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Feasibility of Seismic Monitoring of Hydrogen Storage and Leakage in Sandstone Reservoirs Using Angle-dependent Image Gathers

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Summary

This study examines the applicability of seismic methods for monitoring hydrogen storage and detecting potential leakage in sandstone reservoirs, with a particular focus on amplitude variations in angle-dependent image gathers. Using the FluidFlower benchmark model as a controlled geological framework, two types of sandstone—mildly consolidated and unconsolidated—are considered. Gassmann's fluid substitution is used to model elastic property changes under different hydrogen saturation and leakage scenarios, and seismic responses are generated using Kennett's reflectivity method.

The analysis shows that seismic amplitudes are sensitive to both fluid saturation and lithology. In mildly consolidated sandstones, hydrogen injection leads to observable increases in amplitude at reservoir interfaces. In unconsolidated sandstones, elastic contrasts are more pronounced, resulting in stronger and more detectable seismic responses. These findings highlight the need to account for lithological characteristics when designing seismic monitoring strategies for underground hydrogen storage.

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Introduction

Underground hydrogen storage (UHS) is increasingly significant for enabling sustainable and scalable energy systems. Safe and efficient monitoring of hydrogen distribution and potential leakage is essential to mitigate environmental risks and operational hazards. Seismic methods, traditionally effective in hydrocarbon reservoir monitoring and CCS monitoring, hold promise for application in hydrogen storage scenarios. Despite this potential, quantitative insights into seismic signatures of hydrogen-induced changes in sandstone reservoirs remain limited. This study employs rock-physics modelling and synthetic seismic data to address these knowledge gaps by systematically investigating seismic amplitude variations resulting from hydrogen saturation and leakage scenarios. Understanding seismic responses to hydrogen storage demands accurate rock-physics modelling. Gassmann's fluid substitution theory (Gassmann, 1951) is widely utilized for predicting fluid-driven elastic property changes in porous rocks. Additionally, synthetic seismic modelling and imaging techniques, such as Kennett's reflectivity method (Kennett, 1983), provide critical tools for analyzing expected seismic signatures from subsurface fluid alterations.

Method and Theory

The FluidFlower benchmark (Flemish et al., 2023) provides an ideal experimental framework for seismic modelling due to its well-characterized, meter-scale geological setup that enables controlled fluid injection and monitoring under realistic reservoir conditions (Figure 1).

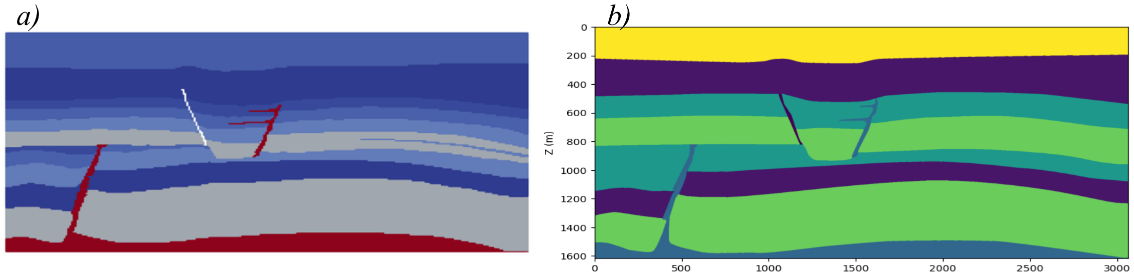


Figure 1 *FluidFlower benchmark model based on (a) permeability and (b) simplified extracted geological settings. Gray area in (a) and green area in (b) are the reservoir layers.*

This study follows a structured approach using FluidFlower model, representing two sandstone types: mildly consolidated with dry bulk modulus K_{dry}=12.0 GPa and dry shear modulus μ_{dry}=7.0 GPa and unconsolidated with dry bulk modulus K_{dry}=2.0 GPa and dry shear modulus μ_{dry}=3.0 GPa. For both types we assume a constant porosity of 25%. The workflow consists of three integrated phases for each type of sandstone. In the first phase, we employ Gassmann's fluid substitution equations to calculate P-wave velocity (Vp), S-wave velocity (Vs), and density variations resulting from fluid substitutions.

For the baseline scenario, we assumed 20% methane and 80% brine saturation in the lower reservoir layer, representing a depleted gas field. The upper reservoir layer is considered fully brine-saturated, representing a saline aquifer. Then we start modelling using Gassmann's equation for hydrogen injection scenarios with 50% and 100% hydrogen saturation in the lower reservoir layer and leakage scenario with 30% hydrogen saturation in the previously brinefilled upper layer, emulating leakage into saline aquifers. Figure 2 illustrates the trend of P-wave and S-wave velocity with hydrogen saturation in the two types of sand.

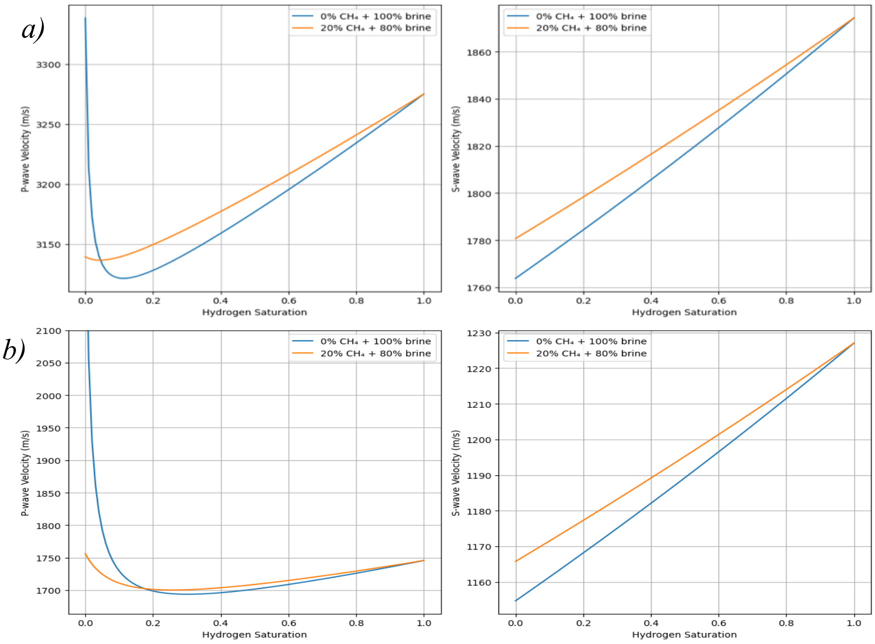


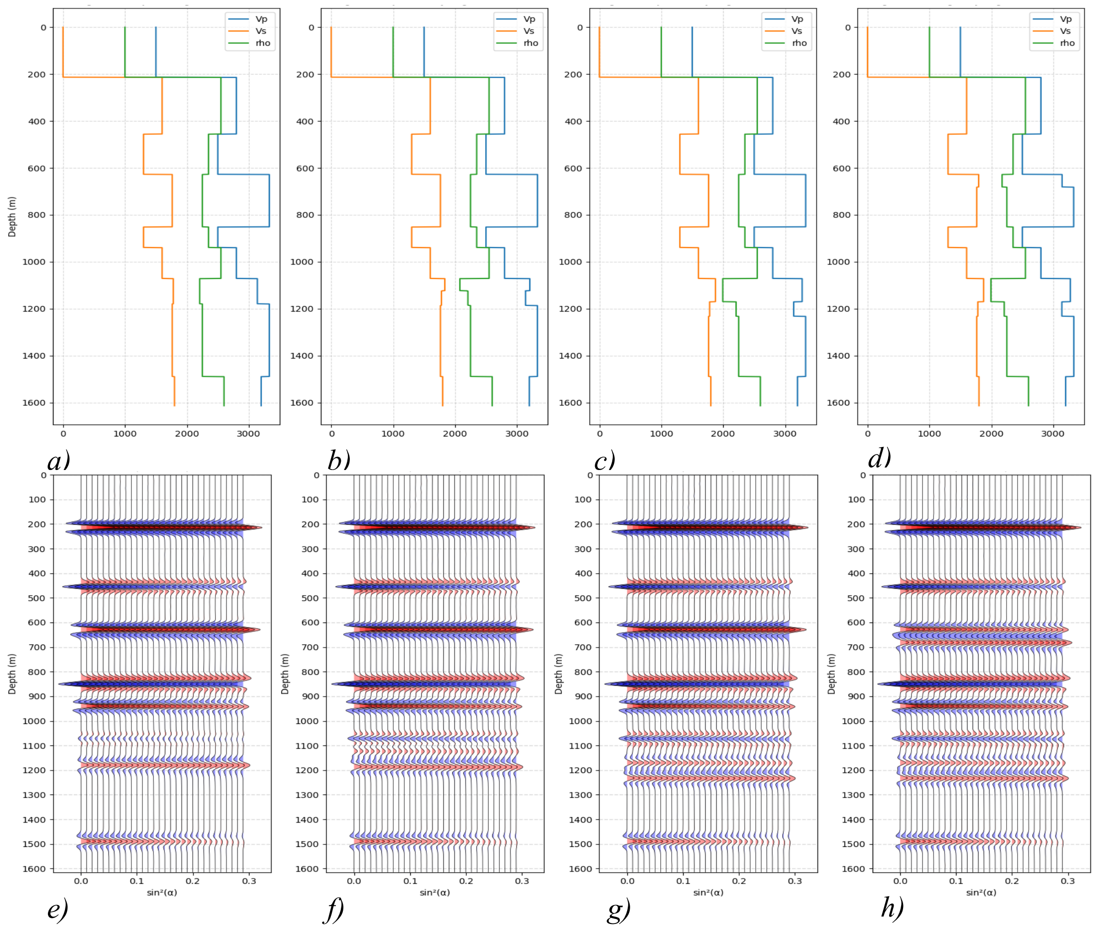
Figure 2 *Effect of hydrogen injection on P-wave and S-wave velocities when the native fluid is brine-only (blue line – aquifer case) versus 20% residual methane (orange line – depleted gas field case) for (a) mildly consolidated sandstone and (b) unconsolidated sandstone.*

In the second phase, 1.5D elastic models (velocity and density logs) extracted from saturation models at location of 2000 m (approximately the crest of reservoir layer) are utilized to generate synthetic seismic responses using Kennett's reflectivity modelling. These seismic data are subsequently transformed into the τ-p domain to decompose into plane-wave responses. Then, we perform wave-equation migration to have flat events with true amplitude response with depth; eventually, we convert the data from the ray-parameters domain into incident angles.

In the third phase, we analyze migration results to produce angle-dependent image gathers (seismic amplitude vs. $\sin^2$ (incident angle)). This analysis enables detailed examination of how varying fluid saturations and lithological differences impact seismic amplitudes.

Results and Discussion

The seismic analyses distinctly highlights the sensitivity of the seismic amplitudes to different fluid saturations and reservoir lithologies. For mildly consolidated sandstone, the initially depleted gas layer shows a very week amplitude for the caprock-reservoir interface and relatively higher contrast for the lower interface (gas-water contact) (Figure 3a and e). Upon introducing hydrogen into the reservoir, the initially weak amplitude at the caprock-reservoir interface becomes stronger due to the higher P-wave and S-wave velocities and lower density due to the hydrogen (Figure 3b-c and f-g). Also, leakage in this case scenario is completely visible in the seismic response (Figure 3d and h), provided the leakage volume and associated contrasts remain above the seismic-resolution limits.



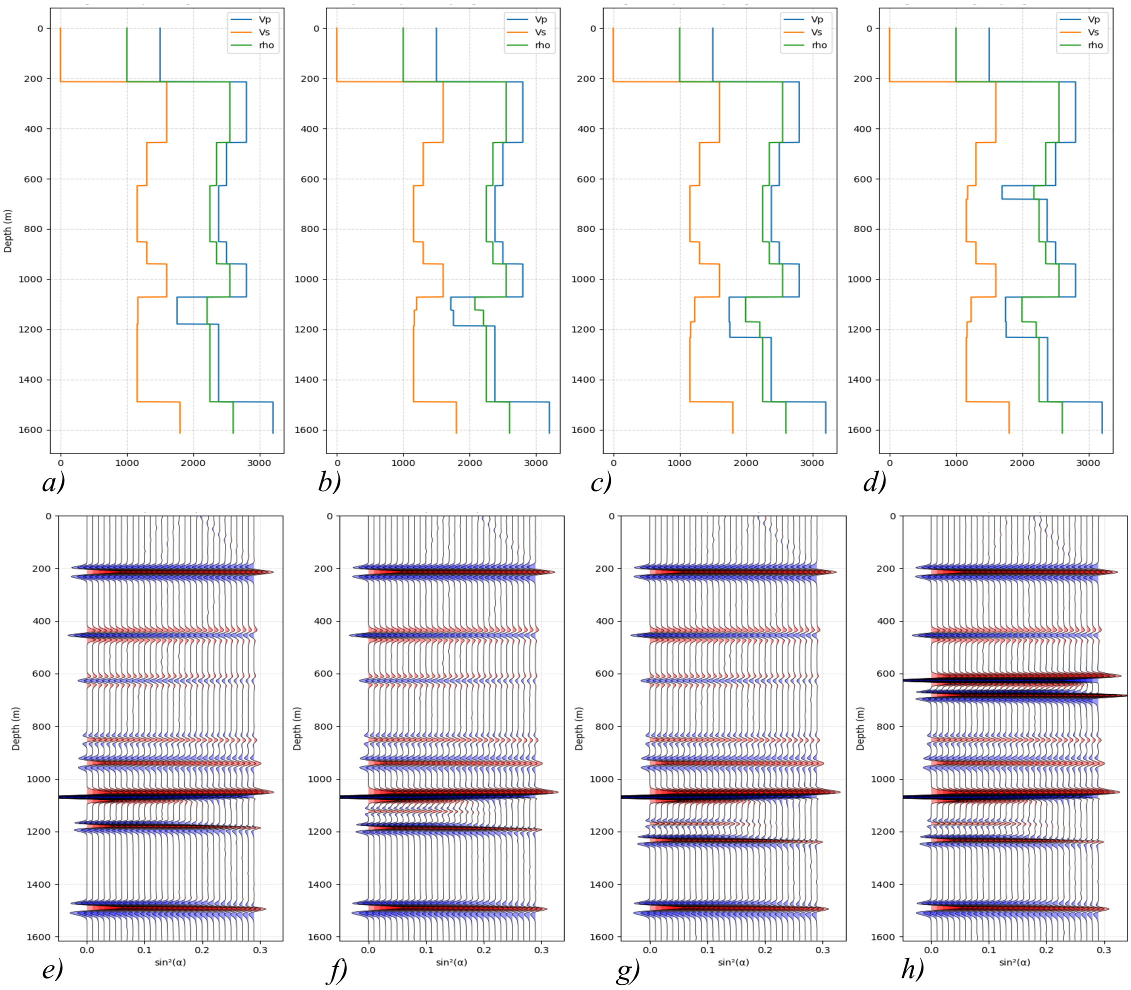
a) b) c) d)

e) f) g) h)

Figure 3 *1.5D elastic models and corresponding angle-dependent image gathers for mildly consolidated sands. (a) and (e) base line, (b) and (f) 50% hydrogen saturation in the lower reservoir, (c) and (g) 100% hydrogen saturation in the lower reservoir, and (d) and (f) 30% hydrogen leaked into the upper layer.*

In the unconsolidated sand type, the methane makes a huge contrast in the reservoir: at the upper layer with a sharp negative amplitude and at the gas-water contact with a sharp positive amplitude (Figure 4a and e). For the monitoring models, the seismic response demonstrates increased sensitivity, with substantially larger amplitude variations for the hydrogen scenarios compared to the mildly consolidated sandstone (Figure 4b-c and f-g) such that even a very small contrast in Vp after hydrogen injection can produce a significantly visible amplitude and response, due to the larger difference in density. The leakage scenario shows significantly stronger seismic-amplitude contrasts, making unconsolidated sandstones particularly advantageous for seismic monitoring (Figure 4d and h).

The results from both lithologies underscore the critical role lithological properties play in seismic detectability and the effectiveness of the seismic method for hydrogen monitoring. Unconsolidated reservoirs exhibit enhanced elastic-contrast responses, offering improved detection of subtle fluid variations such as hydrogen leakage. This suggests that reservoir-specific seismic monitoring strategies must be developed considering local lithological characteristics.



a) b) c) d)

e) f) g) h)

Figure 4 *1.5D elastic models and corresponding angle-dependent image gathers for unconsolidated sands. (a) and (e) base line, (b) and (f) 50% hydrogen saturation in the lower reservoir, (c) and (g) 100% hydrogen saturation in the lower reservoir, and (d) and (f) 30% hydrogen leaked into the upper layer.*

Conclusions

We showed that seismic methods, combined with robust rock- physics modelling and synthetic seismic imaging, are effective for monitoring hydrogen storage and detecting potential leakage in sandstone reservoirs. We showed that significant amplitude variations induced by hydrogen saturation and leakage scenarios emphasize the seismic detectability of hydrogen distribution within subsurface formations. The results strongly advocate for lithology-specific seismic - monitoring approaches to enhance operational safety and environmental protection in underground hydrogen storage.

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