Finite-difference modelling for the optimisation of coherent-noise suppression in very shallow seismic reflection

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SUMMARY

Seismic reflection surveys with targets at depths of 0-100m have been widely reported in the published literature. There are many case studies and theoretical discussions of methodology and technique. However, there exist no significant modelling studies of shallow seismic methodology.

In this study we have used viscoelastic finite-difference modelling to generate shot records that can be processed using a real world sequence. This approach has allowed investigation of a range of problematic issues relating to very-shallow reflection. Perhaps the most fundamental shallow-reflection problem relates to the extraction of signal from beneath coherent noise. Our modelling provides a clear demonstration of the stringent acquisition parameters that are needed if this noise is to be removed using conventional f-k domain processing tools.

Concepts investigated in the modelling are further explored via an engineering scale hammer seismic survey, which successfully images reflectors in the range 0-50m, using both pre-critical and post-critical reflections.

Key words: Shallow seismic reflection, f-k filtering, finite-difference modelling, ray-trace modelling

INTRODUCTION

Over the past 20 years, shallow seismic reflection (SSR) has become increasingly viable for smaller engineering and geotechnical projects due to a reduction in the relative cost of equipment and computational power. The technique has been used in the open-cut coal mining industry to map shallow seam structures, specifically faulting; in the structural geotechnics sector to provide a lateral understanding of bedding thickness for foundation and excavation works (Brabham et, al, 2005; Miller and Steeples, 1994), and to identify voids caused by casting, subsidence and old mine workings; and in hazard analysis, to identify structures and faulting associated with earthquakes (Gosar, 1998).

Applying conventional seismic reflection methodologies in the near-surface zone presents unique challenges (Butler, 2005; Steeples and Miller 1998). Reflections from near-surface interfaces suffer strong interference from surface-related noise events (groundroll, air-blast, guided waves, refractions and direct waves). These noise events occupy the same t-x space as the desired reflections, so that muting approaches are not feasible. Frequency filtering is also difficult due to overlap in the frequency domain.

Coherent noise events are often more effectively removed in the f-k domain. F-k filtering is widely used in SSR and is considered one of the most important filtering processes (Jeng, 1995). The process is generally applied at the shot record stage, with the filter defined in f-k space (e.g. Yilmaz, 2001).

There have been a few studies relating to the limitations of noise filtering in SSR (e.g. Steeples and Miller, 1998). However, a more holistic understanding of the difficulties faced in the near-surface environment is needed. Numerical modelling can fill this gap and can be utilised as a tool to understand both theoretical and practical problems with current SSR techniques. This study uses numerical modelling of SSR to investigate the limitations of filtering coherent noise using f-k domain techniques. A more thorough understanding is achieved by testing the modelled concepts with field data.

VISCOELASTIC FD MODELLING

For the synthetic modelling in this study, a finite-difference technique has been used that is based upon the method proposed by Robertsson et al. (1994). The algorithm uses a stable finite-difference modelling approach for viscoelastic seismic wave simulation. A viscoelastic method is preferred as it can accommodate non-elastic behaviour in the sub-subsurface, defined by Q, the seismic quality factor. This is important for realistic models of the near surface where soils become less cohesive and act in a semi-elastic manner, causing significant attenuation.

Geological Model

For the example to follow, we refer to the simple near-surface (100m) model in Figure 1. The model includes ten horizontal layers, whose velocities and densities increase with depth. Q values are low, as is realistic for the near surface. Acquisition parameters for the model are outlined in Table 1.

COHERENT NOISE in SSR

The shot record created using the model of Figure 1 is displayed in Figure 2. The original synthetic record has been decimated to show 80 channels at a 1.0 meter spacing. Coherent noise dominates. To clarify the predicted locations of the true primary reflections, events generated by ray-trace modelling are also displayed (orange). It is clear that other strong multiple reflections are also present.

Without any further processing, only a limited amount of usable information can be extracted from the raw shot record. A conventional approach is to utilise reflection energy in the

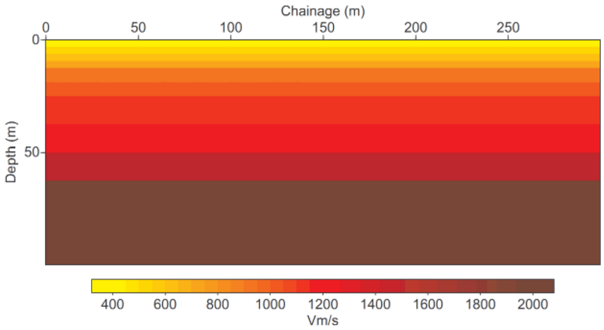

Figure 1 . Horizontally layered geological model used to illustrate coherent-noise rejection. The vertical extent is 100 m. The velocity (v) of each layer is colour coded, and density ranges from 2.0 g/cc at the surface to 2.4 g/cc at the base of the model.

Parameter	Value
Number of Channels	800
Geophone Spacing	0.125m
Spread Length	99.875m
Number of Shots	1
Shot Spacing	0
Sample Interval	0.0005ms
Recording Length	0.25s
Source Dominant Frequency	200Hz

Table 1. FD modelling parameters.

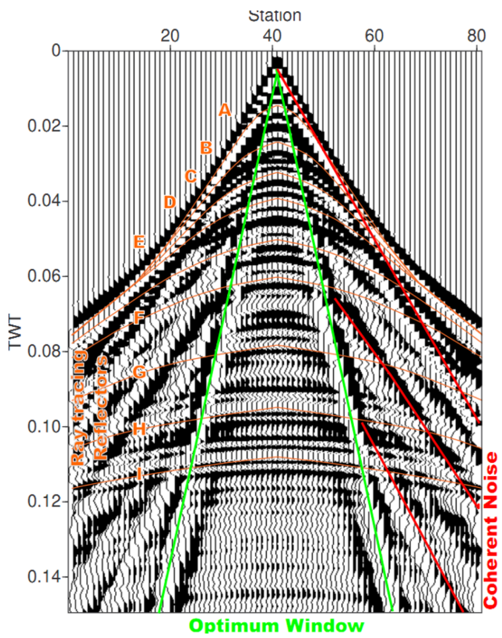

Figure 2. Example shot record for the model in Figure 1. Reflectors are highlighted in orange, coherent noise in red and the optimum window which is unaffected by coherent noise is highlighted in green.

optimum window (Hunter, 1985), which occurs between the two surface waves at the centre of the shot record. A disdvantage of that approach is that there is very little differential NMO between primaries and multiples. For effective multiple rejection, longer offsets are desirable.

Unfortunately, outside of this optimum window, reflections can only be identified at times beyond 0.08s and even then they are badly obscured by coherent noise. The difficulty of obtaining ultra-shallow reflection information with reasonable offset coverage is obvious.

The f-k spectrum of the amplitude corrected record in Figure 2 is depicted in Figure 3. There exists a broad area of linear noise events which lie between a point at k=0, f=0 Hz and extend towards points at k=±0.5 and $f \approx$ 200Hz. Aliasing also occurs as the events wrap around towards approximately k=0, f=400 Hz. These linear events in f-k space represent the coherent noise in the time domain shot record. The wrapping of energy is the result of aliasing due to inadequate spatial sampling along the survey direction. The bulk of the reflection energy is contained at the centre of the plot (around k=0) and is surrounded by the coherent noise.

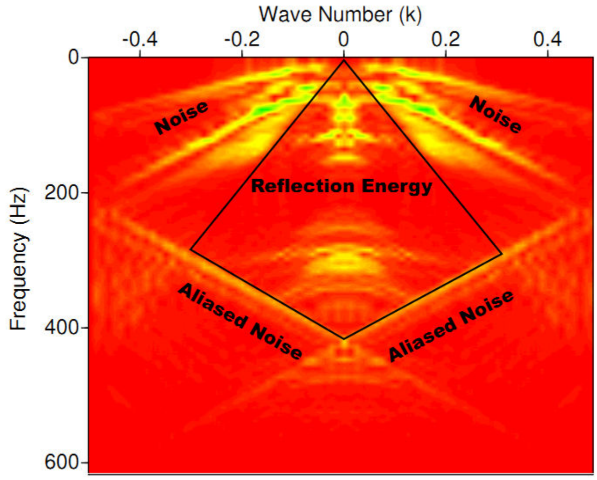

Figure 3. f-k domain representation of the shot record in Figure 2. The polygon defining the edge of the f-k pass band is shown in black.

In this case, although aliasing does occur, it is possible to define a polygonal filter in f-k space which appears to retain most of the reflection energy (marked on Figure 3). Figure 4 shows the field record after application of this f-k space filter. The improvement is dramatic with strong noise attenuation. Offset-coverage is improved, particularly for the deeper events

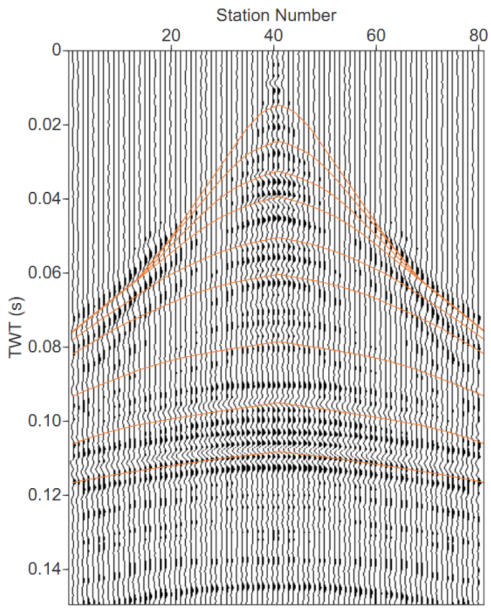

Figure 4. Shot record from Figure 2, f-k filtered using polygon for reflection energy, as defined in Figure 3.

FK ALIASING

The key parameters in f-k transformation are the frequency of the data and the wave number (controlled by the geophone spacing for individual shot records, and the CMP spacing for stacked images).

We now examine the problem of inadequate spatial sampling in more detail. We saw above that even with a geophone spacing of 1m, noise events were aliased, although reflections could be isolated by using a polygonal filter designed to avoid the aliased noise events.

Shallow seismic reflection is often attempted using larger geophone intervals. Consider now an example where only every fourth geophone is used to represent the shot record from Figure 2. This simulates a geophone spacing of 4m. The nyquist wavenumber is dependent on the spatial sampling interval Δx (geophone interval) according to

$$k_{max} = \frac{1}{2\Delta x}$$

The maximum wavenumber is now reduced from 0.5 to 0.125 cycles/m. The new f-k representation is given in Figure 5. Clearly, aliasing is now so severe as to completely obscure the definition of events in f-k space.

The stark differences seen between Figures 3 and 5 are consistent with f-k theory. Consider a particular linear noise even with apparent velocity v . The event is also linear in f-k space, and defined as follows:

$$k - \frac{1}{\lambda} - \frac{f}{v}$$

Hence the maximum frequency that can be recorded without aliasing, which occurs at the nyquist wavenumber (k_{max}), is

$$f_{max} = \frac{v}{2\Delta x}$$

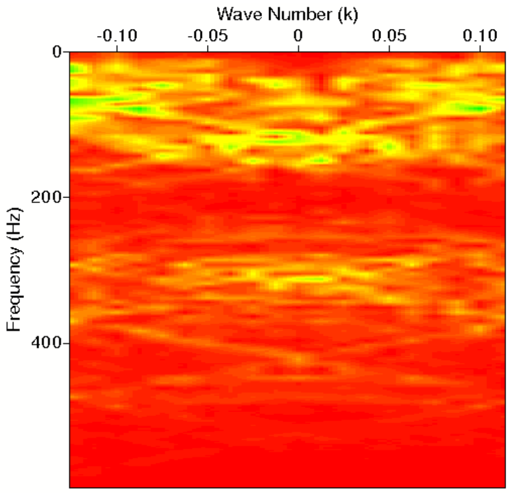

Figure 5, f-k domain representation of shot record in Figure 2, but with 4m geophone spacing.

For the example given above, the strongest noise event has an approximate velocity of 400m/s. The predicted aliasing will occur at 200 Hz for the 1m spacing or 50 Hz for the 4m spacing. This agrees with the modelled results.

This simple modelled example emphasises that in designing production spread parameters for SSR, it is important to consider the likely frequency content of the recorded reflection events, and the minimum velocity of the noise.

Finite-difference modelling over a range of viable near-surface models suggests that, if f-k filtering is to be employed in shallow seismic reflection, it is likely that the geophone interval may often need to be 1m or less.

FIELD EXAMPLE

To further explore the concepts from the synthetic modelling a field trial was carried out at the University of Queensland's farm located in the Pinjarra Hills district west of Brisbane. The survey utilised equipment and expertise from Velseis.

Using local geological knowledge and a visual inspection of the site it was postulated that the survey location would be simple quartenary alluvial cover to a slightly metamorphosed quartzite or shale bedrock. It was expected that the bedrock-overburden interface would provide a practical target reflector somewhere in the depth range of relevance to this study. In light of the modelling results, the geophone interval was restricted to 0.5m. This required the use of a channel count of 240, relatively high for this style of survey. More acquisition details are presented in Table 2.

Parameter	
Acquisition Date	16-9-10
Weather	Windy
Number of Receivers	240
Geophone Spacing	0.5m
Geophone Type	Vertical 30Hz
Spread Length	119.5m
Number of Shots	332
Shot Spacing	1.0m
Sample Interval	1ms

Table 2: Field trial recording parameters.

A typical field record is shown in Figure 6. The event is dominated by coherent noise having low apparent velocities. Possible reflection energy was identified in the field records (far right, 0.1- 0.15s) which modelling suggests may relate to the expected bedrock interface. The processing sequence was very simple and included f-k domain velocity filtering to attenuate the strong coherent noise.

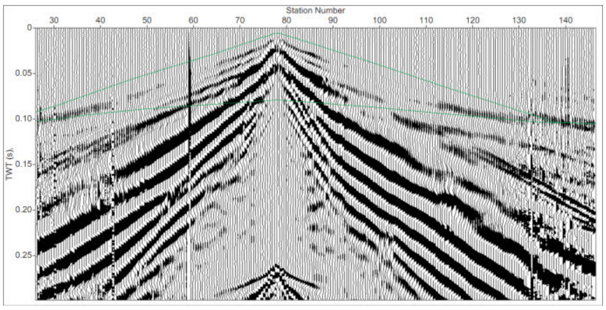

Figure 6, Example field trial shot record with AGC. The horizontal extent is approximately 60m. Vertical extent 0.3s.

Upon being transformed to the f-k domain the field data shows very strong events corresponding to the coherent noise in the record. (Figure 7).

Based on the preceding discussion of f-k representation of linear events, it is relatively simple to identify the corresponding responses in the f-k domain. With reference to the annotations in Figure 7:

A: Airblast waves with a velocity of 330m/s, and dominant frequencies > 100Hz
B: Coherent noise, possibly ground-roll.
C: The aliasing of B, the aliased k zero-crossing would be approximately 160Hz which leaves a 100Hz window to acquire reflection data.

D: Lower frequency, low velocity, high-amplitude surface-wave noise, indicating dispersion(slope changes with frequency).
E: Presumed location of very weak reflection energy.
F: Wind or generator noise of a consistent frequency.
G: 110Hz flat line, possible generator harmonic.

Using the successful methodology of the modelling section, a polygonal filter can be applied in the f-k domain to Zone E where the reflection energy is located.

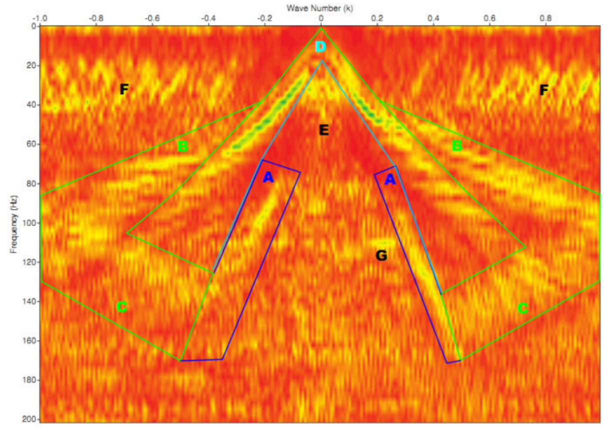

Figure 7, Field trial f-k spectra with AGC for visualisation.

Figure 8 shows a CMP stack with no f-k filtering applied to shot records. When the polygonal f-k filter is applied to shot records, the resultant stack is significantly improved (Figure 9). The well defined reflectors at about 0.02s and 0.08s have been interpreted as geological interfaces at about 2m and 20m depth, by correlation with refraction information. The deeper event incorporates post-critical reflections from relatively long offsets. Phase effects and NMO stretch have reduced the dominant frequency in the CMP stack. This is the subject of current research.

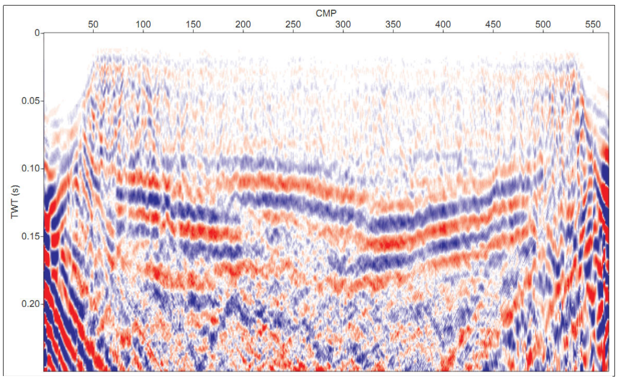

Figure 8, CMP stack from the field trial, with no f-k filtering applied to shot records. Horizontal extent is approximately 140m. Vertical extent is 0.25s.

CONCLUSIONS

Synthetic and field experiments indicate that a small geophone interval is critical for f-k domain filtering of shallow seismic reflection. With an appropriately small interval it is possible to characterise coherent noise events in f-k space. A polygonal f-k filter can then attenuate both unaliased and aliased coherent noise.

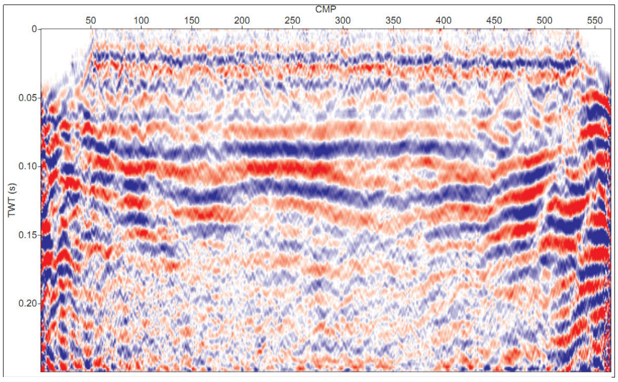

Figure 9, CMP stack from the field trial, with a polygonal f-k filter included in the processing flow.

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REFERENCES

Brabham, P. J., Thomas, J., and Mcdonald, R. J. (2005). The terrestrial shallow seismicreflection technique applied to the characterization and assessment of shallow sedimentary environments. Journal of Engineering Geology, 38:23–38.

Gosar, A. (1998). Seismic reflection surveys of the Krsko basin structure : implicationsfor earthquake hazard at the Krsko nuclear power plant , southeast Slovenia. Journalof Applied Geophysics, 39:131–153.

Hallam, A. R. (2010), Numerical Modelling of Shallow Seismic Reflection. University of Queensland (Thesis)

Hunter, J. A., Gagne, R. M., Pullan, S. E., Burns, R. A., and Good, R. L. (1984). ShortNote Shallow seismic reflection mapping of the overburden-bedrock interface with theengineering seismograph-Some simple techniques. Geophysics, 49(8):1381–1385.

Jeng, Y. (1995). Shallow seismic investigation of a site with poor reflection quality. Geophysics, 60(6):1715.

Miller, R. D. and Steeples, D. W. (1994). Applications of shallow high-resolution seismicreflection to various environmental problems. Journal of Applied Geophysics, 31:65–72.

Robertsson, J., Blanch, J., and Symes, W. (1994). Viscoelastic finite-difference modeling.Geophysics, 59:1444.

Steeples, D. and Miller, R. (1998). Avoiding pitfalls in shallow seismic reflection surveys.Geophysics, 63(4):1213–1224.

Yilmaz, O. (2001). Seismic Data Analysis. Society of Exploration Geophysics, Tulsa, OK, 2nd Edition.