Seismic fault detectability: a view from numerical modelling

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SUMMARY

Modern underground coal mining requires certainty about geological faults and other structural features. Even a fault with a throw of a few metres can create safety issues and lead to costly delays in mine production. In this paper, we investigate the detectability of small faults by the seismic reflection method through numerical modelling in an ideal noise-free environment with homogeneous layering. We find that 1) the smallest faults that can be identified in a 2D survey have throws of 1/8 of the wavelength; 2) faults are more difficult to detect when they occur within other structures.

In typical seismic exploration for coal mining, the dominant seismic frequency is about 100 Hz and the seismic velocity of the overburden ranges from 3000m/s to 4000m/s. The corresponding wavelength is 30m to 40m. This suggests that the detectability limit for faults is about 4 – 5m. However, in the case of 3D seismic surveying we suggest that this can be redefined to 1/16 of wavelength (2 - 2.5m) because of the benefits offered by computer-aided horizon identification and the improved spatial coherence in 3D seismic surveys. In all cases, the actual fault detectability will depend on the quality of the seismic data and the geology of the area under investigation.

Key words: Fault detection, seismic surveying, seismic resolution, coal mining.

INTRODUCTION

The provision of a reliable map of the faulting present is critical in coal mining, especially for longwall coal mining. It reduces the financial and safety risks due to geological uncertainty. To ensure that there are no unwelcome surprises about seam conditions during mining, 3D seismic reflection surveys have been widely accepted by Australian coal mines due to their unprecedented ability to detect small geological structures. While locating faults with throws greater than 5-10 m has been generally accepted for seismic surveys, the ability to resolve the more subtle faults, shears and features which exploration programs should also locate is not well understood. To better understand the issue, we investigate the detectability of small faults through numerical modelling. In addition to dealing with faults associated with general horizontal reflectors, we also study the effects of more complex settings involving dipping reflectors, synclines and anticlines on the detectability of faults.

FAULT DETECTION

Resolution and Small Faults

As investigated by Berkhout (1984), Yilmaz (1987) and Lindesay (1989), the detection of small structures by reflection seismic surveying mainly depends on seismic resolution. For fault detection, faults are recognized on seismic sections by distinct and abrupt changes in the level of a reflecting horizon. Confidence is increased if the discontinuity can be followed across a number of reflecting horizons, a number of nearby lines and if other characteristics such as diffractions are present. Conventionally the limit of the fault resolution on a 2D seismic section is established on the basis of the dominant wavelength, λ, of the reflection event:

$$\lambda = v / f \,, \qquad (1)$$

where v is the velocity and f is the dominant frequency of the seismic wave. The threshold for visual recognition of a change in level is generally taken to be a quarter of the dominant wavelength. For example, if a reflection has a period of 10 ms (100 Hz dominant frequency for typical coal high resolution seismic) and the velocity is 3200 m/s, then a fault with a throw of 8 m ($\lambda/4$) will produce a two-way reflection time displacement of half a period. Across the fault a reflection peak will line up against a trough and should be quite discernable.

To further investigate this criteria, Figure 1 shows a coal seam faulting model with five faults with throws of 32 m, 16 m, 8 m, 4 m and 2 m. In this ideal situation, the changes in the coal seam level are evident even for the smallest fault (throw of $\lambda/16$).

A zero-offset seismic response of the fault model in Figure 1, including diffraction effects, is shown in Figure 2. The modelling program used here is based on reversing the process used in Stolt's (1978) f-k migration algorithm. The source wavelet is a Ricker wavelet with a dominant frequency of 100 Hz and the overburden velocity is 3200 m/s. Diffractions (scattering) from the fault tips and other irregularities now confuse the image. They prolong the seismic events in both the vertical and lateral directions, which are normally related to the Fresnel zone as discussed by Sheriff (1991) and Berkhout (1989). In normal circumstances where CMP stacking is used the diffraction patterns far from the fault tips are stacked out. However, the curvature at the level of the reflections will remain. In such situations, the small fault ($\lambda/16$) on the right side is effectively undetectable as a discontinuity.

It is on the basis of such considerations that, for the visual interpretation of faults on a seismic section, the fault throw should be at least one quarter of the dominant wavelength at the dominant frequency of the seismic reflection (8 m in Figure 2).

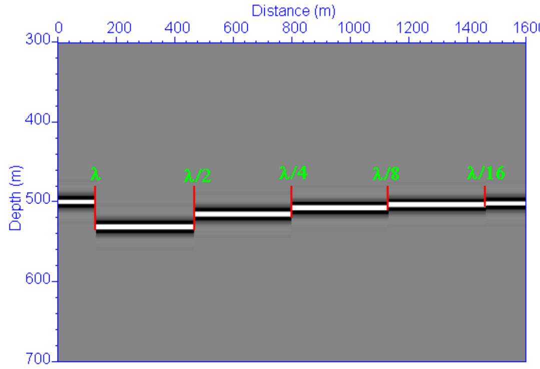

Figure 1 A model with five vertical faults cutting through a coal seam. From left to right the fault throws are 32 m, 16 m, 8 m, 4 m and 2 m. These fault throws correspond to 1, 1/2, 1/4, 1/8 and 1/16 of the dominant wavelength.

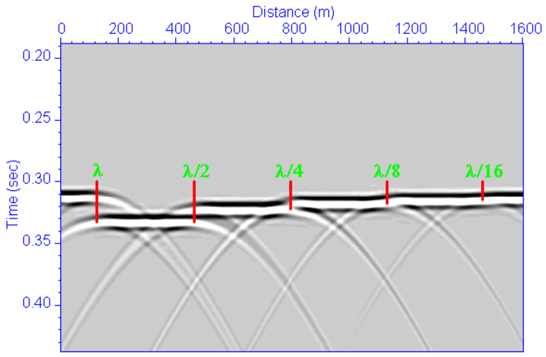

Figure 2 A synthetic zero-offset seismic section from a reflector intersected by the faults shown in Figure 1. The sharp terminations of the faults are smeared by diffractions. The small faults are very difficult to identify visually.

Computer aided interpretation

Such situation can be changed if seismic interpretation is aided by computer as explored by Zhou and Hatherly (2000). Computer aided interpretation has many advantages over manual approaches. By displaying the data at different horizontal and vertical scales, structures become much more evident. High pass filtering of final sections can reveal minor faults. Displays can be tailored to highlight the reflectors of interest.

With computer assistance, it is possible to interactively analyse the results from a grid of seismic data marking the locations of faults and other features on a base map. Accurately picked reflection times from a computer may have sub millisecond accuracy and can reveal subtle changes in reflection times associated with small faults. Figure 3 illustrates the effect of exaggerating the vertical scale and using computer event picking. The time steps at all fault positions are evident even for the fault with a throw of λ/16 (2m). However a more conservative view would be that faults throws of λ/8 (4 m) should be detectable. Furthermore, as demonstrated by Zhou and Hatherly (2000), in the context of the favourable lateral coherency offered by 3D seismic surveying, faults with throws as small as λ/16 (2m) can be identified.

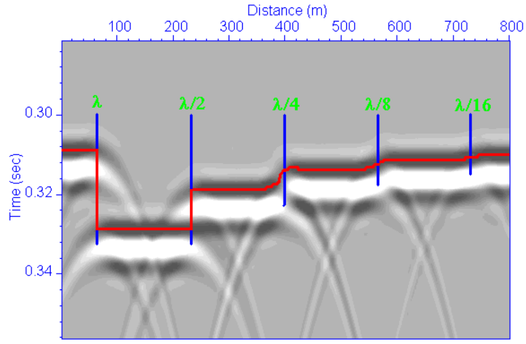

Figure 3 The same data as shown in Figure 2 but vertically exaggerated and with accurate computer-based coal seam picks shown in red. All of the faults can be identified.

Background structures and faults

Dipping reflectors and faults

The previous discussion on fault detectability is based on reflectors that are horizontal. However, with dipping and undulating layers, the implications for vertical and lateral resolutions change. To illustrate this, we first use a model with 5 dipping reflectors which are disrupted by a 5m up-thrown fault (Figure 4(a)) and a 5m down-thrown fault (Figure 5(a)). The corresponding seismic responses are shown in Figure 4(b) and Figure 5(b), respectively. It can be seen in this unmigrated section, that as the dip increases, the fault locations move down-dip. More interestingly, the up-thrown faults are less evident than the down-thrown faults on the seismic section, especially with the increase of the reflector dip.

Syncline, anticline and faults

To further investigate fault expression in relation to background structures, we investigate the syncline model on the left of Figure 6(a). We added faults which were up-thrown (the middle plot of Figure 6 (a)) and down-thrown (the right plot of Figure 6 (a)). The results are presented in Figure 6 (b).

It is evident that apart from a slight shallowing in the syncline, the seismic response of the up-thrown fault is almost identical to the simple syncline model shown on the left of Figure 6 (b). It can therefore be concluded that it would be very difficult, if not impossible, to detect this 5m up-thrown fault. However, the seismic response of the down-thrown fault model is quite pronounced. It can be concluded that as with the faults with throws in the direction of dip, faults in a syncline which amplify the effect of the syncline are more easily detected than faults with throws that oppose the overall structural trend.

The same observations can be made for faulted anticline models.

One way of viewing the overall behaviour that is being exhibited is to regard the background structure as a ‘stack’ of small steps, each with a displacement below the level of resolution (1m in this case) and with a combined effect which maps the structure. The introduction of a small fault will cause just a slight change to that pattern and is undetectable. As its throw increases, the fault will initially appear as a small roll within the overall structure. If such a feature is present on a seismic section, there will be ambiguity about what it represents and additional investigation may be required using other methods.

CONCLUSIONS

In this paper, we have investigated the detectability of small faults by the seismic reflection method through numerical modelling. It is demonstrated that the delineation of faults is strongly dependent on our ability to visually separate reflections laterally and vertically. With computer aided interpretation, the visual fault detection limit with a fault throw of ¼ of seismic wavelength can be reduced to a throw of 1/8 of seismic wavelength for 2D surveys and possibly 1/16 of a wavelength for 3D surveys. In typical coal seismic exploration where the dominant seismic frequency is ~ 100 Hz and the seismic velocity of the overburden is 3000m/s to 4000m/s, this suggests that the smallest faults that can be detected have throws of 4- 5m in the case of 2D surveying and 2-3m with good quality 3D seismic data.

However, these fault detection limits can be complicated by the presence of background structures. Our modelling indicates that faults are more difficult to be detected if their throws oppose the trend of the background structure.

ACKNOWLEDGMENTS

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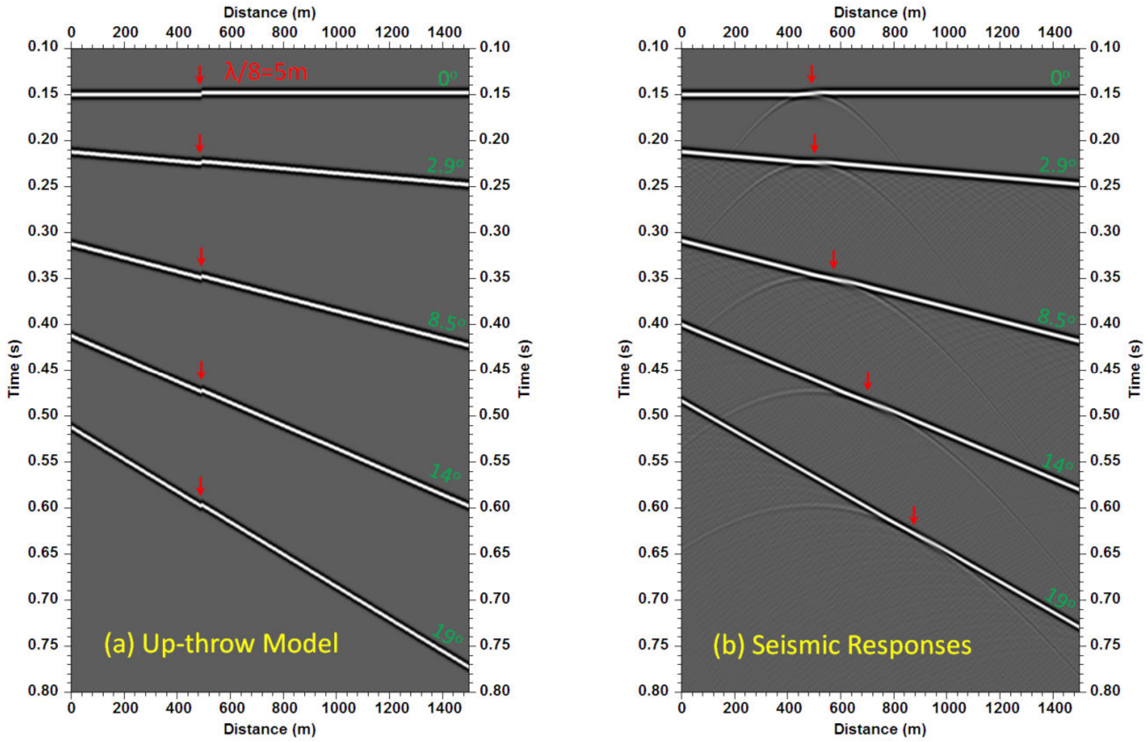

Figure 4 The effect of background structures on fault detection: (a) a 5m up-thrown fault model with dipping reflectors; (b) the seismic responses for the model in (a). A constant average velocity of 4000m/s and a Ricker wavelet with a dominant frequency of 100 Hz were used in the simulation in the F-K domain.

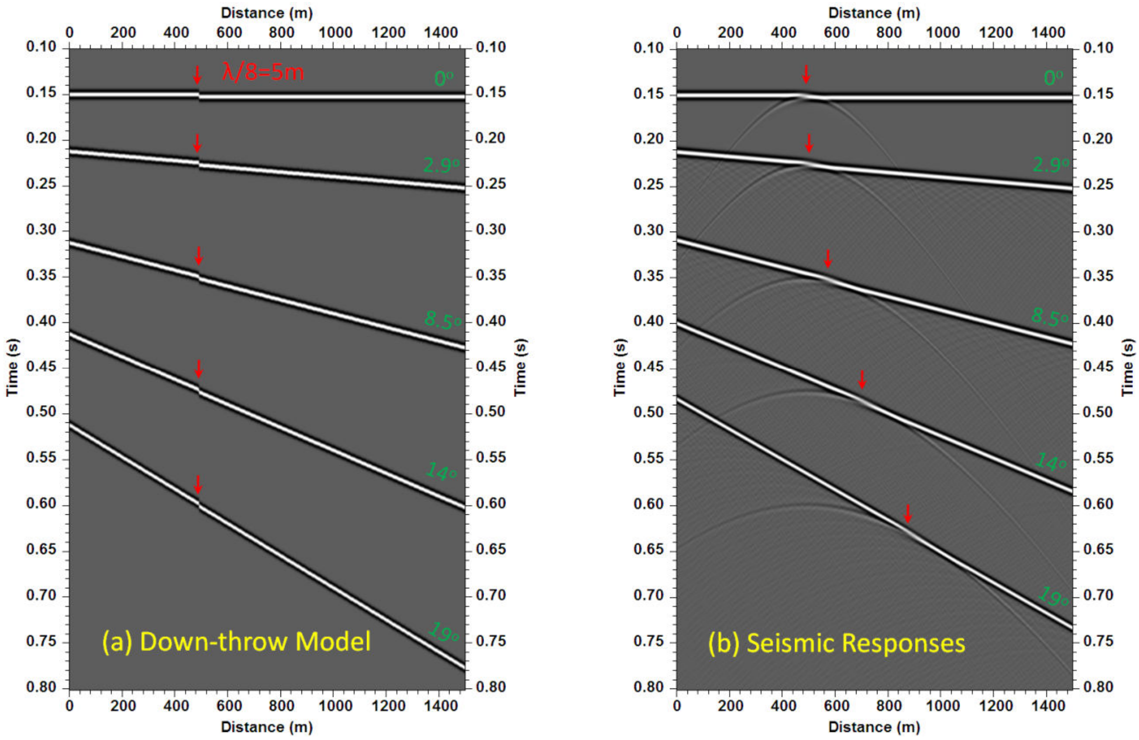

Figure 5 The effect of background structure on fault detection: (a) a 5m down-thrown fault model with dipping reflectors; (b) the seismic responses for the model in (a). A constant average velocity of 4000m/s and a Ricker wavelet with a dominant frequency of 100 Hz were used in the simulation in the F-K domain.

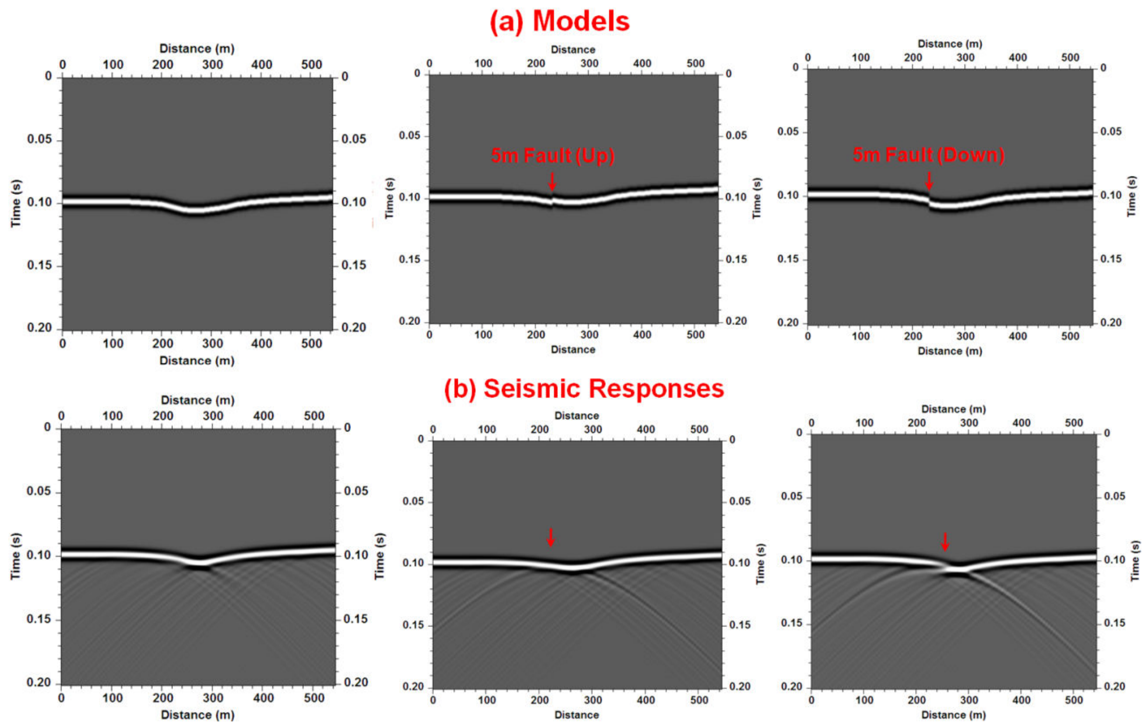

Figure 6 The effect of a syncline on fault detection: (a) fault models (Left: no fault, Middle: syncline with a 5m up-throw fault, and Right: syncline with a 5m down-throw fault); (b) the corresponding seismic responses for the models in (a). A constant average velocity of 4000m/s and a Ricker wavelet with a dominant frequency of 100 Hz were used in the simulation in the F-K domain.