

Table 3 General Correlation of Geological Material with Seismic Velocity in the Marine Environment

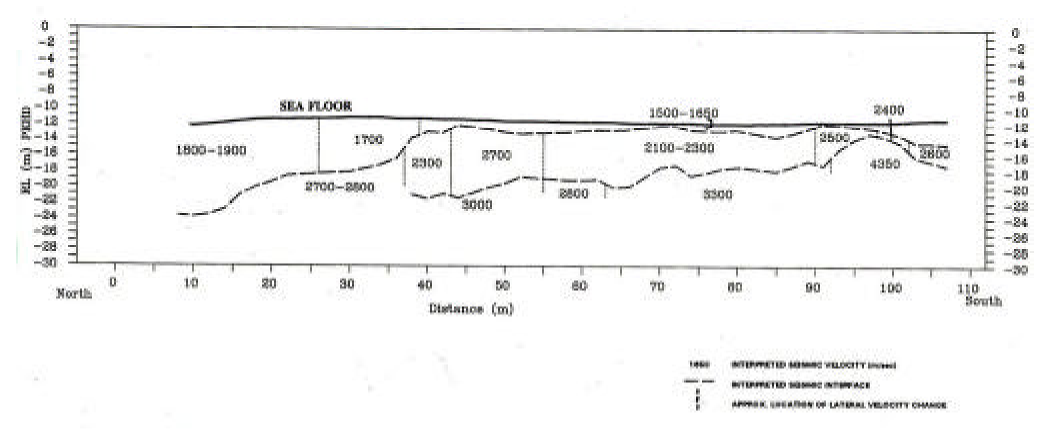
Material	Seismic Velocity (km/s)
Gas-filled fine sediments	0.8-1.4
Silts and soft clays	1.5-1.7
Stiff clays	1.6-1.8
Sands	1.6-1.8
Cemented sands	1.9-2.4
Gravels, cemented gravels	1.8-2.4
Younger limestone (reef)	2.2-3.5
Older limestone (reef)	2.5-6.0
Calcarenite, siliceous calcarenite	2.0-3.7
Boulders/broken rock in sand	1.9-4.0
Weathered sandstone/shale	1.9-2.5
Fresh sandstone/shale	2.7-4.3
Granite	4.3-5.8
Basalt	3.0-6.5
Metamorphics	3.0-7.0

From the earlier discussion, it is not surprising that the key marine geophysical technologies for sub-bottom investigation are marine seismic reflection (Sylwester, 1985) and refraction (Whiteley, 1994; Anderson and Ringis, 1999) supported by the acoustic technologies i.e. echo-sounding and side-scan sonar for sea-floor investigations. These technologies exploit density and seismic velocity contrasts. They are not new technologies but their integration and application with drilling is assuming greater importance with the emphasis both on site exploration and material parameter specification.

Case Study I When is “Rock” not Rock - Material Specification- Port Kembla
During the 1990’s the Port Kembla Ports Corporation embarked on a substantial program of improvements. Figure 4 shows a interpreted USR section from a site in Port Kembla Harbour where dredging and berth construction was proposed at one of a number of difficult sites (Coull, 1999). Over the 100m length of this section a number of materials with different seismic velocities to the proposed dredge depth of about –15m PKHD (Port Kembla Hydrographic Datum) can be seen. Shallow weathered rock with seismic velocities in the range 2100 to 2700 m/s was interpreted to exist over most of the profile above stronger rock with velocities ranging from 2800 to 4350. The lower velocity materials (1500 to 1900 m/s) were interpreted to represent marine sediments that thicken rapidly to the north. A relatively narrow zone (near 40m distance) between these regions was highlighted to represent mixed materials with possible broken rocks or boulders in sands with a bulk seismic velocity of 2300 m/s.

Figure 4 Interpreted Underwater Seismic Refraction Section, Port Kembla Harbour

This limited case study illustrates that material classifications for payment should be based on accurate geotechnical models rather than being arbitrarily imposed.



It is usual for dredging contracts to specify the classes of materials to be dredged. In this case “rock” was defined as in-situ rock of medium strength (15MPa, uniaxial compressive strength, UCS) with a seismic velocity exceeding 2100 m/s. Based on the borehole and USR interpretation “rock” material was considered to be a fine grained, tuffaceous sandstone although other rock types may be present. The other class of material specified in the contract was OTR or “Other than Rock”. This was taken as material not meeting the above definition. OTR materials mostly have the engineering characteristics of soil, including fill, marine and alluvial sediments, residual soils or extremely weathered rock. Within the materials described as soil and extremely weathered rock some higher strength bands may be present. With this definition a significant portion of the material as classified OTR could be considered rock in other types of common definitions. The zone Fig. 4 with a velocity of 2300 m/s that was believed to contain mixed materials (as opposed to OTR materials) would fall into the rock classification on the basis of seismic velocity but could also be treated as a "special" condition i.e. mixed materials and that under such classifications "rock" may not always be rock.

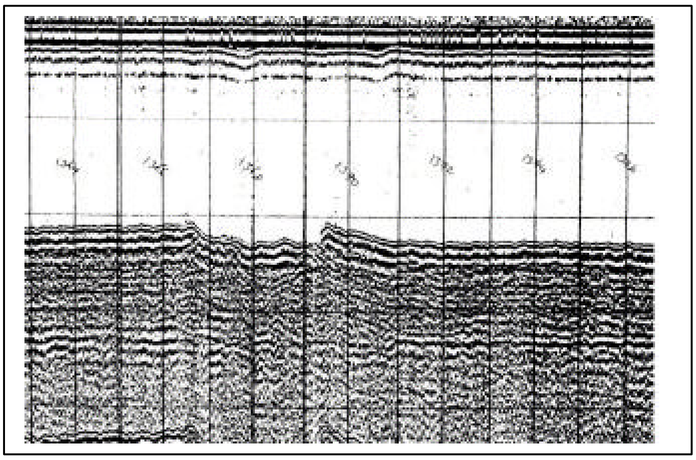
Case Study 2: When the geotechnical model goes wrong –Port Hedland Dredging Project

In 1985 a major dredging project was undertaken at Port Hedland, WA. This required removal of over 12 million m^3 of material mainly by deepening and extending 21 km of approach channel in water depths to 19 m. This particular project is extensively discussed by Verhoff (1997) and offers some valuable lessons today as to how a seemingly complete investigation can go wrong.

Tender documents for this project were prepared a project manager who also designed the geotechnical program, sub-contracted the site investigation activities, mainly to external parties, developed the geotechnical model and complied the geotechnical report. During the tender phase, prospective contractors visited the site to inspect drill cores and were provided with extensive site investigation reports. These included information from an earlier feasibility study that was reviewed by the project manager and the more detailed work carried out in specifically for the tender. The borehole density was one per 175m of channel and since the geological structure revealed was relatively simple, at the time, this was regarded as adequate for dredging projects. Standard Penetration Testing was carried out in 69 boreholes into rock and 107 vibrocore holes to rock. A total of 31 jet probes with laboratory and field strength tests were carried out on selected samples. Soils were described using the PIANC system (PIANC,1984) and the calcareous and siliceous rocks that were encountered were classified according to a modified version of the Clark and Walker (1977) system accepted by the project manager.

These activities were supported by extensive seismic reflection and refraction surveys, side-scan sonar and bathymetry. The seismic reflection survey had the particular objective of assisting the correlation of geological layers between boreholes. In the geotechnical reports provided at tender stage it was stated that the seismic reflection program met all it requirements, however, late performance of the marine geophysical contractor meant that insufficient time was available to fully evaluate both the reflection and refraction results. In the interpreted sections provided continuous layered reflectors were identified outside of the previously dredged area and on the sides of the dredged channel. Particular problems were experienced in the interpretation of the shallow reflection data in the previously dredged channel due to lateral variations in reflection quality over short distances of 10 to 100 m. These were believed due to changes in material properties rather than the earlier dredging and selective blasting operations. Fig. 5 shows a sample of the reflection data near 15km where earlier blasting had removed and disturbed sea floor materials. Note the disturbance to the essentially planar reflections beneath the blasted zone approximately centred on Fix 1368 in fig. 5). The deeper planar reflectors were later interpreted to represent weathered and fresh sandstone layers.

Figure 5 Sample of seismic reflection data from Port Hedland
(10 ms timing line and 100m fix interval).



Some 37 line km. of underwater seismic refraction data were gathered but incompletely analysed prior to the release of documents to contractors. The refraction survey mainly investigated the upper 4m of the material below the sea floor but did not provide depth information because of problems with the field acquisition system. Later examination of the refraction data revealed that seismic velocities as high as 4.0 km/s were measured and for 62% of the data velocities exceeded 2.1 km/s indicative of widespread rock materials.

The geotechnical model provided to contractors incorporated the above information and was based on an interpretation of the local geology and the distribution of the geological units likely to be encountered in the dredging works. At the time, it was probably apparent to the tenders (based on various statements in the reports provided) that this model was not completely clear and that interpretation of the geophysical results had not been successful in defining the units described in the borehole logs. However, as only a few weeks were allowed to prepare and submit tenders i.e., there was insufficient time was available to complete further field investigations, if the contractor so desired. Most if not all accepted and used the information and geotechnical model provided to prepare bids.

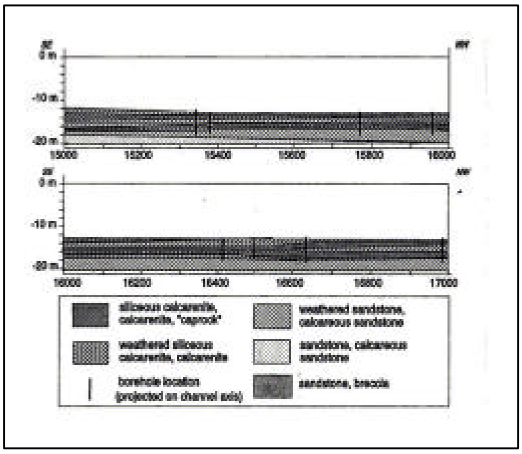
Eleven geological units were distinguished in the geotechnical report, based on the borehole results, with their locations described. The project manager accepted the division of these units into three classes (A,B,C) for volume estimation and payment. Class A (unconsolidated geological sediments: muds, silts gravels, sands), Class B (consolidated geological sediments ,UCS to 10 MPa: sands, clayey sand with calcarenite gravel and cobbles) and Class C (cemented sediments, UCS to 40 Mpa; mainly calcarenite). Dredging of the channel to about -14m depth was required. Interestingly, the successful tenderer selected a cutter-suction dredge to remove an estimated 7.1 million cu. m of the more difficult materials (some B and C classes representing about 60% of the total) and a hopper trailer dredge for the remaining 5.3 million cu. m. of the softer material (Class A and some B). These estimates are close to the percentages that would have been estimated from even a crude analysis of the refraction data alone.

From the start of the dredging work extreme wear problems to the dredge were experienced even though the materials were generally not strong. Tooth wear-rates on the cutter-suction dredge were 4 times higher and pipe wear was 5 times higher than expected. Pump and impeller wear on both dredges also far exceeded expectations. It appeared that the problems being experienced were due to the presence of quartz in the form of large angular crystals. These were present in almost all the materials dredged and greatly increased tooth wear by acting as a harsh abrasive. Stiff clays were also encountered in the dredging and these quartz fragments armoured clay balls that were formed along the pipes during hydraulic transport of the dredged materials. These armoured balls caused excessive scouring of the inner lining of pipes. This problem was worsened as the clay balls within the dredged slurry had to be pumped at higher velocities for transport along the pipes.

It quickly became evident that the contract could not be completed within the 13 months allowed and not profitably for the price at which the project was won. Faced with this situation the contractor instituted a re-assessment of the information provided at the tender stage with a view of claiming additional costs under Clause 12 i.e. encountering physical conditions that could not have been reasonably forseen. The contractor assembled a team of experts in engineering geology, geophysics (the author), and mining engineering. This team operated with the advantage of knowing the problems that were occurring in the dredging. It was clear from the beginning of this re-assessment that the initial geophysical interpretation provided was inadequate and the study was started from this point. All the original seismic data were re-interpreted. This was supported by a review of all other information, inspection of the reclamation area, re-logging of the drill core, additional petrographic study of core samples and engineering geological mapping of the area around Port Hedland. The objective was to evaluate the quality of the original geotechnical model and if necessary to provide a better geotechnical model using the information provided by an improved geophysical interpretation.

It emerged from this study that the initial site investigation had failed to recognise the importance of quartz as an abrasive factor in rock dredging. Emphasis in the rock classification system used to develop the initial model was placed on rock strength and was focussed on calcium carbonate as the cement. While sand was referred to, implying deposition following erosion from the surrounding granites on land, when it was discussed in the site investigation report emphasis was placed on grains of calcium carbonate being present. Also use of an adapted Clark and Walker (1977) classification system for quartz-bearing weak limestones was misleading. If the full form of this system had been used the quartz would have been flagged as siliceous calcarenite. In fact, significant quartz was found in a significant number of core samples that had been logged as calcarenite. Also the presence of quartz was obvious in rocks outcropping at the site and in samples taken from the reclamation area. The project manager also did not perceive the need place the stratigraphic units into a framework that was consistent with the local geology. The geological description in the geotechnical report concentrated on the geological units to be dredged with no description of the older rock formations. The new geotechnical model showed that much of the nearshore environment must have been dry until quite recently and that most of the material to be dredged in this region was a variably weathered siliceous sandstones. Further offshore these materials were overlain by the coastal carbonate rocks including the siliceous calcarenite. Fig. 6 shows example of the new geotechnical sections along the channel for the relatively near shore (1 to 2 km) and offshore regions (15 to 16 km) of the channel together with the material descriptions (from Verhoff, 1999). The earlier geotechnical model had concentrated on the more recent coastal limestones.

Figure 6 Geotechnical Sections along the Port Hedland Channel (from Verhoff, 1999)



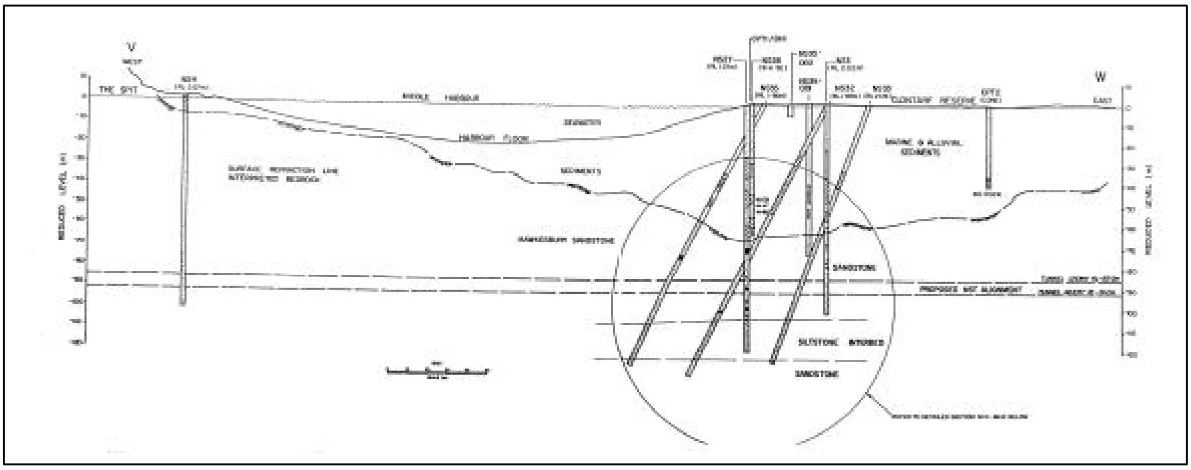
Substantial clay occurred both below the calcarenite and as a residual soil in the more highly weathered areas of the older sandstones. As these materials were derived from the surrounding granite in close proximity they contained angular quartz crystals in a clay matrix. Presented with this new geotechnical model that was, internally consistent, clear and geologically justified the contractors claim was accepted and after re-negotiations the dredging project was successfully completed, albeit at significantly greater cost.

Case Study 3 When the site is environmentally sensitive – Tunnelling under Middle Harbour

Increasingly, environmental considerations are driving civil engineering projects, investigation and construction methodology. This was the case for the recently completed North Side Storage Tunnel (NST) in Sydney. The NST was designed to alleviate stormwater pollution of Sydney Harbour by constructing a 16 km long rock tunnel with a diameter between 3.8 and 6m. This tunnel crossed Middle Harbour at a depth of about 90m and is described in more detail by Whiteley and Parker (2001). The key issues controlling this part of the project was a deep sand channel under Middle Harbour and a strong reluctance to moor overwater drill barges to test the sub-bottom in this heavily trafficked and highly environmentally sensitive area.

Fig 7 shows a cross-section beneath Middle Harbour, showing the location of the deeper sediment-filled channel with the inclined boreholes on land that were used to test the rock beneath the old channel.

Figure 7 Middle Harbour Geotechnical Section



High permeabilites and fractured rock were encountered in some of the inclined boreholes and there were concerns as to the safe tunnelling conditions beneath the harbour where high water inflows and poor ground could occur. Seismic tomography (Whiteley, 1998) was used to extend the information beneath the Harbour and between the boreholes. This method involves the lowering of a hydrophone array in the borehole and placing seismic sources along the harbour floor. The resulting seismic image with contoured seismic velocities is shown in Fig. 8. This clearly observes the base of the sediments and the weak (i.e. low velocity) zones beneath the Harbour. The tunnelling contractor was advised of this situation in advance of the tunnelling.

Figure 8 Seismic Tomographic Image below Middle Harbour

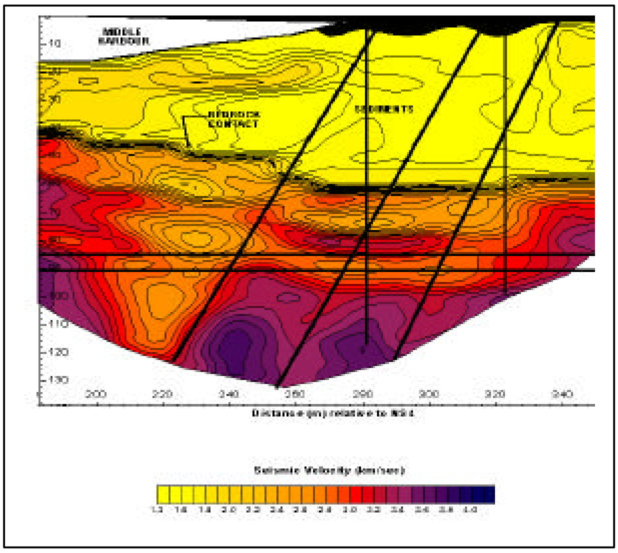
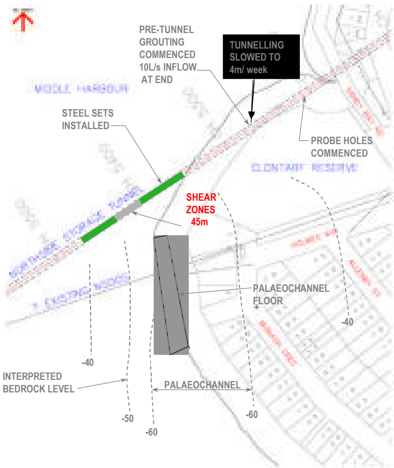


Fig. 8 shows the conditions that were actually encountered along the tunnel route that was to the north of the seismic image section. As the tunnel entered the deeper channel region tunnelling progress was slowed as grouting was needed to reduce water inflows. The tunnel proceeded below the old channel (palaeochannel) and the poor ground was encountered as predicted requiring installation of steel sets to support the roof.

Figure 8 Tunnelling conditions below Middle Harbour



This study illustrates that impacts on ports and harbours and risks can be minimised by used of the latest geophysical technologies.

Conclusions

Geotechnical risk can never be entirely eliminated from dredging and port projects, however, implementation of a comprehensive site assessment process that produces accurate geotechnical models for contractors can minimise this risk and substantially reduce construction costs. Site characterisation using appropriate combinations of geophysical and geotechnical technologies is an effective means of producing geotechnical models in the marine environment.

The case studies from a number of Australian ports and harbours demonstrate how these technologies that include marine seismic reflection, refraction and seismic tomography may be applied to material specification and geotechnical model construction for dredging and for near-shore construction in environmentally sensitive areas.

References

Anderson J. and Ringis J. 1999, Continuous seismic refraction profiling – a major advance in geophysical investigations for port and dredging projects. 14th Aust. Coastal & Ocean Engineering Conference. 14-16 April, 1999, Perth, Western Australia. 40-45.

Clark, A.R. and Walker, B.F. 1977 A proposed scheme for the classification and nomenclature for use in the engineering description of middle Eastern sedimentary rocks. Tech. Note, Geotechnique, 27, 93-99.

Coull, M. 1999, Recent port projects in Australia – overcoming a variety of difficult site conditions. 14th Aust. Coastal & Ocean Engineering Conference. 14-16 April, 1999, Perth, Western Australia, 148 –154.

Cottington, J and Akenhead, R. 1984. Site investigation and the law. Thomas Telford Ltd. London. 184pp.

PIANC1984. Classification of soils and rocks to be dredged. Supplement to Bull. No. 47, Permanent International Association of Navigation Congresss, Brussels, 16pp.

Stapledon, D. H. 1983, The geotechnical specialist and contractural disputes. in Ed. Knight et al. Collected Case Studies in geology, Hydrogeology and Environmental Geology. Geol. Soc. Aust, Sydney.

Stewart, I.E., Williams, J.R. and Walker, C. S. 1997. Modern Geophysics in Engineering Geology. in Ed. Mc Cann et al., Ceol. Soc. Engineering Geology Spec. Pub. 12, 383-390.

Sylwester, R. 1985 Single channel, high resolution seismic reflection profiling: a review of fundamentals and instrumentation. CRC Handbook of Geophysical Exploration at Sea, 77-122.

Verhoef, P.N.W. 1997 Wear of Rock Cutting Tools, Implications for the site investigation of rock dredging projects. Balkema, Rotterdam, 327pp.

Whiteley, R.J. 1994. Seismic refraction testing-a tutorial in geophysical characterization of sites. ed R. C. Woods ISSMFE, Tech. Com. 10, New Delhi, India, 45-47.

Whiteley, R. J. 1998 Reducing geotechnical risk for buried infrastructure with innovative geophysical technology. Proc. 4th Nat. Conf. On Trenchless Technology, Bris. 2-8 Aug. 1998, 285-291.

Whiteley, R. J. and Parker, C. 2001 Application of geophysical and geotechnical technologies to major tunnels in Sydney, Australia. Proc. Rapid Excavation and Tunneling Conference, San Diego USA, Ch. 24, 285-298.

.