Feasibility of seismic monitoring for underground hydrogen storage in porous media using elastic full waveform inversion

Introduction

Hydrogen has the potential to play a significant role in energy transition with decarbonization because it can be produced by renewable energy sources and only emits water vapor as fuel cells. Hydrogen is also a versatile energy carrier that can be employed to store and deliver energy generated from other sources. In the energy carrier, underground hydrogen storage (UHS) is a crucial technology to realize large-scale energy storage with safety (e.g., [1]). Although the geological formation of UHS was commonly salt cavern (e.g., [2]), the target formations are expanded to the reservoirs in depleted oil-gas fields and saline aquifers in porous media (e.g., [3]).

Monitoring approaches required in such hydrogen storage depend on each geological formation. For example, downhole pressure measurement is one of the standard hydrogen monitoring methods in salt caverns [2,4]. Seismic monitoring for the hydrogen in salt caverns using seismic sources and receivers outside the salt would be challenging due to the energy loss of active seismic waves in salt boundaries. On the other hand, when we consider porous media as the target geological formation of UHS, seismic monitoring might become a cost-benefit method. Pfeiffer et al. (2016) and Yang et al. (2024) applied acoustic full waveform inversion (FWI) to synthetic data recorded in cross-hole seismic surveys for subsurface hydrogen monitoring [5-6]. FWI enables us to estimate high-resolution subsurface parameters by using an iterative process for seismic ‘waveform’ data (presented by Tarantola (1984) [7]). Such FWI-based seismic monitoring is a promising technology for subsurface carbon dioxide storage (e.g., [8]). However, because the reports on the actual operations and laboratory experiments (e.g., rock physics for hydrogen) related to UHS in porous media are still limited, the specifications (e.g., P-wave/S-wave velocity change and density change generated by hydrogen injection) required in seismic monitoring with FWI are not understood enough.

Bijay et al. (2024) presented results from a laboratory study on cyclic UHSs in porous media [9]. Their experiment demonstrated that P-wave velocity decreases non-linearly with increasing hydrogen saturation in sandstone specimens. They also reported that attempts to measure S-wave velocity were uninterpretable due to low waveform amplitudes overshadowed by noises [9]. In contrast, existing literature [10] describes rock physics models (e.g., the Gassmann mixing model [11]) to estimate meaningful changes in P-wave and S-wave velocities with hydrogen saturation. These indicate that the changes in S-wave velocity (and consequently density) generated by actual hydrogen injection in porous media are not fully understood.

This study aims to evaluate the feasibility and challenges of hydrogen monitoring using time-lapse elastic FWI (e.g., [12]) for surface seismic data produced by synthetic subsurface models, including hydrogen plume models with different velocity and density parameters. Although elastic FWI can reconstruct not only P-wave velocity but also the other parameters, such as S-wave velocity and density, parameter crosstalk is a challenge in the multi-parameter FWI (e.g., [13]). It can occur when an error in one subsurface parameter (e.g., P-wave velocity) is mapped into the updates of another (e.g., density). Previous studies applied acoustic FWI to estimate only P-wave velocity changes generated by hydrogen injection [5-6]. However, UHS also might incur changes in S-wave velocity and density, which might differ from carbon dioxide storage (Figure 1). Therefore, this study investigates the validity of elastic FWI with the limitation of the parameter crosstalk caused by hydrogen storage in porous media.

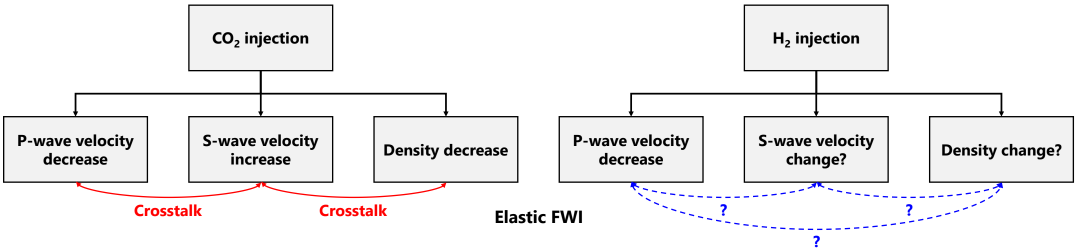


Figure 1 *The relative influence on elastic FWI of CO_2 and H_2 storage.*

Approach

We apply 2D elastic FWI to the shot gathers generated by elastic forward modeling for synthetic subsurface parameters (e.g., velocities and density) with ocean bottom receivers to estimate the change of velocities and density during UHS operation. Ocean bottom receivers commonly record the vertical and horizontal particle-velocity components of the shot gathers. Because the horizontal particle-velocity component is usually noisy compared to the vertical component, this study separately employs the vertical particle-velocity components and the two components for the input of FWI (Figure 2). We perform the inversion for the baseline and monitor data with the same initial parameters, respectively, and then calculate the parameter differences as time-lapse changes.

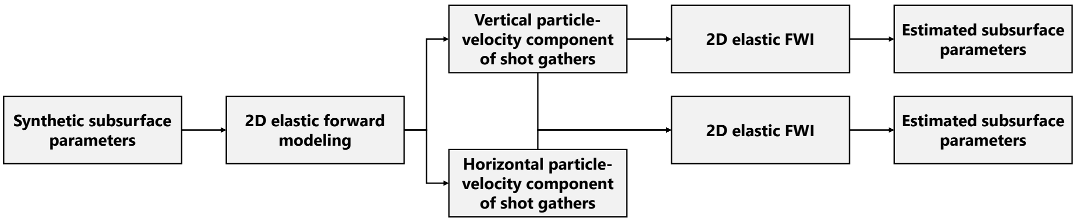


Figure 2 *Workflow used in this study. This workflow is applied to baseline and monitor seismic data.*

Experiments

We conduct numerical experiments using so-called BP-TTI models (Figure 3 (a)-(c)), which are baseline parameters in this study. As mentioned, because the changes in S-wave velocity and density posed by actual hydrogen storage in porous media are not fully understood, this study assumes two extreme hydrogen plume models (Figure 3 (d)-(o)). In both models, the P-wave symmetry-axis velocity (V_{P0}) of the hydrogen plume is assumed to decrease, based on laboratory experimental results [9] (Figure 3 (d) and (j)). The first hydrogen plume model A posits an increase in S-wave symmetry-axis velocity (V_{S0}) (Figure 3 (e)) and an increase in density (ρ) (Figure 3 (f)), exhibiting similarities to the trends observed in carbon dioxide plumes. On the other hand, the second hydrogen plume model B assumes no changes in either V_{S0} or ρ (Figure 3 (k) and (l)) because the changes in V_{S0} and ρ based on Gassman's equation [11] and Wood's law (e.g., [14]) are relatively small at low hydrogen saturation levels.

This study calculates seismic shot data from elastic finite-difference modeling [15] for each synthetic model without generating surface waves. The receiver and source intervals are 20 m and 80 m, respectively. The receivers are placed at a depth of 210 m, while the sources are at 20 m. We apply elastic FWI to 2-13 Hz of the shot data generated by the baseline parameters and the parameters after the injections. The initial parameters for FWI are produced by applying horizontal smoothing to the baseline parameters (Figure 3 (p)-(r)).

These numerical experiments show that hydrogen plume model A (Figure 4 (a)-(f)) exhibits superior plume estimation accuracy compared to hydrogen plume model B (Figure 4 (g)-(l)). While hydrogen plume model A, which has similarities to carbon dioxide storage, is likely affected by elastic FWI crosstalk, the influence appears to be more significant in hydrogen plume model B. This observation highlights a potential intrinsic challenge in the application of elastic FWI to UHS. In both hydrogen plume model A and hydrogen plume model B scenarios, the estimation accuracy of the plume is relatively higher when utilizing only the vertical particle-velocity component of shot gathers (Figure 4 (a)-(c), (g)-(i)), as compared to the results obtained using the two components (Figure 4 (d)-(f), (j)-(l)). A plausible interpretation for these results is that the single-component inversion yields relatively higher accuracy results because the high non-linearity of the two-component inversion makes it more susceptible to accuracy degradation due to crosstalk.

Conclusions

This study presented seismic monitoring for subsurface hydrogen storage in porous media using an elastic FWI algorithm. The numerical experiments demonstrated that elastic FWI can be potentially valid for hydrogen plume estimation. However, the results also suggested that in cases where P-wave velocity decreases while S-wave velocity and density remain unchanged, significant crosstalk effects may occur, posing a challenge in the inversion. Furthermore, they showed that using only the vertical particle-velocity component rather than two components of shot gathers in the FWI was more effective in mitigating the influence of this crosstalk.

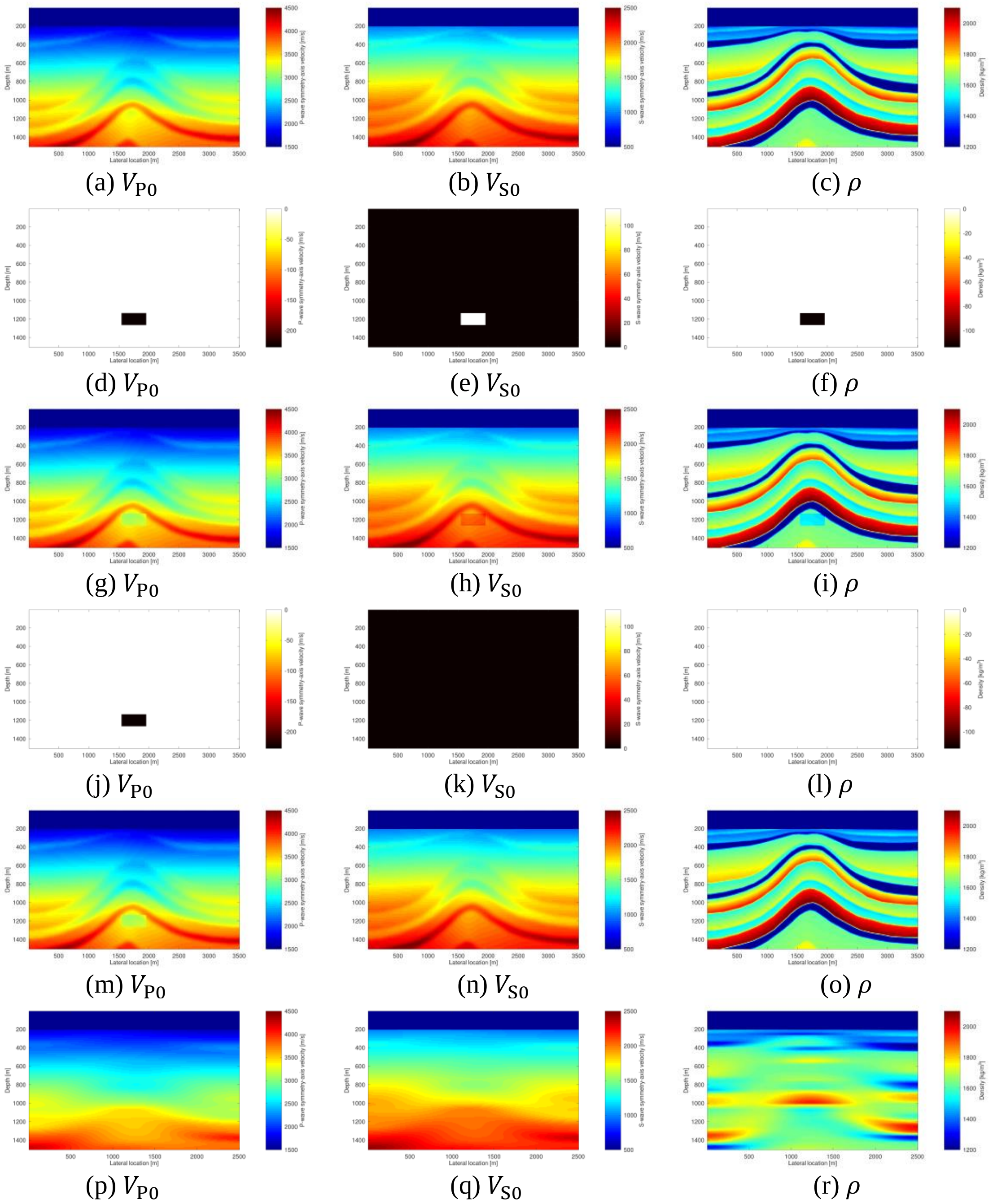
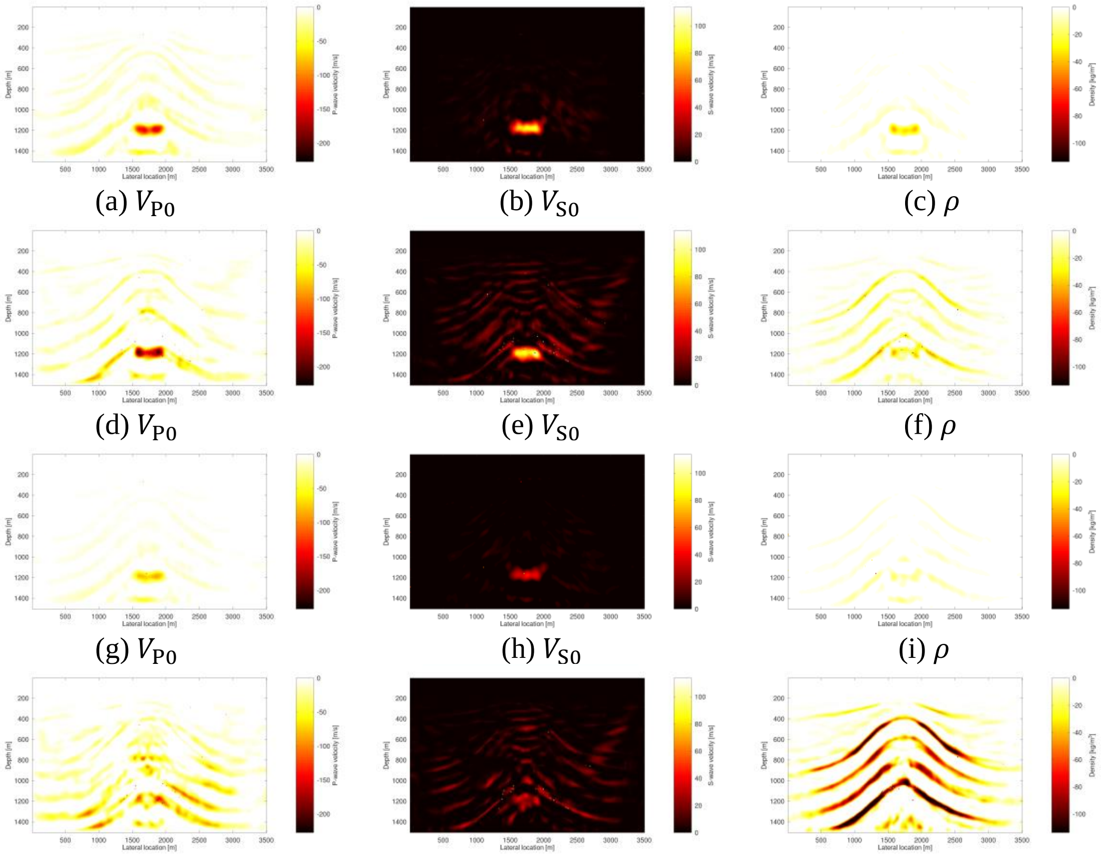


Figure 3 *Examples of synthetic subsurface parameters used in this study and the initial parameters for FWI: (a)-(c) true baseline parameters, (d)-(f) hydrogen plume model A, (g)-(i) true monitor parameters with hydrogen plume model A, (j)-(l) hydrogen plume model B, (m)-(o) true monitor parameters with hydrogen plume model B, (p)-(r) the initial parameters for FWI.*



(a) V_{P0} (b) V_{S0} (c) ρ
(d) V_{P0} (e) V_{S0} (f) ρ
(g) V_{P0} (h) V_{S0} (i) ρ
(j) V_{P0} (k) V_{S0} (l) ρ

Figure 4 *Parameters V_{P0} (left), V_{S0} (middle), and ρ (right) estimated by time-lapse elastic FWI (30 iterations): (a)-(c) hydrogen plume model A inverted by vertical particle-velocity component, (d)-(f) hydrogen plume model A inverted by two components, (g)-(i) hydrogen plume model B inverted by vertical particle-velocity component, (j)-(l) hydrogen plume model B inverted by two components.*

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