Seismic Imaging Methods for Description of Abandoned Mines

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Abstract

- The cavity is commonly filled with some materials to avoid the problems caused by the abandoned mines.
  - ➢ It is necessary to monitor the distribution of materials during or after filling.
- In this study, we apply the seismic method to image the distribution of the filling materials in the near-surface abandoned mines.
  - ➢ We apply full waveform inversion (FWI) and reverse time migration (RTM) to four models that can mainly appear in the abandoned mines.
  - ➢ We also apply RTM to the data redatumed by seismic interferometry.
- Through numerical examples, we investigate the feasibility of the seismic methods for describing the filling material distribution in the abandoned mine.

Introduction

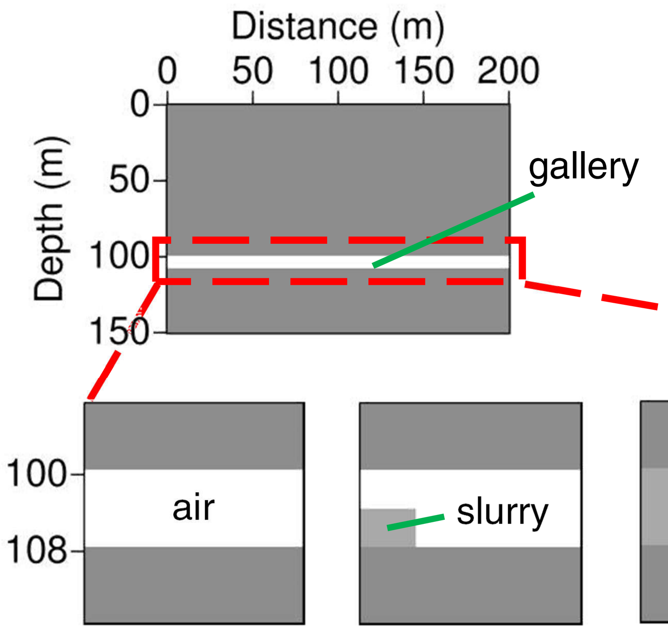
- Abandoned mines can cause serious problems such as subsidence, ground failure, and water pollution.
  - ➢ Therefore, post-treatment, such as preventing leachate and filling with specific substances, has been conducted.
- However, as time goes by, such treatment may not work well, and for some old mines, post-treatment was not even done.
  - ➢ Therefore, it is important to monitor abandoned mines to avoid dangerous situations.
- Various geophysical methods have been selectively applied depending on the environment of the abandoned mines.
  - − Microgravity can be applied for large-sized cavity detection.
    - ➢ However, it is not appropriate to detect relatively small void and cannot be applied to evaluate material distribution in the abandoned mine.
  - − Electrical resistivity and ground penetrating radar (GPR) surveys can be quickly conducted and their imaging processes are relatively simple.
    - ➢ However, they may be appropriate for shallow mines. Also, GPR may not be applied when the topmost sediment is clayey and wet.
  - − Microseismic and seismic methods have been used not only for the prediction of geological structures but also for the stability investigations (Dérobert and Abraham 2000; Luo et al. 2001; Cheng et al. 2014; Kotyrba and Schmidt, 2014).

❖ **The main objective of this study is**

- ➢ to investigate the feasibility of the seismic method for describing the distribution of the filling material during- and post-treatment.

Model & Method

- We assume that the abandoned mine model consists of one-layer gallery at a depth of 100 m, whose dimension is 8 m × 8 m × 200 m (Fig. 1).
- We consider the most common filling method that uses cement slurry, i.e., a mixture of cement, water, and waste.



Material	Vp (km/s)	ρ (g/cm³)
air	0.34	0.1
slurry	2.0	1.5
medium	2.5	2.13

Fig. 1: (Top) The abandoned mine model with (bottom) different distributions of the cement slurry in the gallery.

- To describe material properties, we apply acoustic FWI and RTM to the observed data.
- To enhance signals, we generate redatumed data by applying correlation-type interferometry. RTM is also applied to the redatumed data.

❖ **FWI**

- FWI estimates subsurface material properties by minimizing the objective function built from the residuals between observed and modeled seismic waveforms.
- In the frequency domain, the objective function is defined with the L_2-norm as follows:

$$E(m) = \sum_{\omega} \sum_{s} \frac{1}{2}\left[(\tilde{u} - \tilde{d})^T (\tilde{u} - \tilde{d})^*\right]$$

where m: model parameter vector

$\tilde{u}$ and $\tilde{d}$: modeled and observed data

- The model parameter can be updated by using Hessian matrix H^{-1}.

$$m^{n+1} = m^n - \sum_{\omega} H^{-1} \nabla_m E$$

- In order to reduce computational cost, we used the pseudo-Hessian matrix

$$H^p = (F^v)^T (F^v)^*$$

where F^V: virtual source vector

❖ **RTM**

- In the RTM method, the imaging section is calculated by cross-correlation between source wavefield and receiver wavefield.
- The source wavefield (U_s) is the result of modeling assuming a real source; the receiver wavefield (R_s) is the result obtained by reverse time propagating the recorded data at the receiver. It is expressed as

$$I(x, z) = \sum_s \sum_t U_s(x, z, t) R_s(x, z, t)$$

❖ **Correlation-type interferometry**

- Crosscorrelation cancels the common raypath when the ray passes the stationary point.
  - ➢ Therefore, we can redatum source and receiver locations by reconstructing the events with shorter traveltimes for the redatumed sources and receivers.

Numerical tests

❖ **Receiver at the surface**

- For the source-receiver geometry, we first consider the surface seismic profile.
- We assume that sources are applied at the surface.

- **Fig. 2 shows**:
  - ➢ Material distribution can be distinguished when the material touches the ceiling.
  - ➢ However, if the material does not reach the ceiling, it is difficult to confirm the distribution of the material.
  - ➢ Because of the small velocity and density of the air, most of the energy is reflected from the ceiling and thus the energy propagating downward (into the tunnel) is very small.
  - ➢ FWI updates the model parameter by minimizing the objective function (residual of the waveform).
  - ➢ Thus, the events that have more energy, such as the reflections from the ceiling, have more influence on the results than those with less energy (such as the reflections from the floor).

❖ **Thus, when the air is present, the properties obtained by FWI are not accurate.**

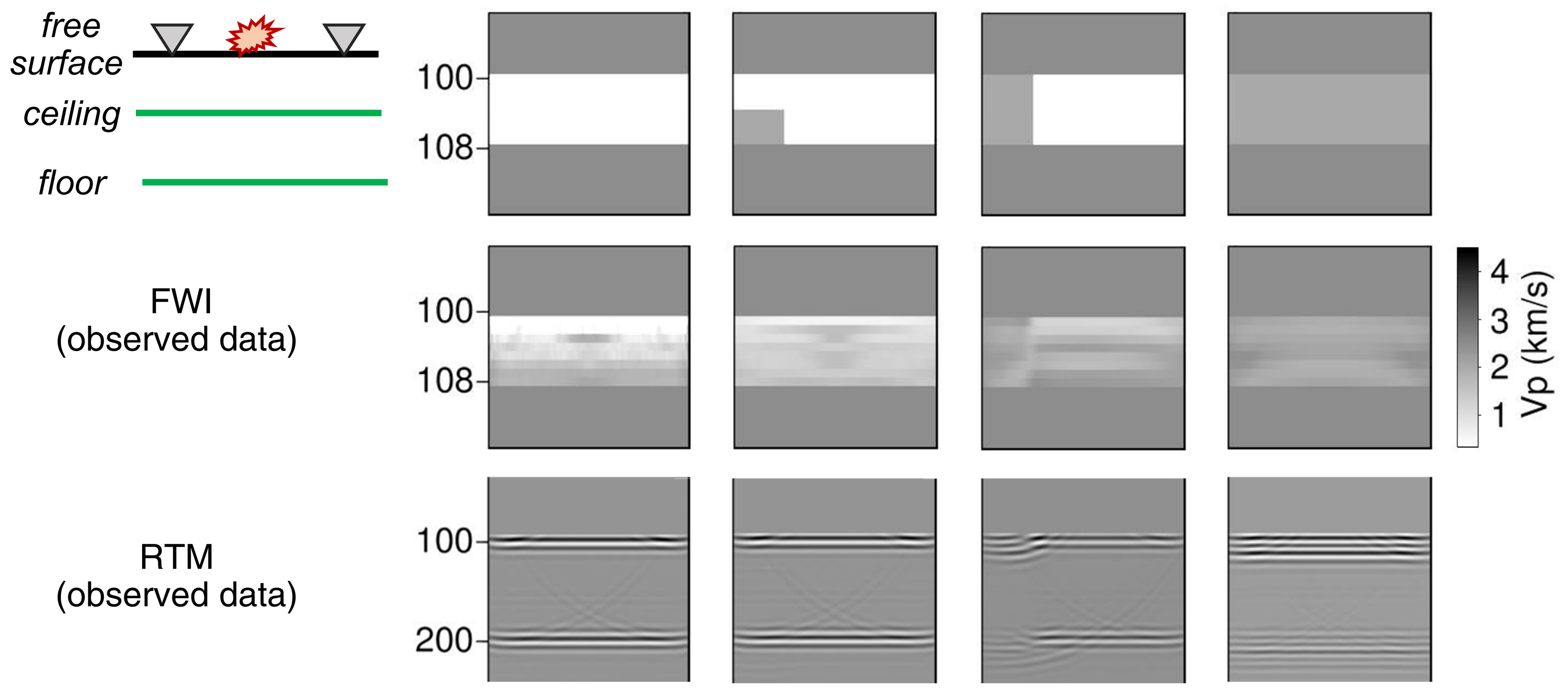


Fig. 2: (Middle) FWI and (bottom) RTM results from the data observed at the surface for (top) the four models with different distributions of the cement slurry in the gallery.

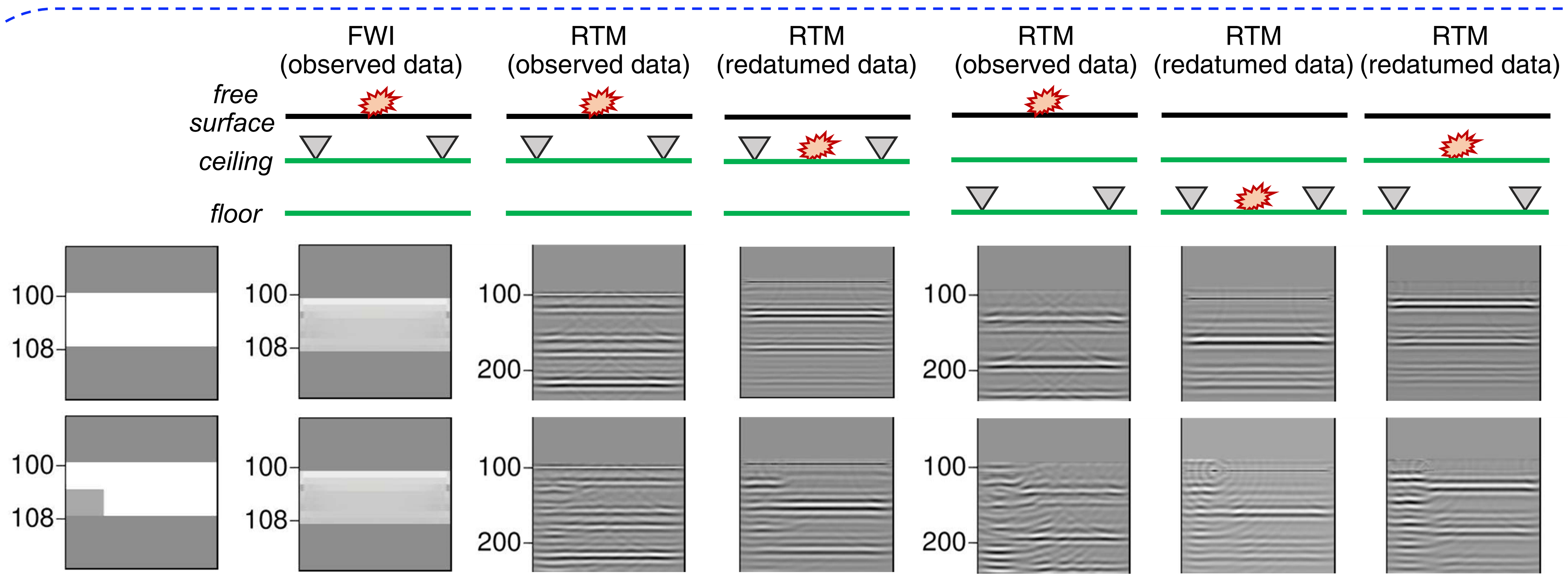


Fig. 3: FWI and RTM results from observed and redatumed data. Here, receivers are distributed at the ceiling and floor.

❖ **Receiver at the gallery**

- For the source-receiver geometry, we now consider the case that geophones are fixed at the gallery.
  - ➢ It is difficult to use inversion to investigate the distribution of the material in the presence of the air.
  - ➢ Although the material distribution can be described roughly, the results are not good due to the strong energy of the multiples.
- When the gallery is positioned at a deep part, reflected signals are small.
- To enhance signals, we also apply seismic interferometry to redatum the sources.
- **RTM images obtained from the redatumed data give better results** than those obtained from the observed data.

Conclusions

- We applied acoustic FWI and RTM to investigate the feasibility of material distribution detection in the abandoned mine.
- FWI was applied to the observed data; RTM was used to both the observed data and the data reconstructed by seismic interferometry.
- Unlike typical underground structures, there is air in the abandoned mine, thus, most of the energy is reflected from the ceiling, only a small amount of energy propagates downward.
- Therefore, it **may not be appropriate to use acoustic FWI** for the material distribution investigation.
- RTM can be used to the investigation if the data are measured in or near the gallery.
- We suggest **applying RTM to the reconstructed data** to improve the reliability when using RTM.
- For the future study, the seismic methods will be considered jointly with other geophysical techniques.

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Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2017R1A2B4002031) and by the project funded by the Ministry of Oceans and Fisheries, Korea (D11603317H480000112).