3D curvature analysis of seismic waveform and its interpretational implications

Haihin Di*, Motaz Alfarraj, and Ghassan AlRegib
Center for Energy & Geo Processing (CeGP), Georgia Institute of Technology

Summary

In 3D seismic interpretation, curvature analysis has been widely used for structural delineation and fault detection by quantifying the lateral variation of the geometry of seismic reflectors. However, such geometric curvature is limited to the horizontal plane of a seismic survey and thereby utilizes only partial information of the reflection signals. This study extends the 3D curvature analysis to the seismic waveforms in the vertical planes, here denoted as waveform curvature, and investigates the associated interpretational implications. Applications to the F3 seismic dataset over the Netherlands North Sea demonstrate the added values of the proposed waveform curvature analysis in assisting 3D seismic interpretation in three aspects. First, the signed maximum waveform curvature enhances the vertical resolution of the seismic signals on weak reflector identification and interpretation. Second, the signed minimum waveform curvature is closely related to the least waveform variation (or maximum waveform continuity) parallel to a seismic reflector, and thereby the associated azimuth is indicative of the reflector dip. Third, the capability of the curvature operator in differentiating convex and concave bending makes it possible for the decomposition of a seismic image by the reflector types (peaks, troughs and zero-crossings) to facilitate computer-aided horizon interpretation, such as horizon volume extraction.

Introduction

As one of the most fundamental tools of signal processing, curvature analysis has wide applications in various industries and disciplines, e.g., medical brain scanners, optometry, and terrain analysis. Since its first introduction to the subsurface interpretation and hydrocarbon reservoir characterization (Lisle, 1994), it has been widely used for depicting the surface morphology of rock layers and more importantly highlighting the potential faults and fractures caused by anticlinal bending (e.g., Roberts, 2001). However, the reflector geometry is only partial information offered in a seismic cube, and the reflection amplitude/waveform is also of significant importance for interpreting the seismic signals, such as rock property prediction, quantitative amplitude interpretation, inversion, and modelling (e.g., Widess, 1973).

Considering the capability of the curvature operator in highlighting subtle features and differentiating the concave and convex components of a curve, this study proposes extending the traditional curvature analysis to the waveforms of a seismic dataset, here denoted as waveform curvature, and more importantly investigating the associated implications for assisting seismic interpretation and reservoir characterization. Such analysis is demonstrated through applications to the F3 block over the Netherlands North Sea.

Geometric curvature vs. waveform curvature

Table 1. Comparisons between the traditional geometric curvature and the proposed waveform curvature of reflection seismic signals.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Geometric curvature</th>
<th>Waveform curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>Curvature analysis of seismic signals</td>
<td>Reflection waveform</td>
</tr>
<tr>
<td>b.</td>
<td>Reflection amplitude</td>
<td>Vertical (the x-z and/or y-z plane)</td>
</tr>
<tr>
<td>c.</td>
<td>Fault detection</td>
<td>Waveform analysis:</td>
</tr>
<tr>
<td>d.</td>
<td>Fracture characterization</td>
<td>a. Resolution enhancement</td>
</tr>
<tr>
<td>e.</td>
<td>Reflector morphology</td>
<td>b. Dip estimation</td>
</tr>
<tr>
<td>f.</td>
<td>delineation</td>
<td>c. Reflector isolation</td>
</tr>
</tbody>
</table>

Reflection seismic data is the response of the rock layers when a wave propagates through them, and correspondingly, two sets of information are available at every sample, including its spatial location (inline, crossline, and depth/time) and the intensity of wave reflection (or seismic amplitude) at it. For the convenience of description in this paper, we use $x$, $y$, and $z$ for representing the three dimensions, inline, crossline, and depth/time; and $w$ represents the reflection amplitude. Therefore, there exist three planes for curvature analysis, one horizontal plane ($x$-$y$) and two vertical planes ($x$-$z$ and $y$-$z$). Among them, the curvature analysis in the horizontal $x$-$y$ plane has been well investigated for the purpose of structure interpretation and fault delineation (e.g., Roberts, 2001), and we denote such analysis as geometric curvature, since it quantifies the spatial geometry of seismic reflectors.

In math, however, such 2D/3D curvature analysis could also be performed on the waveforms in the vertical $x$-$z$ and $y$-$z$
3D Waveform curvature analysis

planes, which we denote as waveform curvature in this paper. Table 1 summarizes the comparisons between the traditional geometric curvature analysis and the proposed waveform curvature analysis. To be clear, among various algorithms for computing 2D/3D geometric curvature (e.g., Roberts, 2001; Al-Dossary and Marfurt, 2006; Di and Gao, 2014, 2016), this study adapts the one by Di and Gao (2016) to work for seismic waveforms.

Interpretational implications

For demonstrating the added values of the proposed waveform curvature analysis on seismic interpretation, we use the F3 seismic dataset over the Netherlands North Sea, and Figure 1 displays the post-stack amplitude of the vertical section of crossline 625, in which we notice a set of subparallel reflectors with varying reflection intensity. As listed in Table 1, the proposed waveform curvature analysis could assist seismic interpretation in the following aspects,

- **a. Resolution enhancement**

  In mathematics, the curvature analysis is capable of capturing the subtle features in a signal by computing the second-order derivatives. When turning to a seismic section and/or volume that often contains numbers of traces that are laterally continuous in geology, performing 3D curvature analysis could not only highlight such subtle variation of seismic waveforms, but also take into account the lateral waveform continuity. Therefore, it helps retrieve the seismic signals in a way that is most geologically reliable and accurate. Figure 2 displays the signed maximum curvature of the vertical section, which offers a higher resolution for interpreting the reflectors in this section compared to the original image (Figure 1). We notice that, not only the major reflectors are well delineated without any distortions in their locations, but also it helps recognize more reflectors that are not discernible from the original amplitude due to its limited resolution (denoted by circles). Such enhancement in the seismic resolution could further assist the existing methods/workflows of seismic interpretation, such as horizon/fault picking and edge detection.

- **b. Dip estimation**

  While the signed maximum curvature of a vertical section helps enhance its resolution for more reliable reflector interpretation, the signed minimum curvature is considered most indicative of least waveform variation, or maximum reflector continuity, implying its potential for estimating the dipping angle of seismic reflectors. Figure 3 displays the dip estimates of the vertical section by the proposed curvature analysis, with the positive values for downward dipping (blue) and the negative values for upward dipping (red). By the dip map, we notice all reflectors in the section dip slightly; specifically, the upward dipping dominates in the upper area, whereas the downward dipping dominates in the lower area, indicating the differences in their depositional environment and/or geologic deformation.

**Figure 1:** The vertical section of crossline 625 from the F3 seismic dataset over the Netherlands North Sea for demonstrating the implications of the proposed waveform curvature analysis for seismic interpretation.

**Figure 2:** The waveform curvature of the vertical section of crossline 625. Note the enhanced resolution on the reflectors in the section compared to the original amplitude (Figure 1) (denoted by circles).

**Figure 3:** The reflector dip of the vertical section of crossline 625 by the proposed waveform curvature analysis.
3D Waveform curvature analysis

c. Reflector isolation

Traditionally, reflector interpretation is based on the post-stack amplitude, in which all reflectors are shown in an image. Three major reflector types of interpretational interest are the peaks, troughs and zero-crossings. In practice, reflector interpretation of a seismic dataset often focuses on a certain type, and isolating it from the others could be helpful for computer-aided horizon interpretation without the interference from the surroundings reflectors of no interest. By treating a waveform as a signal of convex and concave components, performing the proposed waveform curvature analysis is capable of differentiating the waveform peaks and troughs with positive curvatures and negative curvatures, respectively. Correspondingly, reflector isolation becomes possible, which decomposes the waveform into two components, with one for the peak reflectors and the other for the trough reflectors. Moreover, with integrating such isolation method with the complex seismic trace analysis (Taner et al., 1979), the zero-crossings could be isolated from the quadrature amplitude in a similar way, including the peak-over-troughs and the trough-over-peaks, often known as s-crossings and z-crossings. Figure 4 displays the reflector isolation from the vertical section, in which all four reflector types are separated into different images for the convenience of horizon interpretation and analysis.

Applications: Horizon volume extraction

A general workflow of horizon volume extraction often consists of three steps: first to select the seeds for all reflectors of interest in the target formation, then to sort and determine the picking order of these reflectors, and finally to perform seeded picking for each horizon with geologic constraints between them. While the latter has been well developed and implemented, the automatic seed selection is the prerequisite and the key to reliable extraction of a horizon volume, and it is often challenging for computers to determine the picking priorities between a series of reflectors, especially in the area of geologic complexities (Yu et al., 2011; Wu and Hale, 2015). Such limitation could be resolved with the assistance of the proposed waveform curvature analysis. Take the peak reflectors for example.

Figure 4: The isolation of the reflectors in the vertical section of crossline 625 by the proposed waveform curvature analysis, including peaks (a), troughs (b), s-crossings (c), and z-crossings (d).

Figure 5: The seed selection for extracting the volume of peak reflectors in the vertical section of crossline 625, based on the proposed waveform curvature. First, the isolated peaks are thinned to be one-pixel thick by local peak detection, and then these peaks are sorted and the seeds are picked at the samples of high magnitude (denoted by dots). Considering the correlation between strong amplitude and high curvature, the magnitude could help determine the priorities for picking these reflectors (denoted by dot size).

Figure 6: The horizon cube extracted from the F3 seismic dataset in 3D chair view.
3D Waveform curvature analysis

Figure 7: The horizon cube clipped to the vertical section of crossline 625 with peaks in solid curves and troughs in dotted curves. Note the good match between the pickings and the seismic image.

(Figure 4a). First, the isolated reflectors are thinned to be one-pixel-thick by local peak detection (Figure 5). Then, for a given trace, the computer retrieves all samples with curvature magnitude larger than a defined threshold, with one seed for each reflector. Finally, these seeds are sorted by their curvature magnitude from high to low (denoted by dot size), and a seed with the largest magnitude is given the highest picking priority. Based on the estimated reflector dip (Figure 3), performing horizon picking on the sorted seeds leads to a volume of all peak horizons.

Figure 6 displays the horizon cube extracted from the F3 dataset, and all pickings are then clipped to the vertical section of crossline 625 for quality control (Figure 7), with peaks in solid curves and troughs in dotted curves. We notice good matches between the picked horizons and the original seismic images, indicating the potential of the proposed waveform curvature analysis in assisting the extraction of a horizon volume from seismic data.

Conclusions

This study has extended the traditional geometric curvature analysis to the waveforms of a seismic volume and investigated its implications for assisting seismic interpretation. In general, among all possible waveform curvatures, the signed maximum one provides an enhanced vertical resolution, from which the weak reflectors are better delineated and become more recognizable for interpretation. The signed minimum waveform curvature provides an analytical approach for finding the orientation of least waveform variation (or maximum reflector continuity), which leads to an innovative method for reflector dip estimate. Moreover, integrating the proposed waveform curvature analysis with the complex seismic trace analysis makes it possible for the isolation of the reflectors into four major groups (peaks, troughs, s-crossings, and z-crossings), which could further facilitate the computer-aided reflector interpretation in various aspects, such as automatic seed selection and sorting for horizon volume extraction.

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REFERENCES


