Subsurface Monitoring of Geological CO2 Storage

Course Number: SU-02-504

PDH: 7

Approved for: AK, AL, AR, DE, FL, GA, IA, ID, IL, IN, KS, KY, LA, MD, ME, MI, MN, MO, MS, MT, NC, ND, NE, NH, NJ, NM, NV, NY, OH, OK, OR, PA, SC, SD, TN, TX, UT, VA, VT, WI, WV, and WY

State Board Approvals

Florida Provider # 0009553 License #868
Indiana Continuing Education Provider #CE21800088
Maryland Approved Provider of Continuing Professional Competency
New Jersey Professional Competency Approval #24GP00025600
North Carolina Approved Sponsor #S-0695
NYSED Sponsor #274

How Our Written Courses Work

This document is the course text. You may review this material at your leisure before or after you purchase the course.
After the course has been purchased, review the technical material and then complete the quiz at your convenience.
A Certificate of Completion is available once you pass the exam (70% or greater). If a passing grade is not obtained, you may take the quiz as many times as necessary until a passing grade is obtained).
If you have any questions or technical difficulties, please call (508) 298-4787 or email us at admin@PDH Pro.com.

Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the primary geological storage formations used for CO2 sequestration.
- **Evaluate** the limitations of conventional 4-D seismic monitoring in terms of cost and temporal resolution.
- **Select** appropriate seismic geometries and instrumentation for continuous, sparse-data monitoring.

Executive Summary: Effective CO2 sequestration requires a transition from intermittent 3-D seismic surveys to continuous, "true 4-D" monitoring paradigms. While various geophysical methods exist, seismic technology offers the highest spatial resolution for critical safety tasks like leak detection. A robust monitoring strategy must combine daily reconnaissance surveys using sparse, embedded arrays with high-resolution, rapidly deployable resources to adapt to changing reservoir conditions.

Overview of CO2 Sequestration

CO2 Sequestration is the comprehensive process of capturing, separating, transporting, and storing waste CO2 to mitigate its impact on global climate change.

Primary Geological Storage Options

- Depleted oil and gas reservoirs.
- Deep saline aquifers.
- Unminable coal beds.

The Necessity of Monitoring

Site monitoring is essential to manage the injection process and ensure public safety by detecting inadvertent leaks. Monitoring must account for potential leak paths, such as faults in the sealing layers above the reservoir.

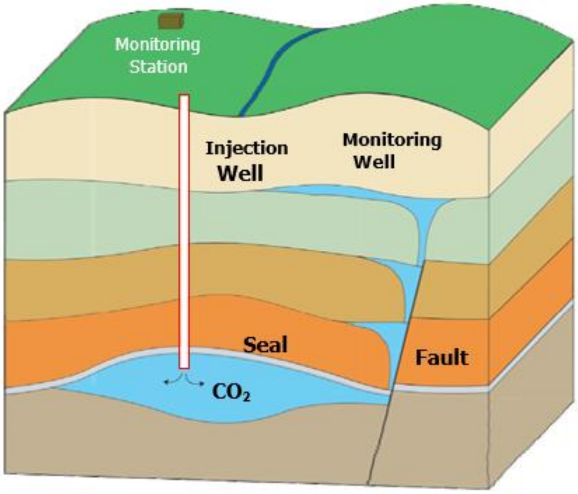

Figure 1.1: This drawing of a CO2 storage site illustrates the need subsurface monitoring. The layers above the reservoir provides sealing and flow barriers. A fault indicates a possible CO2 leak path.

Global Sequestration Milestones

Geological sequestration tests have been implemented globally across various scales:

- **Commercial Scale**: Sleipner (Norway), Weyburn (Canada), In Salah (Algeria), and Snohvit (Norway).
- **Pilot Scale**: K12B (Netherlands), Otway (Australia), RECOPOL (Poland), Hokkaido (Japan), and CASTOR (Europe).

At the **Sleipner** field, time-lapse seismic surveys conducted between 1994 and 2005 have successfully verified the CO2 plume containment within a saline formation.

The Shift to Continuous 4-D Monitoring

Traditional **4-D seismic imaging** relies on repeating complete 3-D surveys every few years. However, this conventional approach presents two critical failures for long-term monitoring:

1. **Economic Infeasibility**: The cost of repeated 3-D surveys is prohibitive for monitoring programs intended to run for decades.
2. **Safety Gaps**: Surveys conducted years apart cannot effectively detect leaks in real-time or meet modern site licensing requirements.

A New Paradigm

The goal is to move toward a **true 4-D strategy** where time is the sampled fourth dimension. After investigating electromagnetic, gravity, and deformation methods, research confirms that **seismic methods** remain the superior choice due to their wide applicability and high spatial resolution for leak detection.

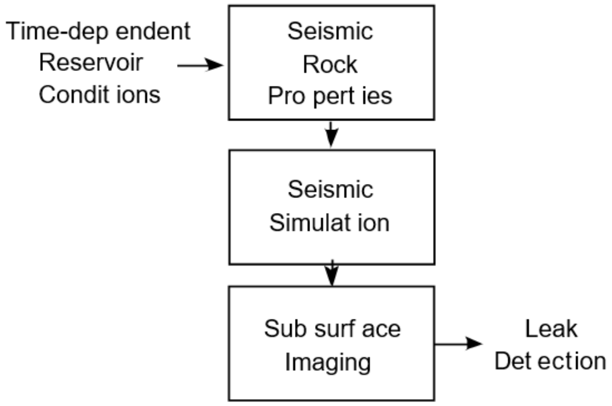

Figure 1.2: The development of seismic monitoring strategies involves three tasks: Rock properties analysis, survey simulation, and imaging. To test the approach, one could use time- dependent flow simulation results or surrogate models.

Technical Design Fundamentals

Seismic monitoring detects changes in **acoustic impedance** driven by CO2 saturation. Injected CO2 alters the **wave speed** and **density** of water-saturated formations.

Complementary Seismic Methods

- Surface-based reflection seismic.
- Borehole Vertical Seismic Profiles (VSP) and cross-well seismic.
- Passive micro-seismic.
- Sonic logs.

Strategy for Leak Detection

To resolve the conflict between detecting small changes and monitoring large volumes, engineers should implement:

- **Reconnaissance Surveys**: Sparse spatial coverage using embedded sources and detectors, implemented daily for high temporal resolution.
- **High-Resolution Response**: Rapidly activating existing embedded arrays to target specific regions if unexpected changes occur.
- **Sparse Observation Systems**: Utilizing circular and cross arrays to reduce costs while maintaining monitoring efficacy.

⚠ **Safety Constraint:** Effective leak detection requires monitoring that can identify small temporal changes at small spatial scales within a volume that expands over time.

💡 **Design Tip:** Utilize low-power transducers that radiate continuous wave signals or coded waveforms to allow for permanent embedding of sources.

🧮 **Calculation Note:** Interpretation of field data depends on understanding the magnitude of change in rock properties (velocity, density, and attenuation). Preliminary laboratory methods like **Differential Acoustical Resonance Spectroscopy (DARS)** can measure these properties at low frequencies (~1000 Hz) using small rock samples.

Checkpoint Quiz

1. **Which geological storage option is specifically mentioned as being considered alongside depleted reservoirs and saline aquifers?**
   a) Active volcanic vents
   b) Unminable coal beds
   c) Shallow freshwater aquifers
   d) Crystalline basement rock

Answer: (b). The text identifies these as one of the three principal potential storage options.

2. **What is the primary technical limitation of conventional 3-D seismic surveys for leak detection?**
   a) Lack of spatial resolution
   b) Inability to detect acoustic impedance
   c) Low temporal resolution (surveys conducted years apart)
   d) Incompatibility with saline formations

Answer: (c). Conventional surveys conducted at intervals of years are ineffective for safety-critical leak detection.

3. **In the proposed continuous monitoring paradigm, how is high temporal resolution achieved efficiently?**
   a) By conducting full 3-D surveys every week
   b) By using sparse spatial coverage with embedded daily reconnaissance surveys
   c) By relying exclusively on electromagnetic gravity sensors
   d) By decreasing the total volume of the subsurface sampled

Answer: (b). The strategy uses daily sparse sampling to provide high temporal resolution for leak detection.

Module 2: Seismic Rock Properties

Learning Objectives

By the end of this section, you will be able to:

- **Evaluate** the impact of fluid substitution and effective stress on seismic velocities using Gassmann and Eberhart-Phillips models.
- **Identify** the differences in seismic response between soft (sandstone) and stiff (carbonate) formations during CO2 injection.
- **Analyze** the role of Differential Acoustic Resonance Spectroscopy (DARS) in bridging the frequency gap between laboratory and field measurements.

Executive Summary: Seismic monitoring feasibility depends on the magnitude of change in rock properties (velocity, reflectivity, and attenuation) caused by CO2 injection. These changes are a combined result of fluid saturation and effective stress. While "soft" rocks like sandstones exhibit significant velocity drops suitable for monitoring, "stiff" rocks like carbonates present greater detection challenges. Advanced laboratory methods like DARS are essential for accurately predicting these field-scale responses.

Seismic Model for Brine Aquifers and Depleted Oil and Gas Fields

The seismic properties of pore fluids—specifically **density** and **bulk modulus**—drive the observed changes in the reservoir. While brine and oil properties are relatively stable, CO2 properties are highly sensitive to pressure and temperature.

Fluid Substitution Theory (Gassmann)

To determine the effect of pore fluid changes on rock moduli at low frequencies, we use the Gassmann fluid substitution equation.

Equation 2.1:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_0}\right)^2}{\frac{\phi}{K_{fl}} + \frac{1-\phi}{K_0} - \frac{K_{dry}}{K_0^2}}$$

Where:

- **Ksat** = Saturated bulk modulus
- **Kdry** = Dry rock bulk modulus
- **K0** = Mineral bulk modulus
- **Kfl** = Effective fluid bulk modulus
- **ϕ** = Porosity

Note: Under Gassmann’s theory, the **shear modulus (mu)** remains unchanged upon fluid substitution (msat = mdry).