TECHNICAL ARTICLE

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

R. J. Whiteley & S. B. Stewart, Coffey Geotechnics Pty. Ltd.

ABSTRACT

Strong world demand for energy, mineral and agricultural products and the advent of larger transport vessels is underpinning new construction and upgrades at many Asia-Pacific and Australian ports. Overwater geotechnical investigations are required at the feasibility and design stages of these projects, directed mainly at entrance channels, pipeline routes and supporting land-based facilities. These are costly and difficult when overwater drilling is involved due to the costs of jack-up rigs and barges and restricted drilling sites within busy waterways. Consequently, there is increasing reliance on marine geophysics to provide the necessary subsurface information, typically in water depths of less than 20 metres.

Since water is acoustically transparent, continuous seismic reflection profiling (CSP) using boomer, sparker or airgun sources has been applied to these projects for many years, despite its limitations in certain conditions. From a geotechnical perspective a more important problem is that it is very difficult to determine engineering properties from single channel marine CSP data as Australia's near shore marine environment is essentially a drowned continental land mass that has experienced a wide range of both terrestrial and coastal weathering and depositional processes over an extended geological time scale. These have created wide range of materials with very different geotechnical properties and behaviours that are not easily quantified with marine seismic reflection alone. Recently, single-ended, continuous underwater seismic refraction (CUSR) with near-bottom towed equipment and air-gun sources and static USR (SUSR) systems have been developed. These provide sub-bottom seismic P-wave velocities that can be correlated with engineering properties.

We present a series of case studies to demonstrate the application and integration of CSP, CUSR and static SUSR methods using advanced geophysical analysis processes to port infrastructure and near shore construction. In Victoria, combining conventional boomer CSP and CUSR improved the definition of a submerged, buried basalt flow and assisted dredging design along the Geelong Ports navigation channels. In East Malaysia, the same technologies assisted assessment of the viability of HDD (Horizontal Directional Drilling) as a pipeline installation option in variably weathered granites. In Western Australia, SUSR imaged the granitic regolith beneath sediments and indurated layers at a proposed new berthing where deep piling was required. This allowed preferred piling sites to be identified that minimised pile lengths.

USR technologies supported by advanced processing and analysis methods have demonstrated an ability to improve marine geotechnics in a diverse range of applications and will be increasingly applied in Australia's coastal waters.

1 INTRODUCTION

In recent years population growth and increasing commodities demand have driven major port, harbour and infrastructure developments. Typical projects involve deepening and widening of navigation channels, berth and nearshore construction and require geotechnical investigations at the feasibility and design stages. These are expensive and difficult when overwater drilling is involved due to the costs of jack-up rigs and barges and restricted drilling sites within busy ports and waterways. Consequently, there is increasing reliance on marine geophysics, integrated with geotechnics, to provide this subsurface information (Whiteley, 2002).

Since water is acoustically transparent at seismic frequencies, shallow reflection using boomer, sparker or airgun sources has enjoyed considerable application to marine exploration for many years (e.g. Mosher and Simpkins, 1999). Despite their widespread use these, so called continuous seismic profiling (CSP) techniques have limitations in certain conditions, for example, in shallow water where strong multiple reflections obscure deeper primary reflections and in areas of restricted water circulation and/or rapid sedimentation when shallow gas layers form (Bertin and Chaumillon, 2005).

TECHNICAL ARTICLE (Continued)

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

Also Australia's near shore marine environment is essentially a drowned continental land mass that has experienced a wide range of both terrestrial and coastal weathering and depositional processes over an extended geological time scale (Johnson, 2005). These have created materials with very different geotechnical properties and behaviours that are not easily quantified with marine reflection and has led to the increased application of static and underwater seismic refraction (USR) technologies adapted to the marine environment as these provide seismic (P-wave) velocities that are more easily related to these properties (Whiteley 1983). For example, Table 1 provides a general correlation of geological materials with seismic velocity that is applicable to the Australian marine environment.

Table 1 General Correlation of Geological Material with Seismic Velocity in the Australian 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
Loose to dense sands	1.6-1.8
Cemented sands	1.9-2.4
Loose 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

The static USR method (SUSR) is identical to the land refraction method (Whiteley, 1994) except that bottom-placed hydrophones rather than geophones are used with either a bottom-laid or floating connecting cables and multiple offset, reversed, bottom-placed, seismic sources. A continuous USR system (CUSR) has been previously described by Anderson and Ringis (1999) and involves a near-bottom, towed hydrophone array and repeatable seismic source at a single constant-offset distance. In both cases the seismic source is an air-gun. To date much of the near shore CUSR data in WA and elsewhere around Australia has been collected with relatively short hydrophone arrays (< 50m) and a single near-array source as shown in Figure 1(a) and interpreted assuming a horizontal, plane-layered earth model with a uniform velocity in each layer and velocities increasing with depth. This is clearly inadequate where "hard" cap rock, quartzitic, cemented gravel or reef layers occur within sediments or on deeply weathered bedrock rock "highs". These are typically of limited lateral extent with a higher seismic velocity than the surrounding materials (Table 1) and represent the classic seismic velocity reversal (or inversion) problem that many engineers believe to be a key limitation of the seismic refraction method (Whiteley and Greenhalgh, 1979). In the marine environment this limitation can be often overcome and improved resolution in these conditions can be achieved employing a longer underwater seismic array (100m) and multiple offset sources (a minimum of two) as shown schematically in Figure 1(b) together with improved tomographic interpretation methods.

TECHNICAL ARTICLE (Continued)

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

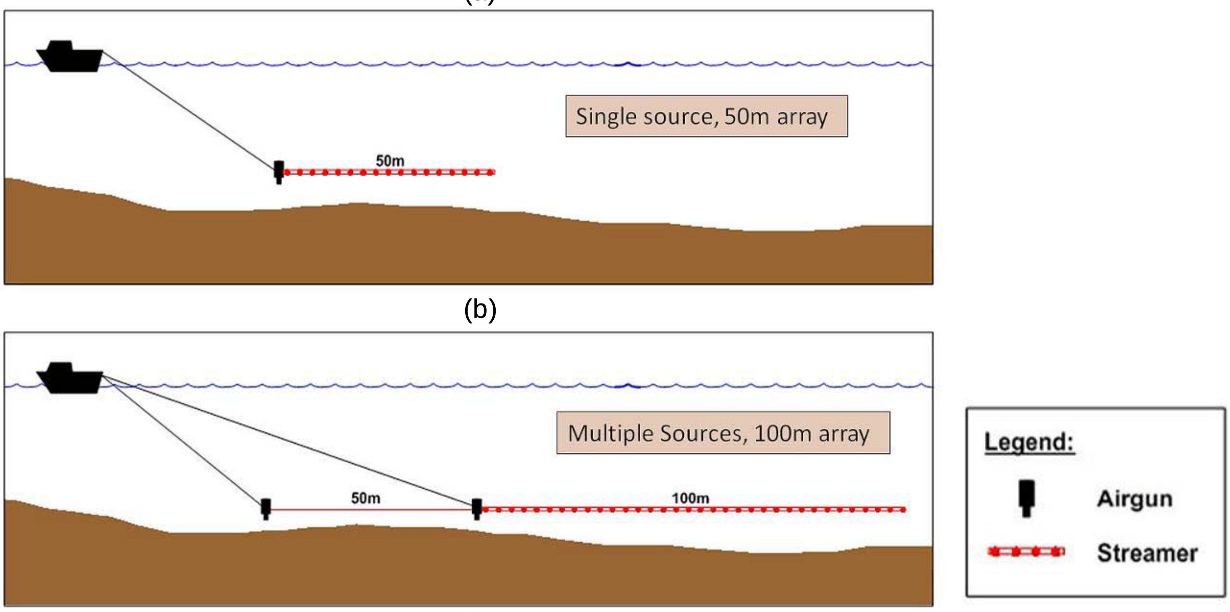


Figure 1 Schematic of single & multiple source CUSR systems

An example of the improvements that can be achieved with this approach is illustrated with multilayered synthetic model with typical seismic velocities containing a relatively thin high velocity "hard" patch or layer of limited lateral extent as shown in Figure 2(a). An actual field example from Western Australia is provided in Whiteley et al. (2010). Single- ended, CUSR first arrival times were computed through this model to a 50m source-receiver array with detectors at 2m intervals, a single source and a 10m source interval. This data was then interpreted using and the smoothed intercept-time interpretation method, that is in common use, as shown in Figure 2(b). This interpretation produces a more extensive high velocity region that has been migrated laterally in the source direction and is a considerable variance with the original model i.e. a geotechnical engineer would normally consider this to be an area of stronger rock extending to considerable depth.

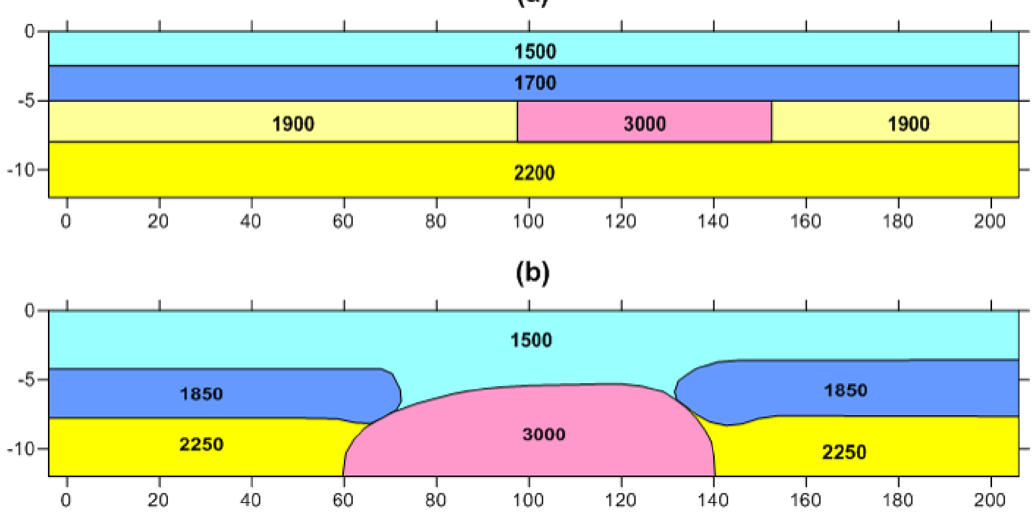


Figure 2(a) Synthetic seismic model with "hard" patch (b) interpreted seismic section from single source synthetic data

TECHNICAL ARTICLE (Continued)

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

The synthetic model in Figure 2(a) was extended to include a deeper higher velocity layers (2500 and 4500m/s) representing weathered and fresh rock at depths of 15 and 20m respectively. First arrival travel-times were again computed through this model for a 100m receiver array with multiple sources at both 0m and 50m offsets and inverted using Wavepath Eikonal Tomography (WET, Schuster and Quintus-Bosz, 1993) from an initial velocity gradient model. This produces a seismic image that is continuous rather than discrete as assumed with the simple interpretation method and is increasingly used in near-surface seismic refraction on land (Whiteley and Eccleston, 2006).

The seismic tomographic image obtained is superimposed on the original synthetic model in Figure 3(a) with the colours representing the different seismic velocities (in m/s) listed on the side of this figure. As well as providing deeper information this image bears a strong resemblance to the discrete shallow model (Figure 2a) and a significant improvement on the simple interpretation of the single source data in Figure 2a, i.e. no shallow detail has been lost and both the lateral extent and depth to the top of the high velocity lens are closely defined in this image. The base is less well defined in Figure 3a but is more clearly observed on the seismic wavepath density diagram in Figure 3b that is produced by the inversion software. The wavepath densities (in paths per pixel) within this interpreted model are listed on the side of this figure. These essentially represent the seismic information content in various part of the image and show the concentration of seismic wavepaths within both the shallow "hard" patch and the deep "harder" bedrock refractor. The geotechnical engineer can easily observe both of these features in the tomographic and wavepath density images.

In the following, a series of recent marine geophysical case studies are presented to demonstrate the application of USR methods with both static and continuous deployments at a variety of sites in Australia. These methods are enhanced with advanced interpretation techniques.

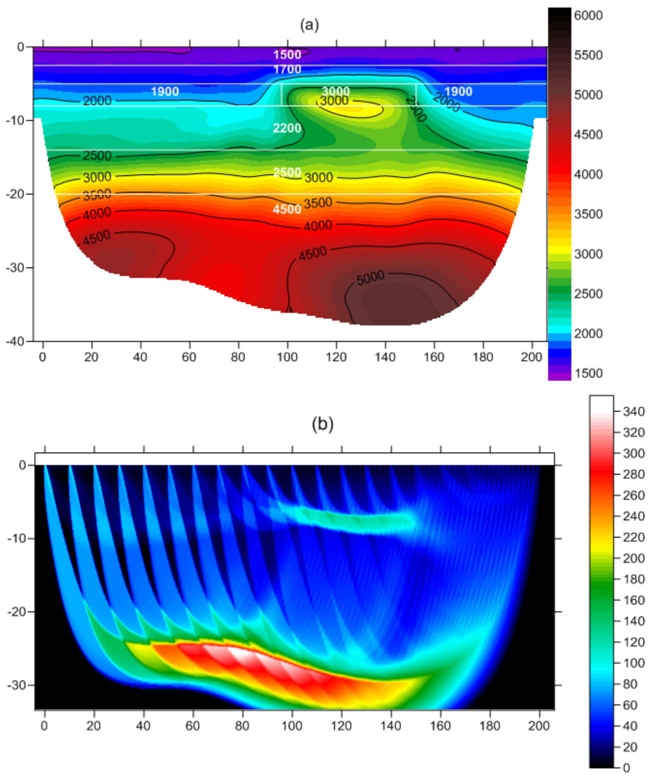


Figure 3(a) Seismic model and interpreted tomographic image (b) wavepath densities

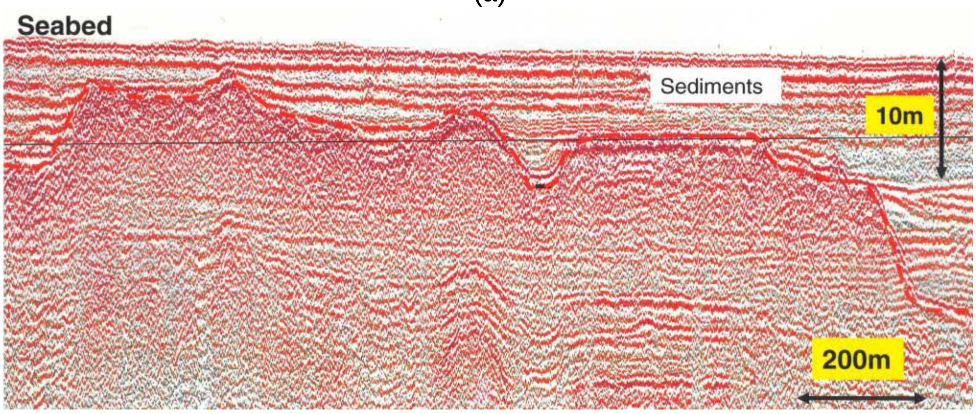
TECHNICAL ARTICLE (Continued)
Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

2 CASE STUDIES

2.1 NAVIGATION CHANNEL UPGRADES GEELONG PORTS, VICTORIA

Marine reflection surveys were completed as part of the navigation channel upgrades at a number of the Geelong Ports in western Port Phillip Bay. Figure 4(a) is a CSP Boomer record section from this project showing an irregular reflector interpreted as a basalt flow within the layered sediments and proposed dredged depth at some locations. The upper surface and lateral limits of this basalt flow are readily identifiable and are marked by the dashed red line in Figure 4(a). It is relatively common in this area for drowned basalt flows to be variably weathered and their upper surface and margins can consist of stiff clays. The reflection record does not readily distinguish such material from the underlying less weathered basalt.

(a)



(b)

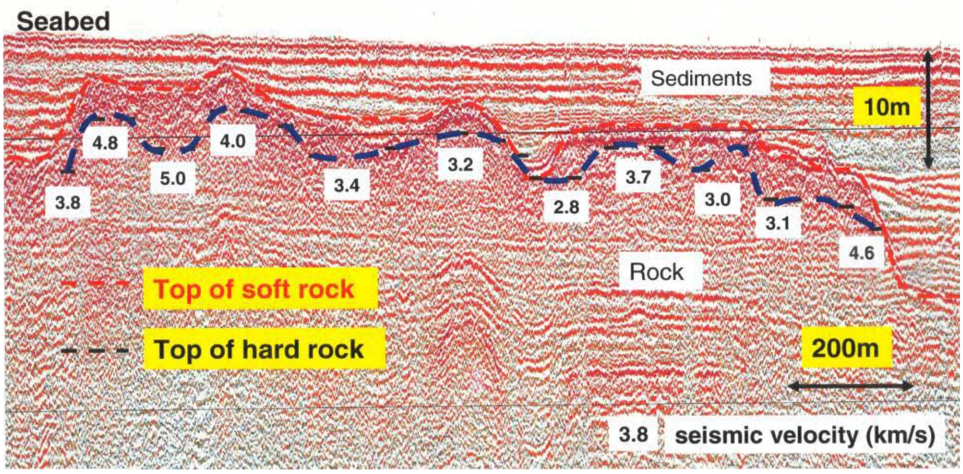


Figure 4(a) CSP Boomer record from Port Phillip Bay (b) Interpreted CSP & CUSR record showing top of "soft" and "hard" rock

TECHNICAL ARTICLE (Continued)
Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

A single source CUSR survey was also completed along this line and was interpreted as a simple two-layer model with the upper layer having a seismic velocity of 1650 to 1850 m/s corresponding to the bedded sediments and stiff clays and a deeper layer whose velocity varied from 3000 to 5400 m/s (2.8 to 5.0 km/s) corresponding to the strong basalt rock. This was an adequate approach for this problem. Figure 4(b) combines the CSP reflection and CUSR refraction interpretations with the “soft” and “hard” rock interfaces marked with the dashed lines and assisted design of the dredging operation and the installation of channel markers over the basalt.

2.2 PROPOSED HDD PIPELINE INSTALLATION, EAST MALAYSIA

Initial overwater drilling along the near-shore section of the alignment of a proposed oil pipeline at a refinery in East Malaysia encountered granitic bedrock beneath sediments. More detailed information was required to assist assessment of the viability of Horizontal Directional Drilling (HDD) as a pipeline installation option. CSP sections obtained in the area of the alignment clearly identified a strong, highly irregular reflector associated with the “harder” granite interface but provided no information on the likely geotechnical properties of the materials present. Also, due to relatively wide CSP line spacing and the highly variable interpreted bedrock surface a reliable 3D surface plan of the weathered granite rock interface could not be obtained from this data.

A CUSR survey was completed to provide further information on the materials along the proposed alignment and to test a number of alternative routes. Figure 5 shows a combined interpreted seismic section along the selected alignment with both the reflection and refraction interpretations. The interpreted weathered granite rock levels from the reflection interpretation generally agree well with the 2200 m/s velocity contour of the refraction data, except in a few local areas where the bedrock elevation changes rapidly. The interpreted weathered granite level from the CSP shown as the black line in Figure 5 lies mainly between the 2200 m/s and 3500 m/s velocity contours from the CUSR interpretation.

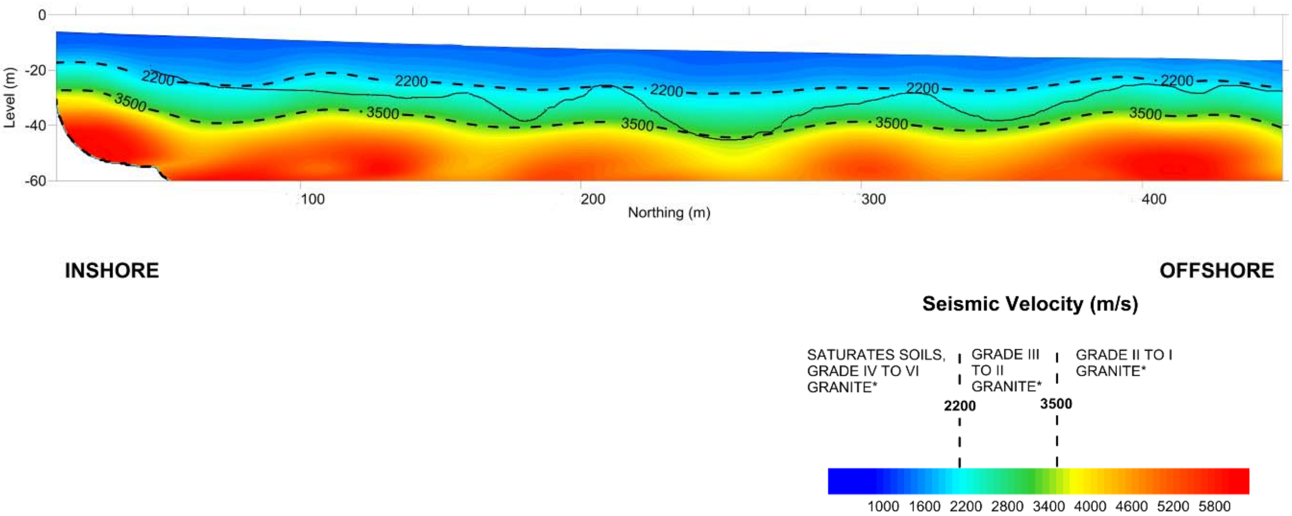


Figure 5 Interpreted CSP and CUSR seismic section along pipeline alignment

Generally four sub-seabed layers of differing seismic velocity extending from the sea floor were interpreted based on the site geology and correlation with other similar sites in Malaysia and the Asian region. Table 2 provides a correlation between seismic velocities from the CUSR interpretation and weathering grades for Hong Kong granites from Irfan and Powell (1985). On the interpreted seismic section in Figure 5 two seismic velocity contours have been highlighted i.e. 2200m/s and 3500m/s. The 2200m/s velocity contour is taken to represent the approximate interface between the saturated soils, Grade VI, V

TECHNICAL ARTICLE (Continued)

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

and IV granites, and the Grade III granite boulders. The 3500m/s contour has been taken to represent the interface between the Grade III boulders and the jointed to intact Grade II to I granite rock with lower velocity zones correlating with many of the deeper bedrock features on the CSP data. The areas of interpreted deeper bedrock are believed to reflect mainly weathering variations in the granites and areas of closer discontinuity spacing and possibly the regional joint spacing. Many of these features could not easily be correlated across the CSP profiles.

Table 2: Rock Type, Weathering Grade, Seismic Velocity and estimated UCS

Material	Granite Weathering Grade	P-wave Velocity (m/s)	Estimated Range of UCS values (MPa)*
Saturated soils, Granite	V and VI	1600 – 1800	<2.5
Granite	IV	1800 – 2200	2.5 – 15
Granite (boulders and/or jointed)	III to II	2200 – 3500	5 – 225
Granite (jointed to intact)	II to I	3500 – 6000	125 – 275

* from Irfan and Powell (1985).

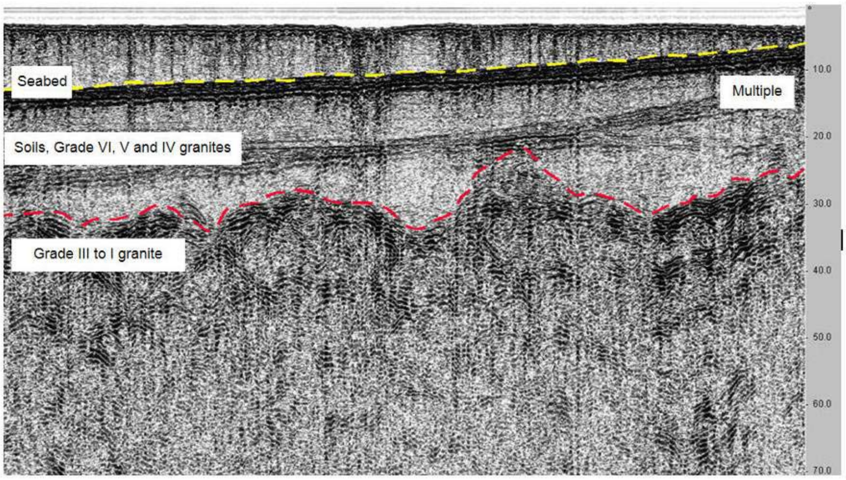


Figure 6 Sample of interpreted CSP line from the pipeline area

Figure 6 is a segment (~ 150m) of an interpreted CSP line from the pipeline area with the geological information from Table 2 included. This clearly shows the seabed reflector (dashed yellow line) over an irregular underlying reflector (dashed red line). The seabed reflector consists of almost acoustically transparent materials with some sub-planar reflectors interpreted as sandy sediments and/or extremely weathered bedrock. The underlying sub-planar reflector that is near the multiple represents the bases of the sediments above extremely weathered granite then the irregular reflector representing the less weathered granite and corestones. The complexity of this interface and the seismic variability of the underlying weathered granite is the result of a long period of weathering. This causes the reflected seismic pulse to scatter and diffract from this interface. This scattering and diffraction character means that side reflections can be projected into the seismic data, resulting in a smoothed interpreted level. Also when rock levels decrease abruptly due to a deeper weathering in areas of reduced discontinuity spacing and/or erosion prior to inundation and burial the weathered granite interface may not be clearly observed.

TECHNICAL ARTICLE (Continued)
Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

2.3 DEEP PILING DESIGN, IRON ORE BERTH, WESTERN AUSTRALIA

Construction or upgrade of new mineral commodity berths or berth upgrades frequently involve deep piling to weathered or fresh rock at sub-bottom depths exceeding 50m. This requires mapping the drowned regolith beneath sediments and indurated layers. Static USR is applied to provide this information in these conditions as the existing berth can remain in operation while the geophysical work proceeds, which is not normally the case with over water drilling.

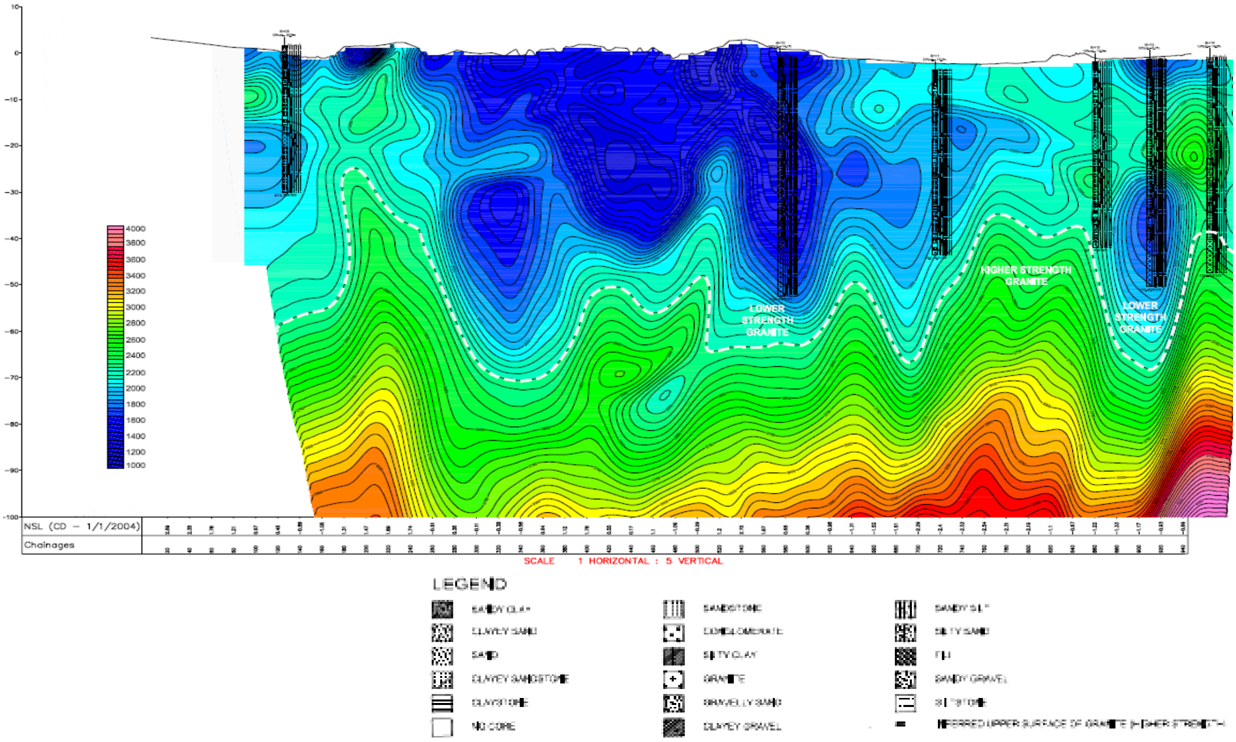


Figure 7 SUSR interpreted seismic tomographic image along berth with geotechnical boreholes

Figure 7 shows an interpreted seismic tomographic image along a SUSR line adjacent to one such berth on the northwest shelf in Western Australia. This was to be sited on variably weathered granite, and the geotechnical boreholes that were drilled along the shoreline have been projected onto this interpreted seismic image, which is about 850 m long and extends to a depth of approximately 100m. Most of the boreholes shown on Figure 7 terminated in weathered, lower strength granite at a depth where the seismic velocities increase rapidly with depth. The irregular upper surface of the fresh, higher strength granite (i.e., the base of the regolith) at greater depth has also been marked on the seismic image. The general separation between the less weathered granite "pinnacles" corresponded with the regional major joint spacing for this rock. The higher velocity regions in some parts of the shallower section also corresponded with areas of indurated calcareous sediments (calcarenites, Table 1), possibly the location of ancient reefs around the granite "pinnacles". These locations were identified as preferred piling sites to reduce overall pile lengths.

TECHNICAL ARTICLE (Continued)

Improved coastal geotechnics with integrated marine seismic reflection and refraction geophysics: Case studies

3 CONCLUSIONS

Appropriately deployed underwater seismic refraction (USR) technologies supported by advanced processing and analysis methods have demonstrated the ability to improve marine geotechnics in a diverse range of applications and represent a cost-effective enhancement of current over water geophysical and geotechnical practice. It is expected that these technologies will be increasingly applied in Australia's coastal waters.

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