Assessment of the detectability of localized strong attenuation zones through finite-difference waveform modelling

Hongyuan Zhou[1], Olga Kovaleva[1], Sheng Ye[1], Dong Shi[2], Qi Zhao[1], Giovanni Grasselli[1]

[1]Department of Civil Engineering, University of Toronto

[2]Department of Earth Sciences, University of Toronto

Summary

Finite difference forward modelling was used to address the detectability of a local strong attenuation zone. Velocity and density structure of the model was based on the *Athabasca Basin geophysical borehole log*. Attenuation was represented using quality factor Q, and introduced to the model as four different configurations; no attenuation, layered attenuation, constant attenuation, and localized attenuation. An explosive source generating Ricker wavelet with dominant frequency of 60Hz, and horizontal and vertical lines of receivers were applied to the models to represent seismic surveys. Simulation results showing wave propagations and seismic traces of different models were assessed and compared.

Introduction

Seismological research methods have traditionally been of special interest to subsurface investigations due to their capability to provide detailed information about earth internal structures. One particular interest is their ability to capture seismic patterns that correspond to local structures. In practice, before direct application of seismic survey, numerical simulations are carried out. Forward modelling of seismic response allows for assessing the feasibility and usefulness of performing seismic survey. Results obtained from numerical modelling aid to plan data acquisition and are as well of high importance for the analysis of actual seismic signals (Anderson et al., 1995).

This study focuses on the detectability of localized strong attenuation zones using forward modelling of 2D wave propagation in transversely isotropic media. Localized strong attenuation zones can indicate non-profitable gas zones encountered in drilling of wellbores. These zones can pose hazards throughout the life time of the well. The encountered gas zones can either destabilize drilling causing borehole blowout or leak through external causing. Borehole blowout has direct impact on the drilling project, increasing costs as a result of loss of well or environmental remediation, and pose health hazards. The slow leakage of gas overtime can breach through isolated geological formations through the path of the wellbore contaminating the atmosphere, ground surface, and groundwater (Dusseault, 2014). Therefore, the detection of such zones has significance in risk assessment and mitigation.

Modelling of 2D wave propagation is done using finite difference (FD) approach in SOFI2D (Seismic mOdelling with FInite differences 2D) (Bohlen, 2002). The implemented model uses the *Athabasca Basin borehole geophysical measurements* done by Mwenifumba et al. (2004) for simulation of seismic signal, induced by close-to-surface explosive source at 60Hz, recorded by a sequence of receivers. The findings of this study have far-reaching implications on exploration seismology and risk assessment and mitigation of drilling projects.

The localized gas zones are characterized with extremely high seismic pulse attenuation due to their viscous material properties (Walls et al., 2005). The strength of attenuation is represented $1/Q$:

$$\frac{1}{Q} = \frac{\Delta E}{2\pi E}$$

Where Q is a dimensionless quantity called the quality factor (Shearer, 1999). $1/Q$ can be interpreted as energy loss per cycle. Having large Q values lead to low attenuation and vice-versa. Three other models with different attenuations are also studied: no attenuation, attenuation representative of the geological layers in the Basin, and constant attenuation throughout the model.

Theory and Method

The FD model had a length of 1000 meters (m) in the horizontal x direction and a depth of 500m in the vertical y direction with 1m grid spacing. A free-surface boundary condition was applied at the top of the model and absorbing boundaries 30m in width were added to the sides and bottom of the model. An explosive source generating Ricker wavelets with dominant frequency of 60 Hertz (Hz) was placed at (x=35 meters [m], y=10m), and seismic wavefield was recorded by two types of receiver geometries (horizontal and borehole). The horizontal line of receivers (surface) had a spacing of 10m with the first receiver located at (40m,10m) and the last receiver at (960m,10m). Borehole receivers started at (960m,10m) and end at (960m, 400m) with a spacing of 5m (Figure 1).

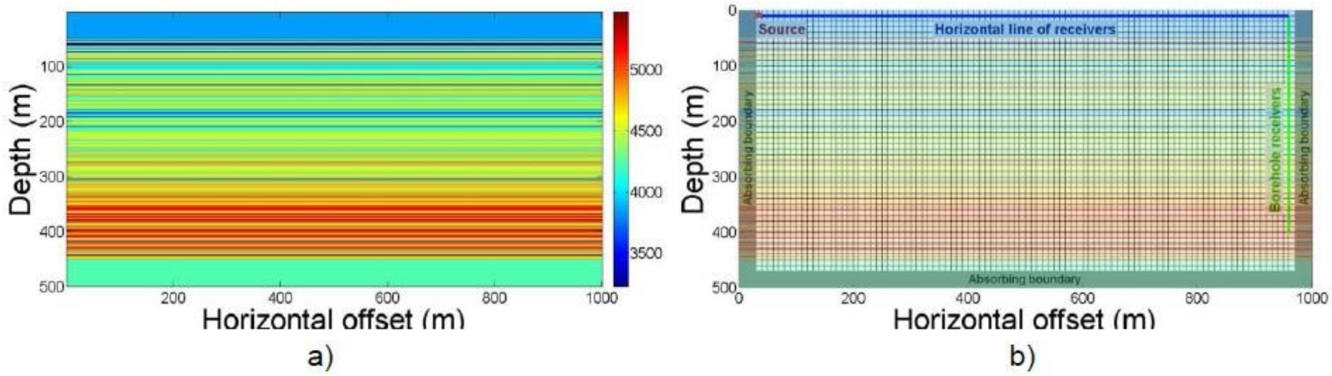

Figure 1 a) Athabasca velocity structure (m/s); b) model geometry

A total of four *Q* configurations were studied (Figure 2); 1) no attenuation; 2) layered attenuation (*Qp* = 0.01 of P velocity); 3) constant attenuation (*Qp* = 60); and 4) localized attenuation (*Qp* = 5 with background *Qp* = 60). *Qp* represents P-wave attenuation, and *Qs* represents S-wave attenuation where *Qs* = 0.8*Qp*.

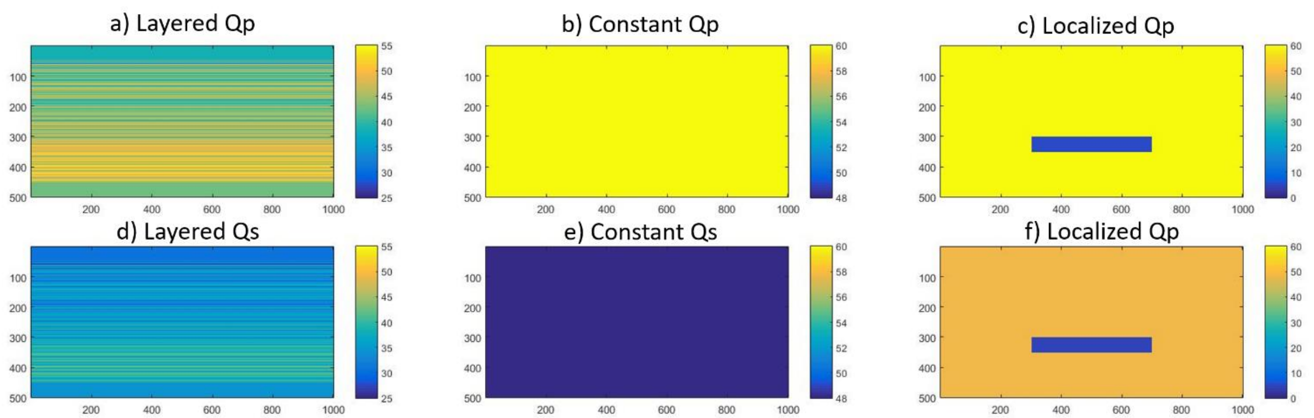

Figure 2 *Q* configurations

Examples

Propagation of seismic wave from the source through the localized strong attenuated zone is illustrated in Figure 3 showing the x component of the wave field at different times. Surface wavefront, P-wavefront, and S-wavefront are captured in the snapshots.

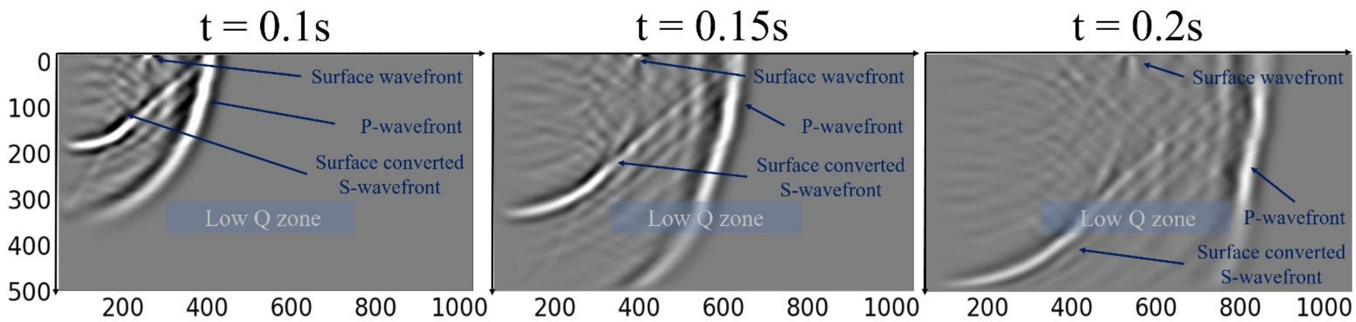

Figure 3 Snapshots for x component wavefield in localized attenuation model

Comparison of models with different attenuations reveal the drastically decreasing amplitude (Figure 4). The constant attenuation model and layered attenuation model shares similar results, indicating that layers are not thick enough to be detected by the source with 60Hz frequency. Nevertheless, decrease in amplitude is quite pronounced in the localized model given its very low *Q* (enclosed in red).

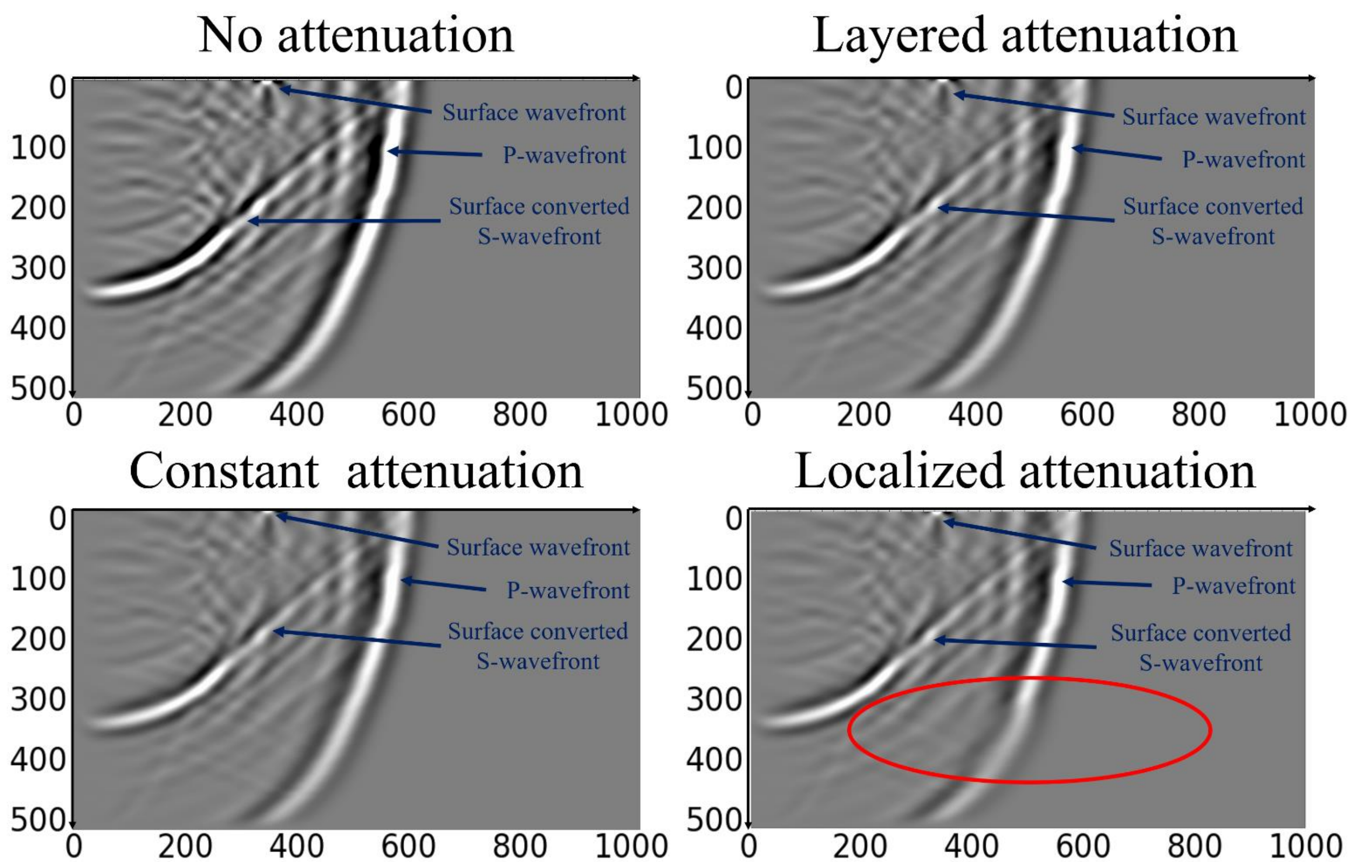

Figure 4 Snapshots of wavefield of different Q structures at t = 0.15s

Spectral analysis of no attenuation, layered attentuation, and localized attenuation models are carried out to study the phase distortion induced by the applied attenuations (Figure 5). Three synthetic seismic recordings from the horizontal line of receivers are used. Since *Q* can be interpreted as energy loss per cycle, given that velocity is an intrinsic property of the medium, higher frequencies are attenuated more per unit time. Therefore, in the amplitude spectra, there should be an observable decrease in amplitude at higher frequencies in the models with higher applied attenuation. The spectral analysis conforms to this trend.

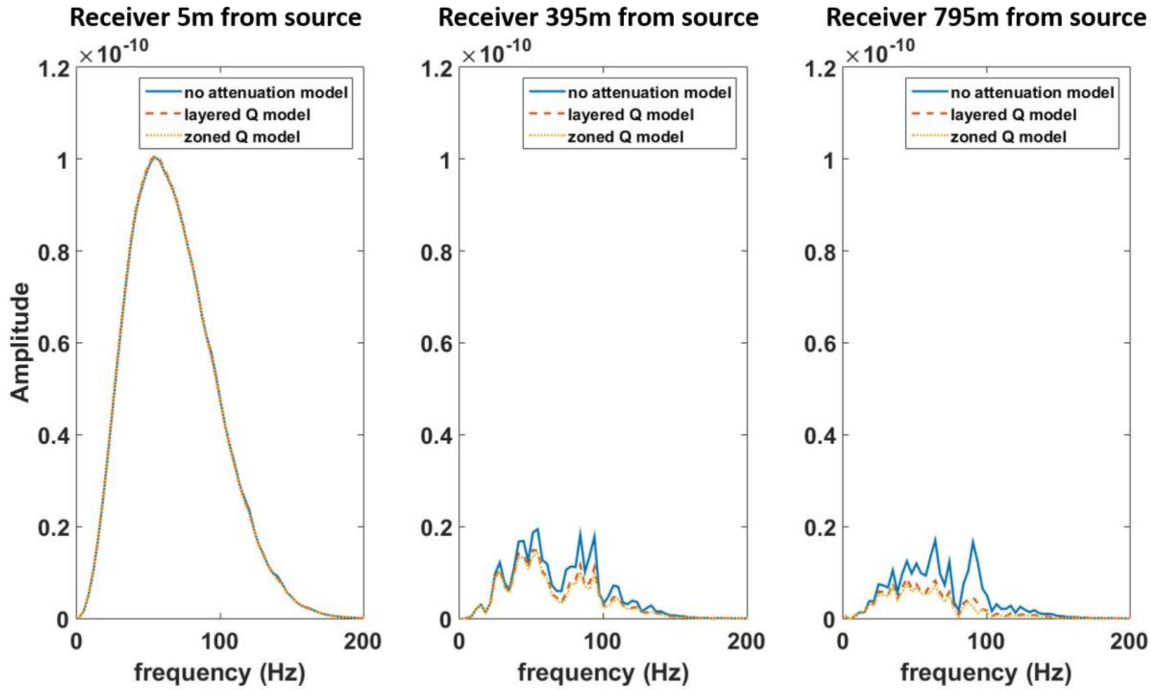

Figure 5 Amplitude spectra of different *Q* configurations at various receiver locations

Conclusions

Different *Q* configurations are applied and wave propagation are simulated using SOFI2D. The local strong attenuation zone is visuallized in wavefield snapshots (refer to Figure 4). Differences between attenuation configurations in the amplitude spectra are also observed. However in the field, seismic traces obtained reflect the subsurface which is unknown or mostly unknown, and there are no baseline models to compare to (like the no attenuation model). Potential baseline model might be established using velocity and density profile of the borehole for borehole receivers. However, depending on the source and receiver locations, different degrees of uncertainty in the profile exist. Therefore, the frequency domain analysis comparison similar to what is done in this study can be highly unreliable. Based on the results of this study and considering limits in the field, for the specific source-receiver-anomaly geometry and model setup studied, detectability of a localized strong attenuation zones is virtually inachievable. We recognize this study is limited in considering source type, frequency, source and receiver locations, Q and velocity structures, and local anomalous zone's geometry and position. Future work considering the above mentioned limitations may provide a more conclusive understanding on the detectability of such zones.

References

Anderson, Neil L., Dennis E. Hedke, and Ralph W. Knapp. "Forward Seismic Modeling-Applications and Utility." *Bulletin-Kansas Geological Survey* (1995): 28-33.

Bohlen, T. (2002). Parallel 3-D viscoelastic finite difference seismic modelling. Computers & Geosciences, 28(8), 887-899.

Dusseault, M. (2014). Energy Well Integrity. Nova Scotia Hydraulic Fracturing Independent Review and Public Engagement Process.

Mwenifumbo, C. J., Elliott, B. E., Jefferson, C. W., Bernius, G. R. Pflug, K. A. (2004). Physical rock properties from the Athabasca Group: designing geophysical exploration models for unconformity uranium deposits. Journal of Applied Geophysics 55, 117-135.

Shearer, P. M. (2009): Introduction to seismology. 2nd ed. Cambridge: Cambridge University Press.