The behavior of least-squares extended reverse time migration for vertical seismic profiling data

Jizhong Yang1*, Jingjing Zong2, Arthur Cheng2, and Yunyue Elita Li2

1Tongji University, State Key Laboratory of Marine Geology, Shanghai 200092, China.
2National University of Singapore, Department of Civil and Environmental Engineering, Singapore 119077.

SUMMARY

Vertical seismic profiling (VSP) survey differentiates itself from surface seismic survey by deploying receivers inside the borehole, while the sources are excited on the surface. Due to this distinctive acquisition geometry, special attentions should be paid in processing and imaging the VSP data. Considering the fact that velocity errors are inevitable for field data application, it is better to utilize least-squares reverse time migration with subsurface offset extension (LSERTM) because of its good property of preserving data information in the extended domain. LSERTM has been actively studied for surface seismic data in academic research, but it is never reported with application to VSP data. We fill this gap by applying LSERTM to VSP data with a simple layered model, and analyze the behavior of the subsurface offset common image gathers (SOCIGs) and the angle domain common image gathers (ADCIGs). Numerical examples demonstrate that there are significant differences in the behavior of SOCIGs and ADCIGs for the surface seismic survey and the VSP survey. We conclude that the strategies functioning well in surface seismic processing workflow may not be suitable for direct application to VSP data.

INTRODUCTION

VSP surveys are arousing more and more interests recently as effective complements to surface seismic acquisition geometries (Lanzarone et al., 2019; van Gestel et al., 2019). In a VSP survey, the receivers are deployed inside the borehole and are much closer to the targets to be imaged. Such a shortened wavepath reduces energy loss during wave propagation. Hence, higher resolution images are expected from the VSP data than those from the surface seismic data.

For practical implementation, imaging algorithms developed for processing surface seismic data are often applied to VSP data directly. This is a good choice when the migration velocity model is well optimized. However, uncertainties in velocity model building are inevitable for field data application (Glogovsky et al., 2009). In particular, Blias and Hughes (2015) point out that VSP data are more sensitive to velocity errors than surface seismic data.

LSERTM has been widely studied for the surface seismic data, with the well-known property that the kinematic data information could be fully preserved in the extended domain (Liu et al., 2013; Hou and Symes, 2016; Li and Demanet, 2017; Yang et al., 2019). A general observation is that when the migration velocity is accurate, the energies in the SOCIGs are focused at the zero subsurface offset; when the migration velocity is inaccurate, curvatures will occur in the SOCIGs. These curvatures are useful information for migration velocity analysis in the framework of differential semblance optimization (Liu et al., 2014; Soubaras and Gratacos, 2017).

To the best of our knowledge, LSERTM has not been reported in the literature to process VSP data. One possible reason may be that there is really no difference in terms of algorithm development and practical implementation strategies.

As a proof of concept, we apply LSERTM to the VSP data using a simple layered model. We analyze the behavior of the SOCIGs in both cases when migration velocity is accurate or not. The SOCIGs are then transformed into ADCIGs through slant stack (Sava and Fomel, 2003). For comparison, we also apply LSERTM to the same layered model with a surface acquisition geometry. Numerical examples demonstrate that there are significant differences in the behavior of SOCIGs and ADCIGs for the surface seismic survey and the VSP survey. These differences indicate that we may need to develop new strategies for utilizing the SOCIGs and ADCIGs for subsequent velocity model building and image enhancement when processing VSP data.

METHODOLOGY

Seismic migration with subsurface offset extension can be formulated as (Symes, 2008):

\[ m_{\text{mig}}(x, h) = \int d\mathbf{x}_r d\mathbf{x}_s dt \frac{d^2}{d\tau^2} f_s(t) G(x - h, \mathbf{x}_s, \tau) \]

\[ G(x + h, \mathbf{x}_r, \tau - \tau) d(\mathbf{x}_s, \mathbf{x}_r, t), \quad (1) \]

where \( G(x, \mathbf{x}_s, \tau) \) and \( G(x, \mathbf{x}_r, \tau) \) are the Green’s functions from the source location \( \mathbf{x}_s \) and the receiver location \( \mathbf{x}_r \) to the subsurface location \( \mathbf{x}_s \) respectively. \( f_s(t) \) denotes the source wavelet function, \( \tau \) is the migration time, and \( h \) stands for the half offset between the source and receiver (Claerbout, 1985). Equation 1 is commonly referred to as extended RTM (ERTM).

The extended forward Born modeling is the adjoint of the extended migration in equation 1:

\[ u(x_s, \mathbf{x}_r, t) = \int d\mathbf{x}_r d\mathbf{x}_s dt \frac{d^2}{d\tau^2} f_s(t) G(x - h, \mathbf{x}_s, \tau) \]

\[ G(x + h, \mathbf{x}_r, \tau - \tau) m_{\text{mig}}(\mathbf{x}, h). \quad (2) \]

LSERTM is generally formulated in a least-squares sense by minimizing the difference between the modeled data \( u(x_s, \mathbf{x}_r, t) \) and the observed data \( d(\mathbf{x}_s, \mathbf{x}_r, t) \):

\[ \min_{\mathbf{m}(\mathbf{x}, h)} f(\mathbf{m}(\mathbf{x}, h)) = \frac{1}{2} \int d\mathbf{x}_r d\mathbf{x}_s dt \| u(x_s, \mathbf{x}_r, t) - d(\mathbf{x}_s, \mathbf{x}_r, t) \|^2. \quad (3) \]
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It is worth mentioning that equations 1 to 3 are the same for both the surface seismic survey and the VSP survey. However, it is not necessary that the behavior of the SOCIGs or the ADCIGs from LSERTM are the same for these two surveys.

NUMERICAL EXAMPLES

We apply LSERTM to both surface seismic and VSP survey with a simple layered model (Figure 1). It has four horizontal reflectors, and the velocity perturbation at the reflection interfaces is 150 m/s. The homogeneous background velocity is 3000 m/s. The model dimensions are of 401 × 151, with 10 m grid intervals. There are 77 shots evenly spaced at 50 m shot intervals excited on the surface. For the surface seismic survey, there are 401 receivers evenly distributed at 10 m receiver spacing on the surface. For the VSP survey, each shot is recorded with 81 receivers at distance $x = 2000$ m from $z = 200$ m to $z = 1000$ m in depth, with receiver spacing of 10 m. The source time function is a Ricker wavelet, with a peak frequency of 20 Hz. The recording length is 2.0 s, with a time interval of 1 ms.

Figure 1: The true simple layered model for LSERTM.

We first implement LSERTM with an accurate homogeneous migration velocity model ($v = 3000$ m/s). The subsurface offset range is [-100 m, 100 m], with an subsurface offset interval of 10 m.

Figure 2a shows the LSERTM image at $h = 0$, the SOCIGs at $x = 1800$ m and $z = 800$ m in the front panel, the right panel, and the top panel, respectively, for the surface seismic survey. Since the migration velocity is accurate, the energies in the SOCIGs are focused at $h = 0$. The corresponding ADCIGs are shown in Figure 3a, in which the events are flat with both positive and negative angles.

In Figure 4a, the front panel shows the LSERTM image at $h = 0$ for the VSP survey. The illumination areas are much narrower than the surface seismic survey. The right panel shows the SOCIGs at $x = 1800$ m, whereas the imaging points are on the left hand side of the receiver line. Although the migration velocity is accurate, the energies in the SOCIGs spread along a line with slope. The ADCIGs from such SOCIGs are shown in Figure 5a. The events are flat, meaning that the migration velocity is accurate or not.

Figure 2: The images from LSERTM with (a) accurate and (b) inaccurate migration velocity models for the surface seismic acquisition geometry. The front panel shows the migration image at $h = 0$. The right and top panels show the SOCIGs at $x = 1800$ m and $z = 800$ m, respectively. When the migration velocity is accurate, the energies in the SOCIGs are focused at $h = 0$. When the migration velocity is slower, the SOCIGs show a downward curvature.

Figure 3: The ADCIGs transformed from SOCIGs in Figure 2 using slant stack. The ADCIGs are flat when the migration velocity is accurate, and they are curved up when the migration velocity is slower.

Figure 4: The images from LSERTM with accurate (top row) and inaccurate (bottom row) migration velocity models for the VSP survey. The front panel shows the migration image at $h = 0$. The top panel shows the SOCIGs at $z = 800$ m. In the left column, the right panel shows the SOCIGs at $x = 1800$ m. In the right column, the right panel shows the SOCIGs at $x = 2200$ m. The SOCIGs have a slope no matter the migration velocity is accurate or not.
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Figure 5: The ADCIGs transformed from SOClGs in Figure 4 using slant stack. When the image points are on the left hand side of the receiver line, the ADCIGs only contain positive angles. When the image points are on the right hand side of the receiver line, the ADCIGs only contain negative angles.

velocity is accurate. In contrast to Figure 3a, only positive angles are present. The subsurface image points are not fairly illuminated from top to the bottom.

In Figure 4b, the right panel shows the SOClGs at $x = 2200$ m, whereas the image points are on the right hand side of the receiver line. The energies in the SOClGs are still distributed along a tilted line, but the slope is different from that in Figure 4a. The resulting ADCIGs in Figure 5b only contain negative angles.

We then implement LSERTM with an inaccurate homogeneous migration velocity model ($v = 2700$ m/s). The velocity errors are 10%. The subsurface offset range is $[-400$ m, $400$ m], with an subsurface offset interval of 10 m.

Figure 2b shows the LSERTM result for the surface seismic survey. The front panel shows the LSERTM image at $h = 0$. The horizontal reflectors are pulled up due the slower migration velocity model. The front panel shows the SOClGs at $x = 1800$ m. A downward curvature appears because of the slower migration velocity. The corresponding ADCIGs are shown in Figure 3b, with curved up events. Both positive and negative angles are present.

Figures 4c and 4d show the LSERTM results for the VSP survey. The front panels show the LSERTM image at $h = 0$. The reflectors become tilted. This indicates that VSP data are more sensitive to velocity errors, which is consistent with (Blais and Hughes, 2015). The right panel in Figure 4c shows the SOClGs at $x = 1800$ m, and the the right panel in Figure 4d shows the SOClGs at $x = 2200$ m. The energies in the SOClGs are distributed along tilted lines. If following the experience from the surface seismic survey, as shown in Figure 3b, we cannot tell whether the migration velocity is faster or slower.

The ADCIGs related with Figures 4c and 4d are shown in Figure 5c and 5d, respectively. The events are curved up, indicating that the migration velocity is slower. Similar to the ADCIGs in Figures 5a and 5b, when the image points are on the left hand side of the receiver line, only positive angles show up; when the image points are on the right hand side of the receiver line, only negative angles show up.

The above examples show clear evidences that the behavior of SOClGs and ADCIGs from LSERTM for VSP data are significantly different from those for surface seismic data. To show the influence of these differences on subsequent work for image enhancement, we adopt the strategy we have proposed previously (Yang et al., 2019) as an illustration.

The subsurface offset images are stacked within the half wavelength limit, and the corresponding results are shown in Figure 6. For the surface seismic survey, the image quality is improved after stacking compared to the images at $h = 0$ shown in Figure 2. For the VSP survey, however, the image quality degrades after stacking. The degradation results from the fact that the reflection angles are not continuously distributed for this particular acquisition configuration. In addition, 10% velocity errors may be too large for imaging the VSP data.

CONCLUSIONS

We have applied LSERTM to VSP data. LSERTM maintains its merit of preserving data information. We note that the behavior of the SOClGs, as well as the ADCIGs, has significant differences compared to those from LSERTM with surface seismic data. These significant differences remind us that we may need different strategies to utilize SOClGs or ADCIGs for velocity model building and image enhancement in VSP surveys. The numerical experiences from surface seismic data may not be applied straightforwardly.

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Figure 6: The final images after stacking the subsurface offset images within the half wavelength limit. The top row shows the images from surface seismic survey, and the bottom row shows the images from VSP survey. The left column shows the images with accurate migration velocity model, and the right column shows the images with inaccurate migration velocity model.
REFERENCES