Low frequency acoustic propagation over calcarenite seabeds with thin, hard caps

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ABSTRACT

Much of Australia's continental shelf consists of a relatively soft limestone called calcarenite, which is variable in geoacoustic properties and covered by a thin veneer of unconsolidated sediment vanishing in some areas. Low frequency underwater acoustic propagation in such environments is strongly influenced by the geoacoustic properties of the calcarenite, which typically has a shear speed slightly lower than the sound speed in water. This often results in strong frequency dependence of the acoustic transmission loss with some frequency bands having a much lower transmission loss than the nearby frequencies. In some cases the upper part of the calcarenite consists of a thin (~1m) layer of hard, well-cemented calcarenite overlaying softer, semi-cemented layers. This paper considers the effect that this hard cap has on the acoustic reflectivity of the seabed and on the resulting acoustic propagation at frequencies sufficiently low that the upper, well-cemented layer is thinner than its shear and compressional wavelengths.

INTRODUCTION

As a result of the continent's low relief and lack of substantial rivers, Australia's southern continental shelf is the largest region of cool-water carbonate sediment deposition in the world (Bird 1979, James et. al 1994, James et. al. 2008). In other words, the sediments comprising the shelf consist of a high proportion of calcium carbonate from the remains of marine organisms. During times of low sea level these sediments have been exposed to the atmosphere and to fresh water, resulting in partial dissolution and re-solidification of the calcium carbonate, cementing the sediment grains together to form a type of limestone called calcarenite. The continental shelf in this region is exposed to a highly energetic ocean wave climate which, when combined with a very low rate of input from land-based (terrigenous) sediment discharge, results in a seabed typically consisting of calcarenite overlain by a thin (< 1m), spatially variable veneer of unconsolidated calcareous sediment (Collins 1998).

Calcarenite is a highly variable material consisting of grains of different sizes held together by varying degrees of cementation, with both factors depending on the exact conditions of the material's formation. Its properties also vary considerably with depth into the seabed, with substantial changes in the degree of cementation often occurring over depth ranges of less than a metre (Fugro, 2004). It is also common for an upper, well cemented layer to overlie a sequence of softer layers leading to non-monotonic changes in the sound speed with depth. This is a result of erosion by currents and/or wave action removing sediment until a relatively hard, and therefore erosion resistant, layer is encountered.

The unusual characteristics of acoustic propagation over calcarenite seabeds stem from the material's shear speed, which is typically somewhat less than the sound speed in the water column. As discussed in Li et. al. (2009) and Duncan et. al. (2009), this results in strong attenuation at low frequencies except for discrete frequencies corresponding to the cut-off frequencies of the water-column modes. The presence of a thin unconsolidated layer (e.g. sand) overlying the calcarenite increases the seabed reflection coefficient and therefore reduces the transmission loss, an effect that becomes more pronounced as the frequency increases.

Duncan and Lu (2011) modelled a two-layer calcarenite seabed in which the lower layer had higher compressional and sheer wave speeds than the upper layer and showed that this had the effect of broadening the low transmission loss bands. Gavrilov et. al. (2012) found that a geoacoustic model comprising a thin, well-cemented calcarenite layer overlying weakly cemented layers explained most features of otherwise anomalous transmission loss and frequency dispersion found in recordings of seismic survey shots made in Bass Strait.

In this paper we extend this work further by investigating the effect that a thin, upper layer of well-cemented calcarenite has on the reflection of sound from a semi-cemented calcarenite halfspace seabed. We concentrate on frequencies sufficiently low that the upper, well-cemented layer is thinner than the shear and compressional wavelengths in the layer.

REFLECTION COEFFICIENTS FOR CALCARENITE SEABEDS

The results described here were calculated using the plane-wave reflection coefficient program BOUNCE (Porter, 2007) applied to a simplified version of the seabed geoacoustic model described in Gavrilov et. al. (2012). The seabed model described in that paper was based on geotechnical data and acoustic measurements made in Bass Strait and consisted of three layers: a semi-cemented sand/calcarenite halfspace overlain by a 60m thick semi-cemented sand/calcarenite layer in which both compressional and shear wave speeds increased with depth, and an upper 1m thick layer of well-cemented calcarenite (cap-rock).

For the purposes of this paper the geoacoustic model has been simplified to a two-layer model consisting of a semi-cemented sand/calcarenite halfspace overlain by a 1m thick layer of well-cemented calcarenite. The assumed geoacoustic properties of these materials are listed in Table 1. Although the simplified model produces results that differ in detail from those obtained from the three-layer model, it captures the important features while simplifying the presentation of results.

Table 1. Seabed geoacoustic properties used in this paper. (Based on Gavrilov et. al. 2012)

Material	Well-cemented calcarenite	Semi-cemented sand/ calcarenite
Density (kg.m^{-1})	2700	2200
Compressional wave speed (m.s^{-1})	2600	2000
Compressional wave attenuation (dB/wavelength)	0.5	0.3
Shear wave speed (m.s^{-1})	1200	900
Shear wave attenuation (dB/wavelength)	0.5	0.27

The black curve in Figure 1 shows the plane-wave reflection coefficient for a seabed consisting of a semi-cemented sand/calcarenite halfspace (i.e. without the upper well-cemented layer). This curve is typical of calcarenite seabeds and shows a pronounced dip at low grazing angles due to coupling of sound in the water column into shear waves in the seabed. The peak at a grazing angle of about 40° corresponds to the critical angle for the seabed compressional wave and is responsible for the bands of low transmission loss that occur at low frequencies. See Li et. al. (2009) and Duncan et. al. (2009) for details but essentially the low transmission loss bands correspond to frequencies at which a water-column mode interacts with the seabed at the grazing angle of this peak. Consequently, the higher this peak, the lower will be the transmission loss in the corresponding frequency band. As the frequency is increased, the modes interact with the seabed at progressively smaller grazing angles and the gradient of the reflection coefficient curve near zero grazing angle becomes the most important factor in determining the transmission loss. The more rapidly the reflection coefficient reduces with increasing grazing angle in this region, the higher the transmission loss.

Figure 1 also shows the plane-wave reflection coefficient as a function of grazing angle for the two-layer seabed model that includes a 1m thick upper layer of well-cemented calcarenite. Results are plotted for a number of different frequencies. The striking thing about these results is the dramatic effect the presence of the cap rock has on the reflection coefficient; reducing the height of the critical angle peak and increasing the rate at which the reflection coefficient reduces with grazing angle at low grazing angles. Both of these effects will lead to an increase in transmission loss. These effects become more pronounced as frequency increases but are visible at all modelled frequencies; even at 20 Hz where the layer thickness is only 0.77% of the compressional wavelength and 1.7% of the shear wavelength (see Table 2).

It is also noteworthy that the presence of the cap-rock increases the reflectivity of the seabed for grazing angles greater than about 50°, the opposite of its effect at lower grazing angles.

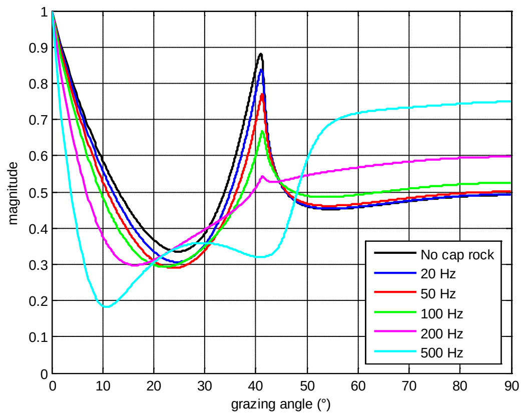

Figure 1. Magnitude of the plane wave reflection coefficient vs. grazing angle for a semi-cemented calcarenite halfspace seabed (black) and for the same seabed overlain by a 1m thick layer of well-cemented calcarenite at the frequencies indicated.

Table 2. Well-cemented calcarenite layer thickness expressed as a percentage of the compressional wavelength and shear wavelength in that layer.

Frequency (Hz)	Percentage of compressional wavelength	Percentage of shear wavelength
20	0.77	1.7
50	1.9	4.2
100	3.8	8.3
200	7.7	17
500	19	42

EFFECT ON ACOUSTIC PROPAGATIOIN

The wavenumber integration program SCOOTER (Porter, 2007) was used to compute the transmission loss vs. range and frequency for a 40 m deep isovelocity water column with a sound speed of 1500 m.s^{-1}, a source depth of 10m, a receiver depth of 20m, and for two seabed geoacoustic models. The first of these was a semi-cemented sand/calcarenite halfspace with the geoacoustic properties listed in Table 1, and the second was for the same seabed overlain by a 1 m thick layer of well-cemented calcarenite.

Plots of transmission loss as a function of range and frequency are given in Figure 2. The narrow, horizontal bands of low transmission loss visible at frequencies below 100 Hz are a consequence of the critical angle peaks in the reflection loss curves described above. As expected from the reflection coefficient results, the presence of the cap-rock results in these bands decaying more rapidly with range, especially at higher frequencies. This is more apparent in the top plot in Figure 3 which compares transmission losses as a function of frequency at a range of 5000m for the two seabed models. The horizontal bands in Figure 2 correspond to the sharp peaks in the transmission loss curves visible below 50 Hz in Figure 3.

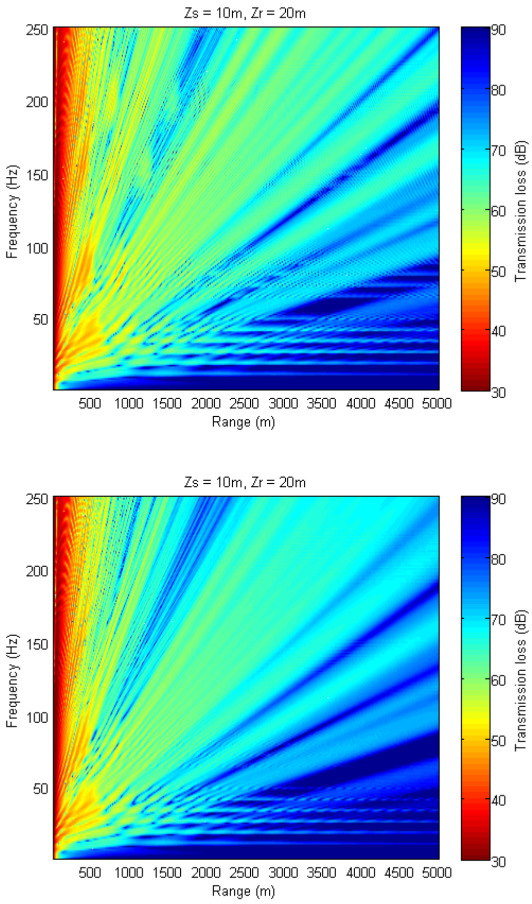

Figure 2. Transmission loss vs. frequency and range for a source depth of 10m, receiver depth of 20m, and water column depth of 40m. Top plot is for a semi-cemented sand/calcarenite halfspace seabed, bottom plot is for the same seabed overlain by a 1m thick layer of well-cemented calcarenite.

At higher frequencies propagation is dominated by modes with low grazing angles and the plots in Figure 2 take on the familiar form of modal interference patterns. Here the more rapid reduction in reflection coefficient with grazing angle that occurs for the seabed with the overlaying cap rock results in reduction of the number of modes that contribute significantly to the received field. As can be seen in Figures 2 and 3, this increases the transmission loss and simplifies the modal interference pattern.

CONCLUSIONS

The modelling work described in this paper has shown that a seabed consisting of a thin cap layer of well-cemented calcarenite overlaying a halfspace of semi-cemented sand/calcarenite is significantly less reflective to low frequency sound than the halfspace alone at grazing angles less than about 45°. For a 1 m thick layer the differences are apparent even at frequencies as low as 20 Hz, but become more pronounced at higher frequencies, at least to the maximum modelled frequency of 500 Hz.

As a consequence, the presence of the well-cemented layer increases the transmission loss, with differences of more than 10 dB being observed at the maximum modelled range of 5000m. These differences would be expected to increase with increasing range.

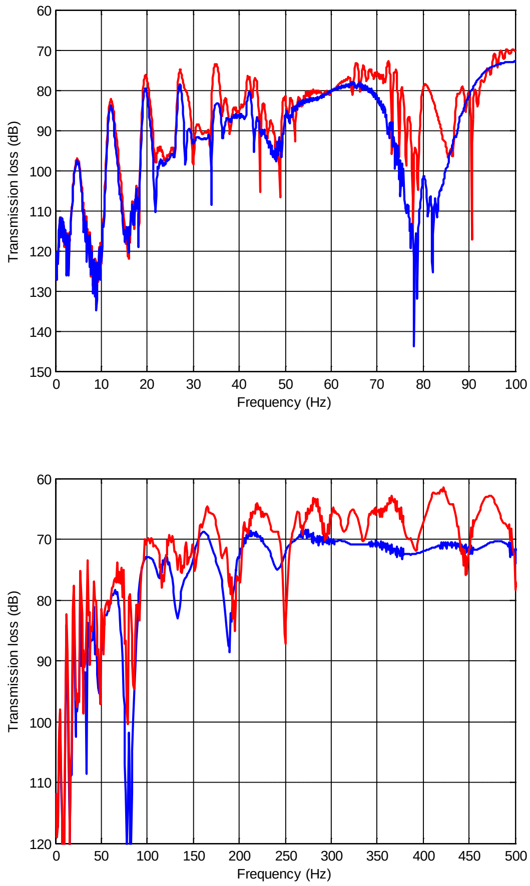

Figure 3. Transmission loss vs. frequency for a range of 5000m, a source depth of 10m, receiver depth of 20m, and water column depth of 40m. Red line is for a semi-cemented sand/calcarenite halfspace seabed, blue line is for the same seabed overlain by a 1m thick layer of well-cemented calcarenite. Top plot is for a frequency range of 0 to 100 Hz, bottom plot is from 0 to 500 Hz.

REFERENCES

Bird, E. C. F., 1979, "Geomorphology of the sea floor around Australia", In *Australia's Continental Shelf*, J R V Prescott (editor), Nelson, 1979, pp. 1-21, ISBN 0 17 005397 0.

Collins, L. B., 1988, "Sediments and history of the Rottnest Shelf, southwest Australia: a swell-dominated, non-tropical carbonate margin", *Sedimentary Geology*, 60, pp. 15-49.

Duncan, A. J., Gavrilov, A., Li, F., 2009, "Acoustic propagation over limestone seabeds", Proc. Acoustics 2009, 23-25 Nov. 2009, Adelaide, Australia.

Duncan, A. J., Lu, L., 2011, "The effect of layering on acoustic propagation over calcarenite seabeds", Proc. Underwater Acoustic Measurements, Technologies and Results, Kos, Greece, 20-24 June 2011.

Fugro, 2004, "Draft geotechnical report, Otway gas project, final platform geotechnical investigation, offshore Victoria, Australia", Fugro Survey Report No. HY 16608, Fugro Engineers BV Report No. N4349/02, January 2004.

Gavrilov, A., Duncan, A. J., McCauley, R. D., Parnum, I., 2012, "Peculiarities of sound propagation over the continental shelf in Bass Strait", Proc. European Conference on Underwater Acoustics, Edinburgh, UK, 2-6 July 2012.

James, N. P., Boreen, T. D., Bone, Y., Feary, D. A., 1994, "Holocene carbonate sedimentation on the west Eucla Shelf, Great Australian Bight: a shaved shelf", *Sedimentary Geology*, 90, pp. 161-177.

James, N. P., Martindale, R. C., Malcolm, I., Bone, Y., Marshall, J., 2008, "Surficial sediments on the continental shelf of Tasmania, Australia", *Sedimentary Geology*, 211, pp. 33-52.

Li, F., Duncan, A. J., Gavrilov, A., 2009, "Propagation and inversion of airgun signals in shallow water over a limestone seabed", Proc. Underwater Acoustic Measurements, Technologies and Results, Nafplion, Greece, 21-26 June 2009.

Porter, M. B., 2007, Acoustics Toolbox, Available from http://oalib.hlsresearch.com/FFP/index.html