Bandwidth requirements for shallow, high-resolution seismic reflection

Steve Hearn
Velseis Pty Ltd and *University of Queensland*
steveh@velseis.com.au

Natasha Hendrick
University of Queensland, Australia
natasha@geoph.uq.edu.au

SUMMARY

The optimum bandwidth for shallow, high-resolution seismic reflection differs from that required for conventional petroleum reflection. An understanding of this issue is essential for correct choice of acquisition instrumentation. Numerical modelling of simple Bowen Basin coal structures illustrates that, for high-resolution imaging, it is important to accurately record all frequencies up to the limit imposed by earth scattering. On the contrary, the seismic image is much less dependent on frequencies at the lower end of the spectrum. These quantitative observations support the use of specialised high-frequency geophones for high-resolution seismic imaging. Synthetic seismic inversion trials demonstrate that, irrespective of the bandwidth of the seismic data, additional low-frequency impedance control is essential for accurate inversion. Inversion provides no compelling argument for the use of conventional petroleum geophones in the high-resolution arena.

Key words: seismic, high-resolution, bandwidth, geophone, inversion.

INTRODUCTION

Shallow seismic reflection (imaging at depths < 1km) has been successfully used in coal and mineral exploration, and in a variety of engineering and environmental activities. Over the past decade, the technique has been increasingly embraced by the coal-mining industry, and can now claim to be the most important geophysical tool for mine planning. Modern 3D seismic imagery is proving capable of detecting faults in coal seams of order 1–2 m. Consequently this technology is having a major impact on reducing the financial risks attached to the use of longwall miners. In this context, there is strong incentive for coal geophysicists to optimise the resolving capability of the method.

The ability of seismic reflection to resolve structures depends on a range of factors relating to the seismic wave itself, and to the properties of the rocks through which the seismic energy propagates (e.g. Hearn and Hendrick, 2000; Hatherly and Zhou, 2000). Perhaps the most fundamental requirement for good quality, high-resolution seismic data relates to the frequency-content of the propagating seismic wavelet. Ideally we require a broad, smoothly-varying frequency bandwidth, which will result in a compact, non-ringy wavelet. Further, the ability of the wavelet to resolve closely spaced features depends on its dominant frequency. An increase in dominant frequency corresponds to a decrease in dominant wavelength, and this intuitively should provide improved resolution. A number of classical rules-of-thumb (e.g. Sheriff, 1991) relate dominant wavelength (λ) to resolving ability, including the notions of detectable limit ($\lambda/30$), and Rayleigh resolution limit ($\lambda/4$).

Many of the traditional ideas regarding seismic resolution have originated in the petroleum arena. As will be seen below, some of these concepts need to be reconsidered in the context of shallow seismic reflection, primarily due to the contrast in available frequency bandwidth. Practical coal-seismic experience suggests that reflected waves span the bandwidth from 0 Hz up to approximately 250–300 Hz. Of course, it may not necessarily be possible to record this full range with high fidelity.

The purpose of this paper is to examine the significance that the different parts of the available frequency spectrum have on shallow, high-resolution seismic images, and hence demonstrate bandwidth requirements for optimal resolution. This in turn facilitates a more effective choice of acquisition instrumentation. Although our examples focus on the coal environment, the concepts can be extended to other high-resolution seismic applications.

THE INFLUENCE OF HIGH FREQUENCIES

The primary physical limitation to recording high-frequency information relates to the ability of seismic waves to successfully propagate through the earth. The earth's normal heterogeneities are more obvious to higher frequency (shorter wavelength) waves, resulting in scattering rather than coherent propagation. As noted above, the limit imposed by the earth for coal-seismic targets (at depths of hundreds of metres) is typically found to be around 250–300 Hz.

Numerical modelling provides a tool for assessing how important the frequencies at this high end of the spectrum are to the final seismic image. Figure 1 gives an example of a synthetic seismogram constructed using a seismic wavelet with an adjustable frequency bandwidth. The geological model used to create the synthetic data comprises just three detectable seismic horizons (base of weathering, and two deeper coal seams). The geology is based on a particular mine in the Bowen Basin, with the lower target seam being at a depth of 125m. Further details on the model parameters are given in Hearn and Hendrick (2000).

In Figure 1 the low-cut frequency of the wavelet has been fixed at 30 Hz, while the high-cut frequency has been progressively increased. Resolution of the three horizons is significantly improved as the high-cut frequency is increased from 60 Hz, through 120 Hz, to 240 Hz (approaching the practical limit imposed by the earth). Beyond this point the effect is more gradual, with broadening of the bandwidth up to 480 Hz providing a subtle, but visible, further improvement.

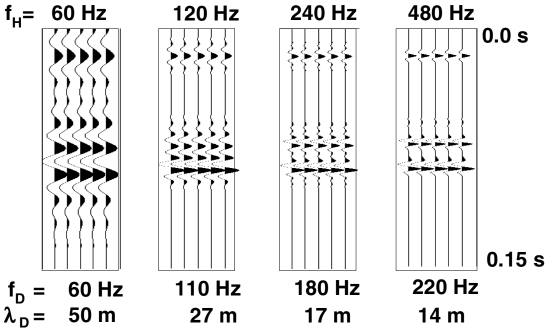

Figure 1. Effect of wavelet high-cut frequency on synthetic seismogram for a simple Bowen Basin coal model. The low-cut frequency is set at 30 Hz. The high-cut frequency (f_H) is shown at the top of each panel. The measured dominant frequency (f_D) and the corresponding dominant wavelength (λ_D, based on a nominal velocity of 3000 m/s) are shown at the bottom.

The improvement in resolution seen in Figure 1 is associated with an increase in dominant frequency. Equivalently, and perhaps more intuitively, it can be thought of as a progressive reduction in dominant wavelength. Figure 2 highlights that the rate of reduction in the seismic wavelength with increasing frequency slows as progressively higher frequencies are reached. So while significant wavelength reduction is achieved by extending the high-frequency content of conventional petroleum-scale seismic data, wavelength reduction is more marginal at coal-seismic frequencies. Nevertheless, if high-resolution structural imaging is the objective, it is important to accurately record all available frequencies at the high end of the spectrum.

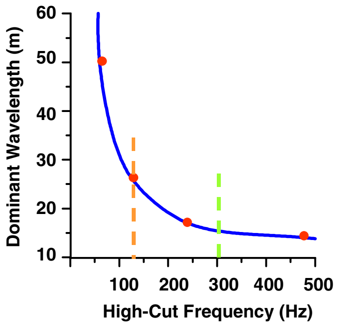

Figure 2. Relationship between dominant wavelength and high-cut frequency, for the model results of Figure 1. The marked points correspond to the 4 panels in Figure 1. Typical high-frequency limits achieved in the petroleum and coal arenas are marked by vertical dashed lines (125 Hz and 300 Hz respectively).

Our seismic instrumentation needs to operate with high fidelity up to the high-frequency limit imposed by earth scattering. This has implications for geophone selection, as will be discussed in detail below.

THE INFLUENCE OF LOW FREQUENCIES

The previous section demonstrates the importance of high-frequency content for optimum seismic resolution. In contrast, the resolving ability of seismic data appears much less sensitive to changes at the lower end of the spectrum. Figure 3 shows synthetic seismograms constructed using a seismic wavelet with a variable low-cut frequency. The high-cut frequency is fixed at 240 Hz (appropriate for coal seismic). As the low-cut frequency is changed from 10 Hz to 60 Hz there is little change in resolving ability, or dominant frequency. In this example even a bandwidth of 120–240 Hz provides reasonable resolution. As the low-cut frequency is increased beyond 120 Hz, there is a slight reduction in dominant wavelength. Unfortunately, however, this narrow bandwidth produces wavelet instability, such that closely spaced horizons can no longer be separated.

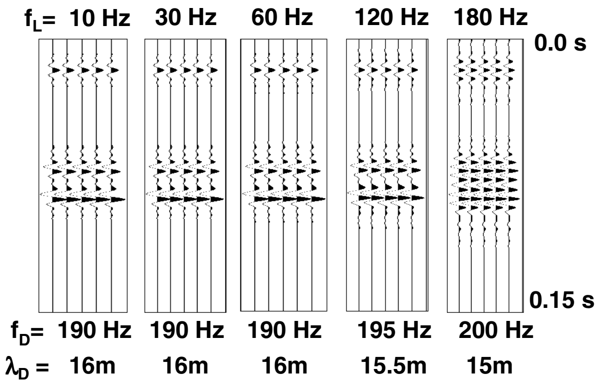

Figure 3. Effect of wavelet low-cut frequency on synthetic seismogram for a simple Bowen Basin coal model. The high-cut frequency is set at 240 Hz. The low-cut frequency (f_L) is shown at the top of each panel. The measured dominant frequency (f_D) and the corresponding dominant wavelength (λ_D) are shown at the bottom.

This example demonstrates that, provided sufficient high-frequency energy is available, frequencies at the low end of the spectrum (< 60 Hz) make relatively little contribution to the seismic image.

GEOPHONE SELECTION

A fundamental constraint on the recorded bandwidth of a seismic signal is provided by the geophone. The geophone acts as the primary low-cut filter, with frequencies below the natural frequency being attenuated on a correctly damped geophone. In theory, the geophone has a flat response from natural frequency up to very high frequencies. In practice, however, geophones are subject to an undesirable parasitic resonance phenomenon, caused by transverse compliance in the suspension spring (e.g. Ziolkowski and Lerwill, 1979). A commonly used rule-of-thumb is that a geophone of natural frequency f_n should be free of such spurious effects up to about $10 f_n$ (Knapp and Steeples, 1986).

Based on the numerical modelling results presented above, high-resolution seismic imaging requires high-fidelity recording up to the frequency limit imposed by the earth. Standard petroleum geophones (10–15 Hz) can not necessarily be guaranteed to provide perfect fidelity up to the highest frequencies observed in the coal environment. Geophones with a natural frequency of 30–40 Hz should be more able to provide high fidelity recording up to the 250–350 Hz region. These geophones also provide the incidental advantage of attenuating low-frequency surface-wave noise, which is often associated with surface or near-surface sources.

The preceding modelling analysis of low-frequency effects has indicated that frequencies below about 60 Hz make minimal contribution to the resolution of the coal-seismic image. This strengthens the argument that, for coal reflection, geophones of natural frequency around 30-40 Hz are preferred over conventional petroleum style phones.

Our analysis has focussed on typical coal-seismic situations, since coal mining is the major high-resolution market in Australia. The analysis presented here can logically be extended into the environmental and engineering arena (imaging depths < 100 m). At this scale, the earth's high frequency limit may be significantly higher. Consequently, it would be expected that higher frequency geophones (say f_n = 100 Hz) would optimally provide a broadband, resonance-free, recording.

SEISMIC TRACE INVERSION

To this point, our assessment of the significance of bandwidth has been based on the criterion of resolution of the seismic image itself. In practice this is certainly the primary focus in coal-seismic reflection. There is, however, emerging experimental interest in auxiliary analysis tools such as attribute analysis and seismic trace inversion.

We have just seen that lower frequencies contribute minimally to the high-resolution seismic image. On the contrary we expect them to play a more important role in inversion. The expectation that low-frequency content is important to inversion is based on the theoretical transfer function relating reflectivity to impedance, illustrated in Figure 4. How does this impact on the preceding arguments relating to geophone selection?

To gain insight into the significance of low-frequency information to seismic inversion, a number of synthetic seismic traces exhibiting various frequency bandwidths have been constructed for seismic inversion trials. The traces have been built from log data acquired at the same Bowen Basin mine considered in the earlier numerical modelling exercises. Figure 5 shows synthetic traces built by convolving the well-log reflectivity function with 10–250 Hz and 30–250 Hz wavelets respectively. These traces are indicative of recordings made using 10 Hz and 30 Hz geophones respectively – currently the two most widely used geophone-types in coal-seismic exploration. The two seismic traces are virtually indistinguishable, as would be expected based on the preceding model analysis of low-frequency effects.

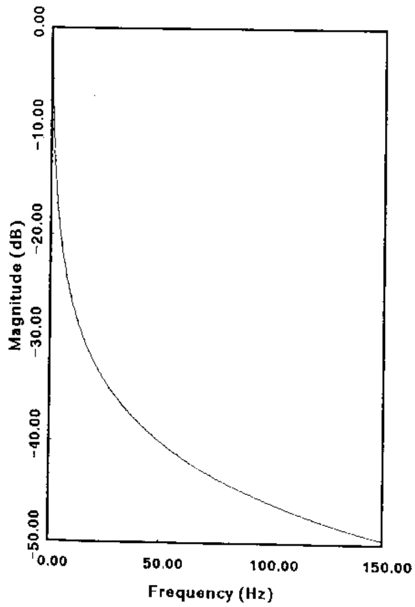

Figure 4. Magnitude of the theoretical transfer function $T(f) = V_0 / (\pi if)$ corresponding to inversion from reflectivity to impedance (Todoeschuck and Jensen, 1988). The initial impedance V_0 has been taken as 6.3 x 10^6 SI units. Since the function is undefined at $f = 0$, the zero-dB level has been arbitrarily taken as the first frequency point of 0.5 Hz. (After Hendrick and Hearn, 1993.)

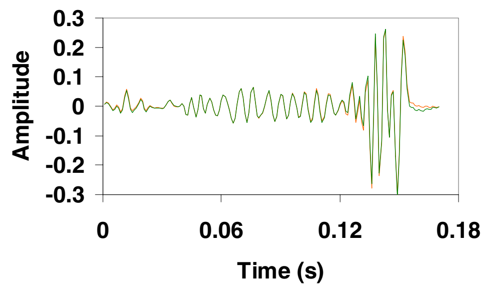

Figure 5. Synthetic seismograms derived from Bowen Basin well log data. Traces resulting from convolution of the reflectivity with 10-250 Hz and 30-250 Hz wavelets are shown (orange and green respectively).

Figure 6 compares the true model impedance with the impedance estimates obtained by unconstrained, classical recursive inversion (e.g. Hendrick and Hearn, 1993) of the 10–250 Hz and 30–250 Hz traces. Both inversions have successfully estimated the higher-frequency impedance character, but both have failed to recover the lower-frequency trend. Consistent with the transfer function of Figure 4, loss of information below 10 Hz has already severely compromised the inversion. In this context, the additional deterioration caused by loss of 10–30 Hz information is of secondary importance.

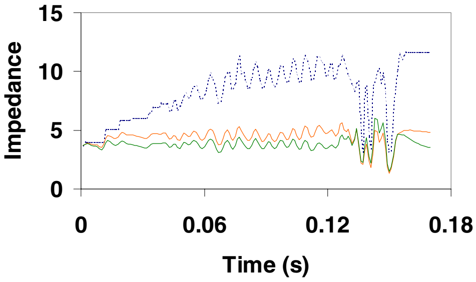

Figure 6. Impedance estimates obtained by classical recursive inversion of the 10–250 Hz trace (orange) and 30–250 Hz trace (green) compared with the known model impedance profile (dashed).

It is well known that any geophone-based recording cannot provide the low frequencies needed for trace inversion. Hence the accepted approach is to constrain the actual trace inversion with some other form of low-frequency impedance information. To illustrate one such approach, Figure 7 shows inversion estimates which incorporate the constraint of an RMS velocity function, as would typically be available from CMP analysis. With this constraint, the low-frequency character of the recovered impedance is much improved for both the 10–250 Hz and 30–250 Hz input traces. The two inversions are of comparable accuracy. Hence, in this inversion analysis, the lower-frequency geophone provides no discernible advantage .

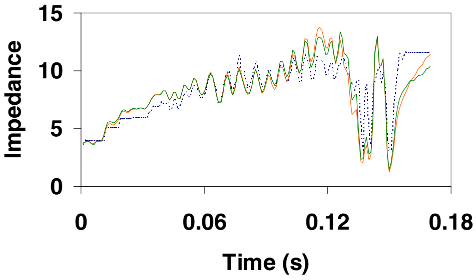

Figure 7. Impedance estimates obtained using generalised linear inversion with RMS impedance constraints (Hendrick and Hearn, 1993). Inversions of the 10–250 Hz trace (orange) and 30–250 Hz trace (green) are compared with the known model impedance profile (dashed).

CONCLUSIONS

Synthetic seismograms, constructed for a simple model based on northern Bowen Basin geology, demonstrate the important role high frequencies play in producing a high-resolution seismic image. It is important to accurately record high frequencies up to the limit imposed by earth scattering. In contrast, the resolution of the seismic image is relatively unaffected by the loss of low-frequency information. These quantitative observations support the view that, where the primary focus is seismic imaging, geophones used in high-resolution reflection should have higher natural frequencies than used for conventional petroleum seismology. For coal-scale reflection, geophones of natural frequency 30-40 Hz provide optimum bandwidth coverage.

While it is recognised that low frequency information is crucial to seismic inversion, the low frequency information required for successful inversion typically extends below the lower recording limit of both the conventional petroleum and high-resolution geophones. Low-frequency impedance constraints must always be inserted from alternative sources. Our tests to date suggest that, with such constraints applied, the inversion result is relatively insensitive to the precise low-cut frequency of the seismic trace. Thus, unless it is the primary focus of the seismic survey, inversion provides no compelling argument for the use of conventional petroleum geophones in the high-resolution arena.

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