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4D Seismic Monitoring in Highly Populated Area: Study of CCUS in Sukowati Oil Field, East Java

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ABSTRACT - Indonesia is resolutely addressing climate change with a commitment to reduce carbon emissions by 29% in 2030, and we are on track to achieve net-zero emissions in 2050. This country acknowledges the important role of Carbon Capture, Utilization, and Storage (CCUS) in mitigating carbon emissions, especially from the energy sector, and at the same time increasing oil and gas production. This kind of approach is also well known as CO_2-EOR (Enhanced Oil Recovery) and CO_2-EGR (Enhanced Gas Recovery). Sukowati field is situated in the East Java Province and will serve as a pioneering CO_2 Enhanced Oil Recovery (EOR) project aimed at revitalizing the field. This initiative focuses on increasing oil production while capturing and storing carbon dioxide (CO_2), contributing to environmental sustainability. To ensure its success, a robust monitoring system must be implemented for real-time data collection and analysis, optimizing recovery processes and minimizing environmental impact. Monitoring activities deliver information regarding the CO_2 injected into the reservoir and the risk of leakage into the surrounding injection region. Several methods are discussed for monitoring CO_2 plumes, but in the subsurface, seismic methods stand out as the most promising option. However, despite their effectiveness, seismic methods are also among the most expensive to execute, necessitating significant investment in technology and expertise to ensure accurate and reliable data. 4D seismic, also known as time-lapse seismic, entails performing repeated seismic surveys over a designated area to monitor changes in the subsurface effectively. This imaging technique enables us to visualize the movement of CO_2 plumes within the target formation and can identify alterations in the reservoir that may suggest a potential CO_2 leak. A seismic survey before the injection is needed to create a baseline image of the subsurface target reservoir. Changes in velocity and amplitude are identified when the seismic waves encounter the CO_2 plumes injected into the reservoir target. The challenges of performing a 4D seismic imaging survey in a densely populated area are social impact, the possibility of damaging infrastructure, high noise levels, and high operating costs, particularly if it uses a subterranean explosive (dynamite) as a source of seismic signals. To address these challenges, the study introduces a novel approach to designing irregular 4D seismic surveys. This method features a flexible acquisition layout that departs from traditional geometric symmetry. The survey utilizes a non-impulsive (vibrator) of semi-permanent seismic source and a highly sensitive, wireless seismic recording system. The irregular design is adaptively tailored based on the field's spatial characteristics, potential surface disruptions, and cost considerations. Despite not adhering to a conventional grid or orthogonal configuration, this approach ensures adequate offset and azimuth coverage necessary for detecting subsurface changes.

Keywords: CCUS, 4D seismic, monitoring.

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INTRODUCTION

Climate change is a pressing global issue requiring innovative solutions. Carbon Capture Utilization and Storage (CCUS) has emerged as a promising technology to mitigate and reduce CO_2 emissions. Nevertheless, it is crucial to provide clear assurances that the CO_2 gas injected into the geological formations will remain securely trapped and will not migrate back to the surface. This is vital to ensure that the surrounding environment remains safe and undisturbed, protecting the delicate ecosystems in the area from any potential harm. The area of study is Sukowati oil field, an onshore carbonate oil-bearing reservoir located in East Java, Indonesia, which was discovered in 2001. It resides within the West Tuban Block in the East Java province, which contains an estimated 308 million STB of oil in place. To date, it has successfully produced over 100 million barrels of oil, demonstrating its significant potential for further development and production. Oil production is derived from the carbonate reef buildup formations associated with the Lower Miocene and Upper Oligocene epochs. These formations are characterized by their significant porosity and permeability, composed of skeletal packstones and wackestones. Structurally, this field is located at the height of East Cepu in the Northeast at a depth of approximately 6,300 feet TVDSS, adjacent to the interior of the Kening (Kening Trough), which separates from the height of West Cepu. The Kening Trough is interpreted as the origin area of hydrocarbon source rocks for most of the oil and gas discoveries found around the height of the Cepu Block, such as the Kedung Tuban, Cendana, Banyu Urip, and Sukowati fields. The Kening Trough is believed to contain the hydrocarbon source rocks for most of the oil and gas discovered in the Cepu Block. Typical oil production in East Java is waxy, indicating that it is derived from a non-marine source rock (Satyana et al., 2002). The reserves in this block include the Kedung Tuban, Cendana, Banyu Urip, and Sukowati fields. The distribution and geometry of the reservoir rocks in the block are influenced by Paleogene normal faulting, which created paleo topographic highs with trends running east-west and east-northeast to west-southwest (Figure 1). Oil production reached its peak in 2011, with an initial reservoir pressure of 2,800 psi and containing 20-25% CO_2 by mass. This CO_2 is currently being routed to the nearest central processing area (CPA) for venting. (Hedriana et al., 2021).

To fulfill the requirements of the CCUS project in Indonesia, it is crucial to implement a CO_2 monitoring program at the injection site. This necessity is highlighted in the special regulations set forth by the Minister of Energy and Mineral Resources (PERMEN) No. 16 of 2024, as well as in the Presidential Regulations (PERPRES) No. 14 of 2024. According to these regulations, the contractor or permit holder responsible for the storage operation must monitor CO_2 levels to ensure the safety of workers, installations, and the environment, under

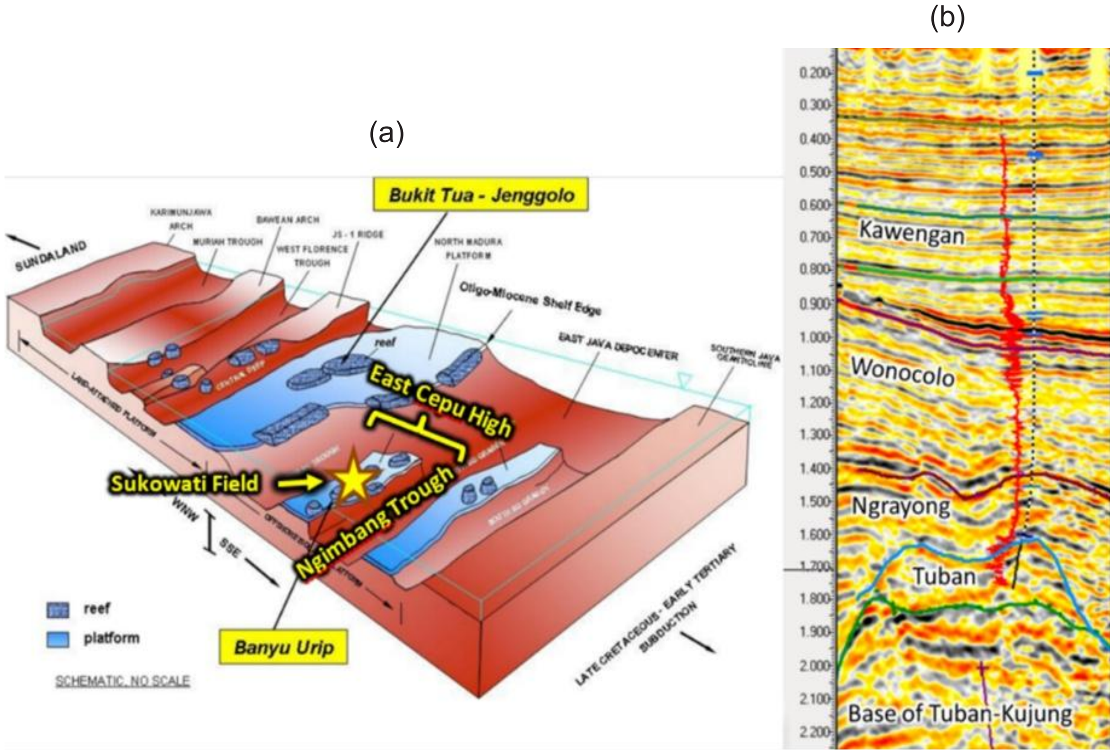

Figure 1. (a). Schematic diagram showing oligo-miocene carbonate development on the segmented east java basement (satyana 2002). (b). Example seismic profile of the late oligocene to early miocene sukowati carbonate.

legal requirements. Monitoring will take place during the initial data collection phase (baseline), throughout carbon storage operations, and will continue for ten years after the site has been closed. A significant subsurface challenge associated with carbon storage projects is the potential migration of injected CO_2 beyond the designated storage area. During the development of a carbon storage initiative, the operator undertakes a comprehensive evaluation to identify suitable geological zones for CO_2 injection and secure long-term storage. This assessment involves detailed geological analyses to ensure that the selected formations can effectively contain the CO_2, thereby minimizing the risk of unintended migration, which is crucial for achieving the project's environmental integrity and objectives (Hnottavange-Telleen et al., 2011).

CO_2 monitoring targets two primary domains: near-surface and deep subsurface. Near-surface monitoring involves tracking CO_2 concentrations in the atmosphere, soil, and potable water formations, all critical for public health and environmental protection. Deep monitoring, on the other hand, focuses on geological reservoirs at depth, aiming to observe the movement of the CO_2 plume within the subsurface. A variety of techniques are available for deep monitoring, encompassing both reservoir-level assessments and evaluations of the overlying strata.

A variety of advanced tools have been thoroughly tested and proven effective in detecting shallow leakage and carbon monoxide emissions at the surface. Surface monitoring tools fall into three categories: geophysical, chemical, and biological (IEAGHG 2015). Chemical sampling methods are essential for identifying and understanding changes in surface layers, shallow sediments, or the seawater column caused by the emission of CO_2 and precursor fluids from the subsurface. Quantifying bubble fluxes using geophysical methods poses research challenges. Active and passive acoustic systems show promise for quantitative measurement with advanced processing techniques. Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) has performed Geophysical techniques used in reservoir, seal, and environmental monitoring at the Otway project in Australia since 2005, with surface geophones, and in 2021, has evolved to using fiber optics and surface orbital vibrators (SOV) to provide more fit-for-purpose and cost-effective techniques (Ennis-King et al., 2021).

Among the various CO_2 injection deep monitoring technologies currently available and in development, 4D (time-lapse) seismic monitoring is considered well-suited for tracking subsurface CO_2 plume in reservoirs (Chadwick et al., 2006). The terminology of time-lapse seismic methods and examples from CCS fields like Nagaoka in Japan, Ketzin in Germany, and Otway in Australia have been explained by Kasahara & Hasada (2017). A significant case study showcasing this technology is the Sleipner Field in Norway, where around 15 million tons of CO_2 have been injected successfully since 1996. Seismic surveys utilize acoustic sources or vibrations transmitted to the Earth's surface. When a seismic source is activated, it generates waves that travel in all directions and are reflected to the surface by rock layers with different acoustic impedances. A group of receivers captures these returning waves, which are then processed to create a subsurface cross-section. Recent global applications of 4D seismic acquisition have highlighted both the potential and limitations of time-lapse monitoring. For instance, Shearwater GeoServices conducted a full 4D processing project on the Pluto Gas Field in Northwest Australia, demonstrating strong 4D signal detection around the gas-water contact and refining workflows for repeatability and noise suppression (Peterson & Gerhardt 2020). In offshore Abu Dhabi, 4D co-processing techniques were applied to improve seismic imaging in areas with limited acquisition repeatability, showing that optimized workflows can compensate for geometric inconsistencies (Mahgoub et al., 2023). Another case in a shallow offshore carbonate field in Qatar revealed how guided co-denoising and demultiple strategies enhanced 4D signal clarity despite severe multiples and weak reflectivity contrasts (Adeyemi et al., 2020). While these projects underscore the value of 4D seismic in reservoir management such as tracking fluid movement and optimizing production they also expose challenges like high costs, logistical complexity, and the need for precise acquisition geometry. These issues become even more critical in densely populated areas, where conventional grid-based designs are often impractical. To address this, a novel irregular 4D seismic survey design has been proposed, featuring flexible acquisition geometries, non-impulsive vibroseis sources, and wireless sensor systems. This approach is tailored to urban constraints, minimizing surface disturbance while maintaining sufficient offset and azimuth coverage. By adapting to spatial characteristics, surface obstacles, and cost considerations, this design offers a promising solution for seismic monitoring in complex environments such as CCUS sites in urban or industrial zones.

METHODOLOGY

This study is divided into three main stages. The first is the design stage of the seismic survey, which considers various technical and non-technical factors, including subsurface geological conditions, surface topography, and social and operational constraints around the field. The second is the synthetic modeling stage, aimed at simulating seismic wave propagation and predicting subsurface responses to CO_2 injection. The third is the processing of time-lapse seismic survey data to analyze differences between the baseline and monitoring datasets and to accurately interpret the spatial distribution of the CO_2 plume.

To develop an effective 4D seismic acquisition design, it is required to identify the location and depth of the target CO_2 plume. The Sukowati oil field is situated in Bojonegoro, East Java. Bojonegoro occupies an area of 2,307.06 km^2, most of the area consists of lowlands along the Bengawan Solo River, with hilly regions located in the southern part of the regency (Figure 4). The landscape in Bojonegoro is primarily characterized by extensive rice fields. In this region, the Bengawan Solo River shifts its flow from north to east. Bojonegoro has around 1.4 million residents, resulting in a population density of 600 people per square kilometer (Pemkab Bojonegoro, n.d.), which aligns with our target for CO_2 monitoring 4D seismic area. Environmental and social issues are crucial considerations during seismic data acquisition. It is essential to protect the environment as much as possible during all field operations. Line cutting in forested areas and damaging public infrastructure should be minimized to the smallest width necessary. Additionally, small jogs in the lines are often requested to maintain the pristine appearance of residences and to prevent damage to the environment. The workflow for developing this design is outlined in Figure 2. A geological static model for this injection simulation has been developed using wellbore data and 3D seismic results from an older survey (Figure 3). These findings illustrate the subsurface area of the reservoirs, indicating that the *Tuban Reef* formation is the designated target for CO_2 injection, situated at a depth of approximately 1,700 meters. The CO_2 plume is determined through the injection simulation result of the reservoir using Computer Modeling Group's GEM and Builder modeling software. Initializing an injection reservoir simulation involves setting various parameters, including grid size, rock types, initial saturations, fluid contacts, and pressure gradients. The simulator uses these inputs to calculate reference pressure and saturation values for each grid block, as well as to determine the volumes of fluids present in the reservoir. This result is influenced by reservoir properties such as lithology, thickness, oil gravity, permeability, porosity, pressure, temperature, viscosity, and water-oil contact (Table 1). Calibrating the reservoir model to align with actual field production data is essential for obtaining a reliable starting point for performance predictions.

This simulation involves the injection of supercritical CO_2 into the gas cap at a rate of 29 million standard cubic feet per day (MMSCFD), maintained consistently over 20 years, allowing the hydrocarbons and CO_2 to form a single-phase fluid. The injection pattern uses an inverted five-spot configuration, which includes one injection well located in the center and four production wells surrounding it. All wells, whether they are injections or producing wells, should undergo workovers and remedial cementing due to poor cement bond quality. Additionally, to fulfill the requirements of a CO_2 EOR project, it is also essential to change well completion equipment, tubular, and wellhead/christmas tree components.

The typical history-matching process focuses on aligning the oil production rate while adjusting rock properties, such as the absolute permeability curves. As for the results of the obtained history match, the simulated oil production rate matched actual field data, which was probably one of the constraints of the history matching process. The source of the injected CO_2 comes from the Sukowati field, contributing 4 MMSCFD, while the remaining 25 MMSCFD is sourced from the Jambaran Tiung Biru gas processing field, located 30 kilometers from the injection site. The outcomes of the simulation regarding CO_2 plume migration from the injection perforation are presented in Figure 5-8, leading to several conclusions: 1). Significant amounts of CO_2 are trapped through structural mechanisms characterized by numerous CO_2 mole fractions (color bar) in the upper layer near the caprock; 2). The presence of multiple moles of CO_2 in the middle layer indicates that certain amounts of CO_2 are trapped through solubility and residual mechanisms, potentially due to its interaction with the formation brine; 3). Total cumulative oil production after 20 years of CO_2 injection is approximately 9.8 MMBBL, resulting in an additional recovery factor of 12.9%; 4). The thickness and area of the CO_2 plume, after 20 years of injection in the model, are approximately 400 feet and 4 square kilometers, respectively.

Table 1. Sukowati oil field properties

Reservoir properties	
Initial Pressure	2,889.47 psi
Initial Temperature	275 F
Oil Gravity	45.375 API
Water-Oil Contact Depth	6,680 ft
Lithology	Carbonate
Thickness	91 m
Porosity	0.19
Permeability	425 mD
Effective Reservoir Radius	4264 ft
Viscosity	0.4 cP

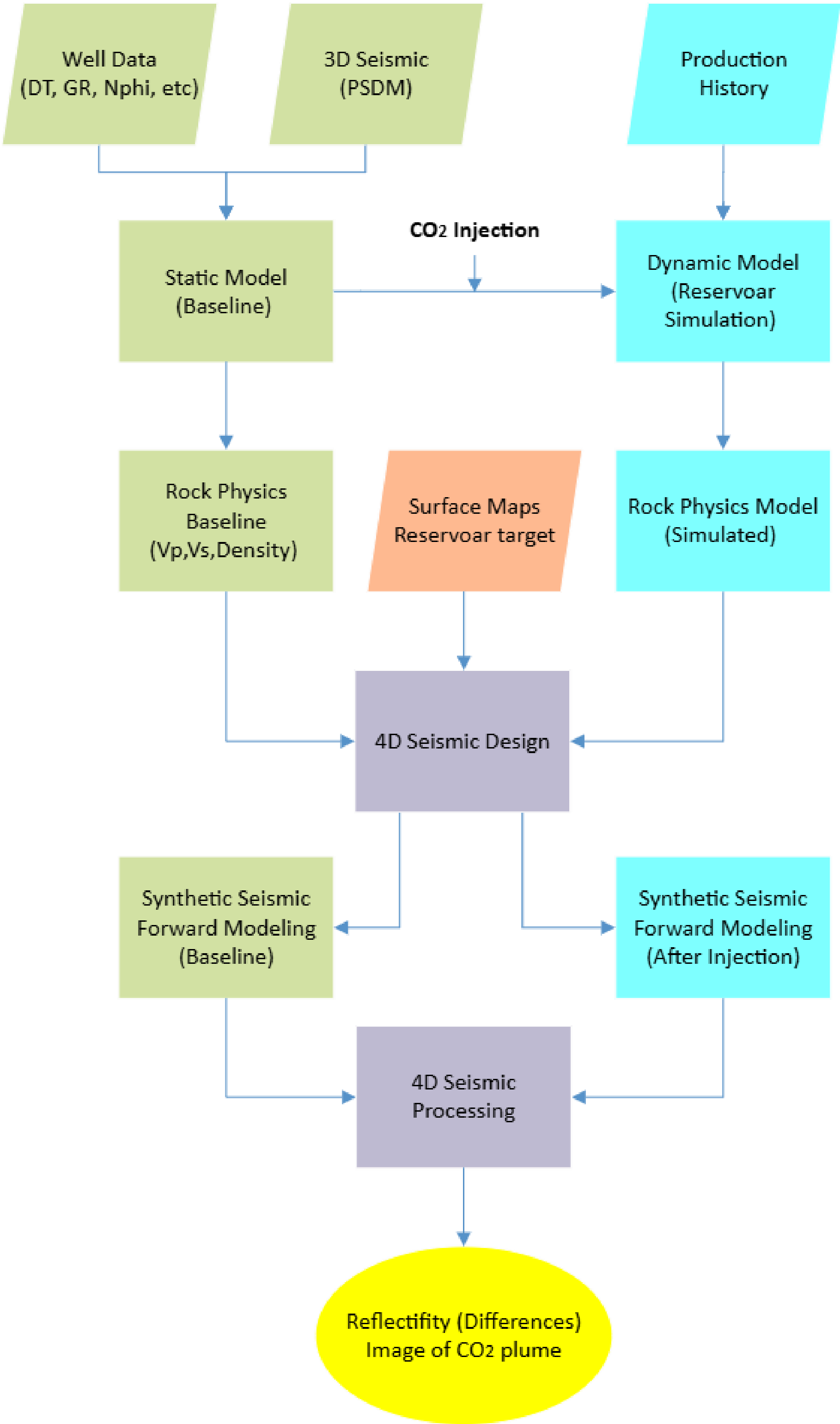

Figure 2. Workflow diagram of 4D seismic design

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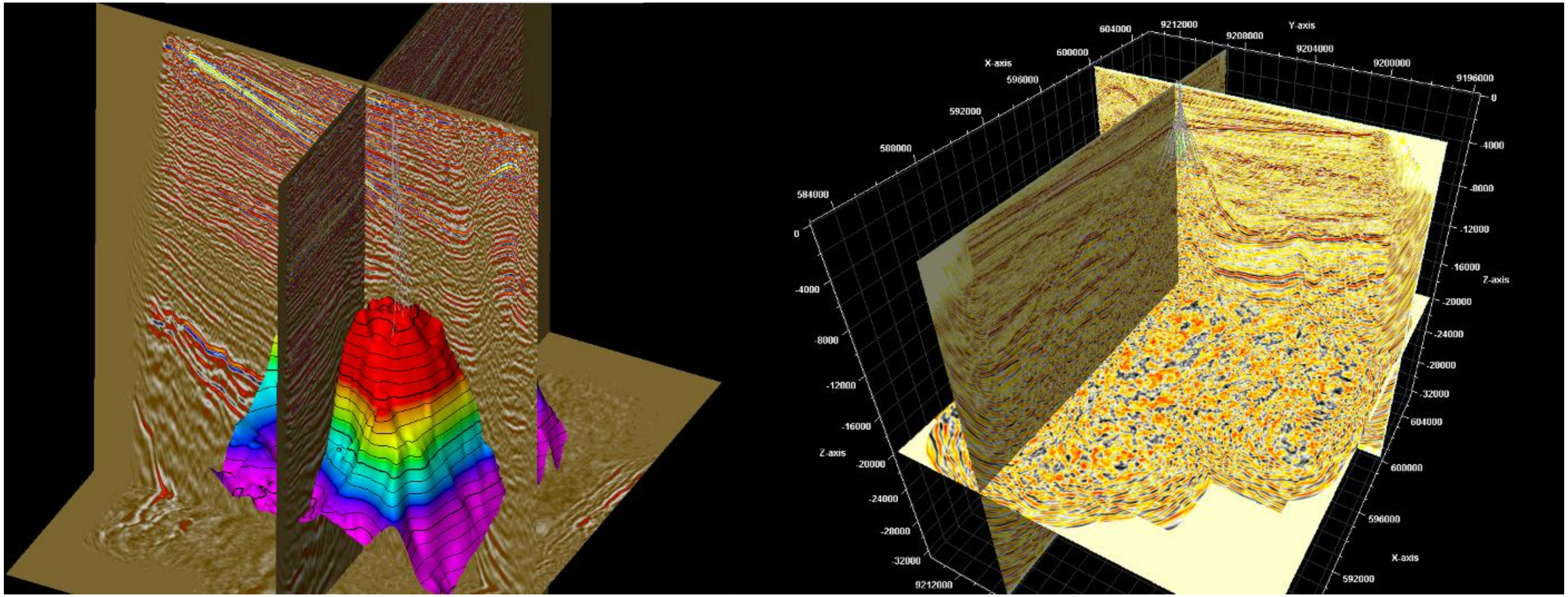

Figure 3. (a). Tuban reef subsurface mapping (b). 3D PSTM seismic cube from old survey

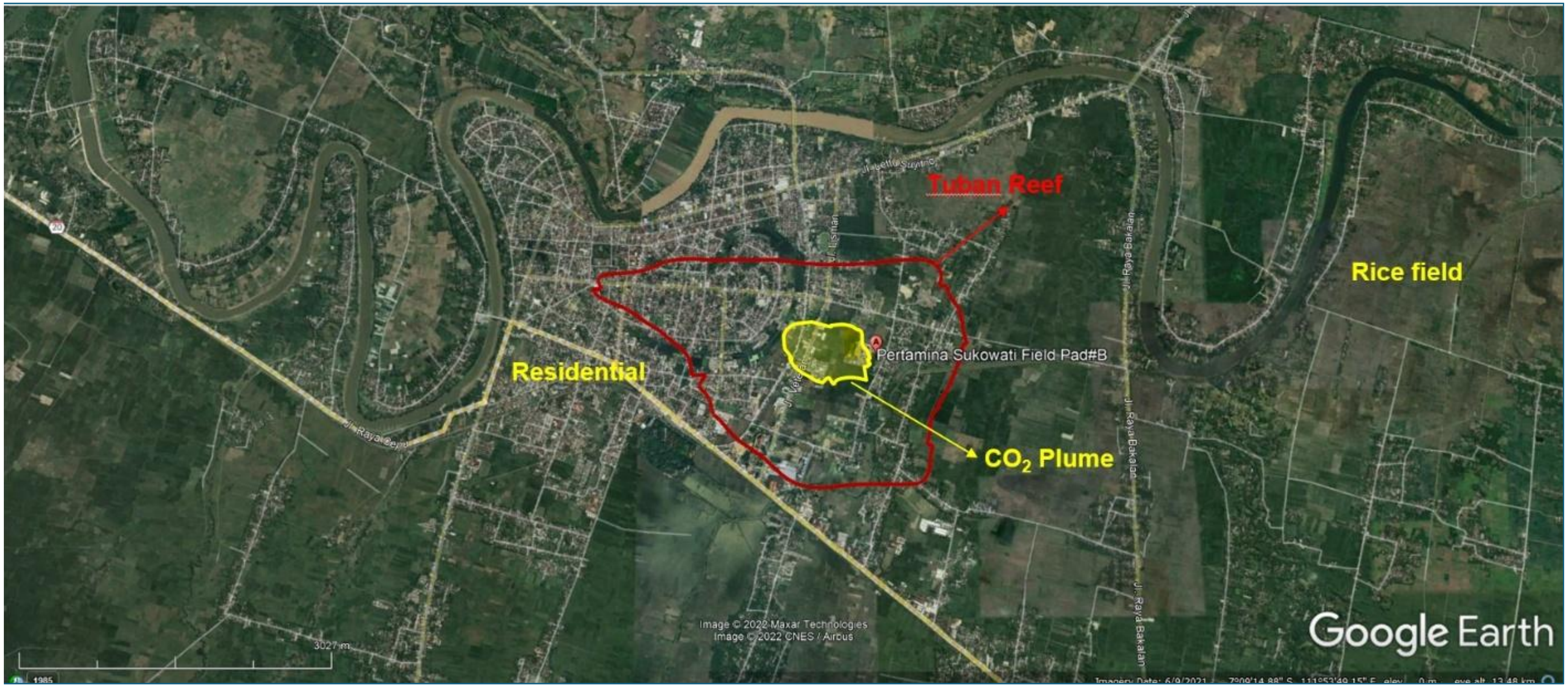

Figure 4. Tuban Reef formation and CO_2 plume (model) reflected in the surface area.

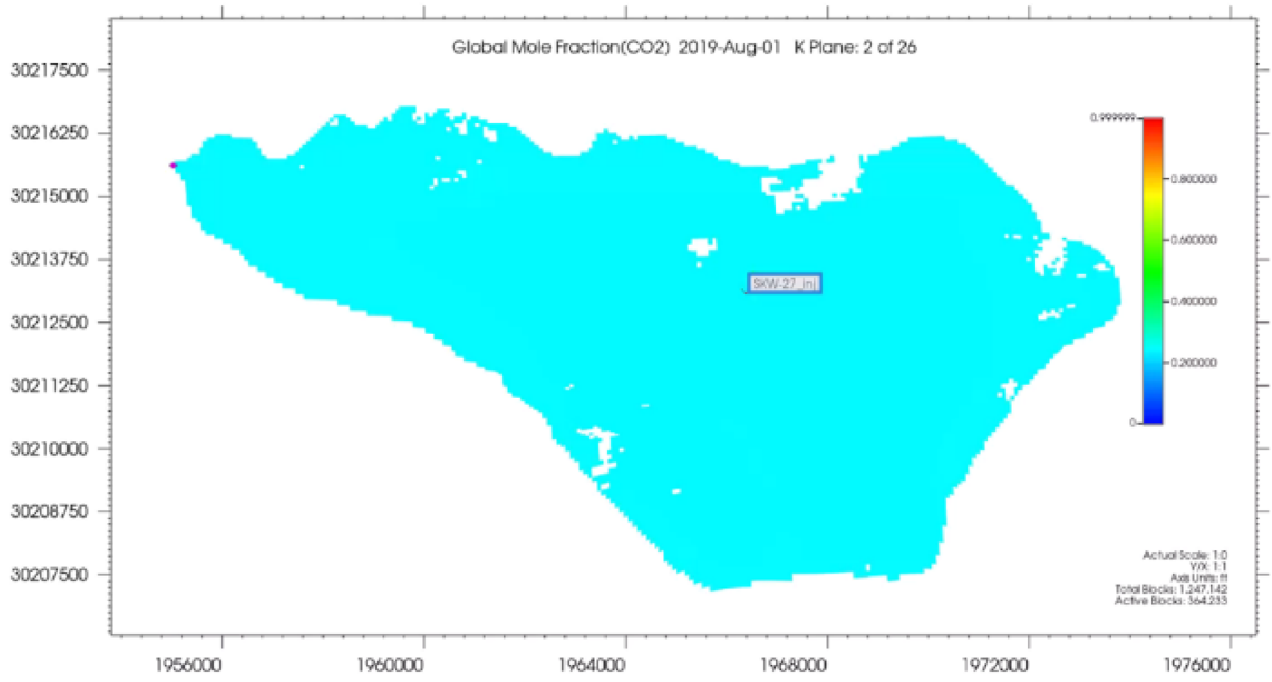

Figure 5. The distribution of CO_2 gas before the injection started

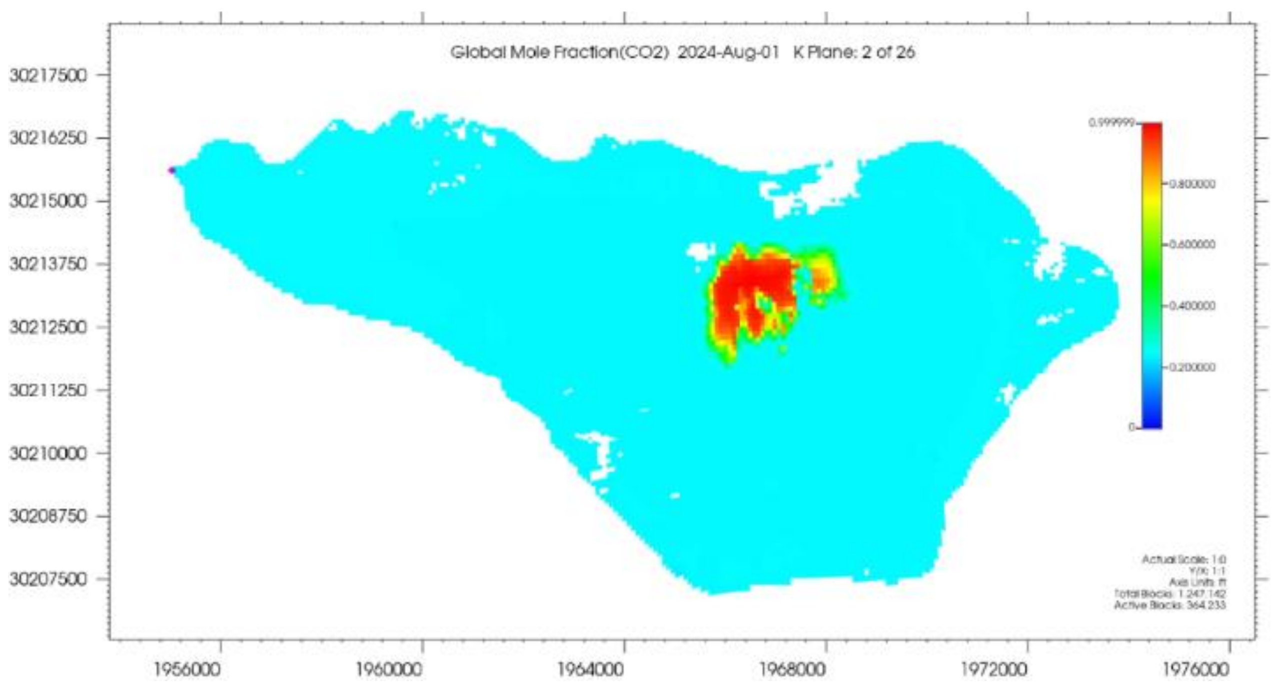

Figure 6. The distribution of CO_2 gas after 5 years of injection.

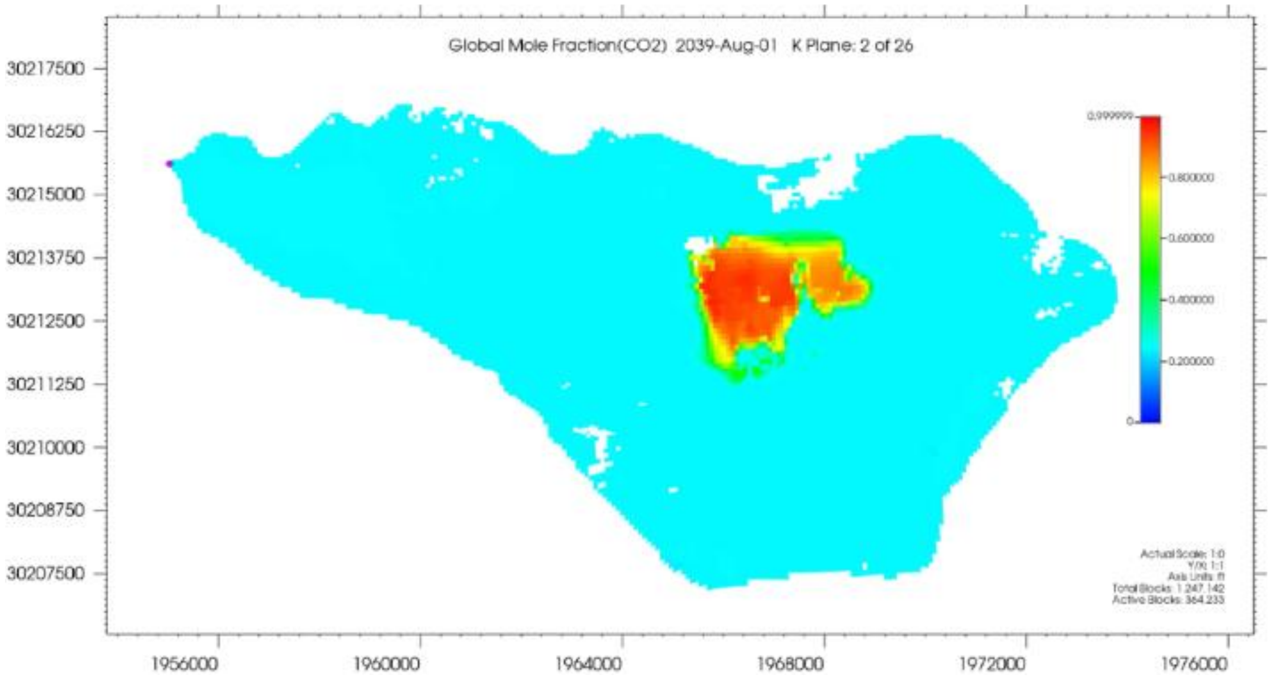

Figure 7. The distribution of CO_2 gas after 20 years of injection.

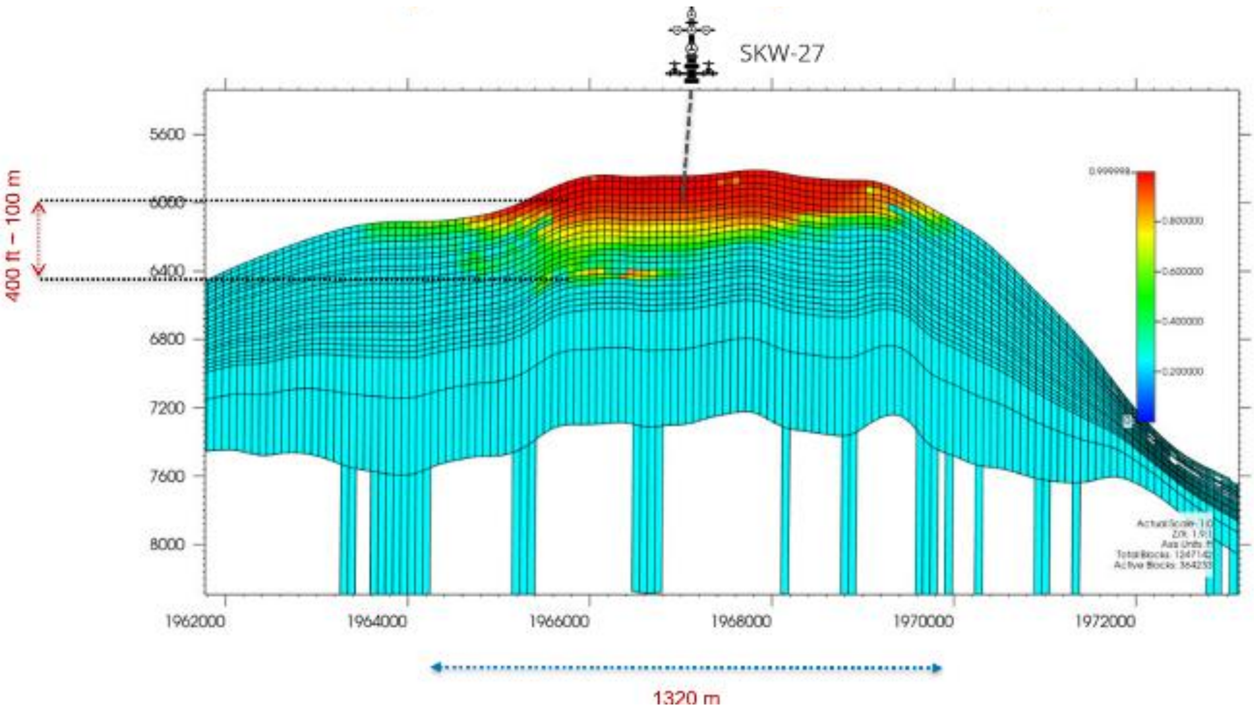

Figure 8
Vertical distribution of the CO2 plume after 20 years of injection.

RESULTS AND DISCUSSION

4D seismic acquisition design

The adoption of modern seismic technologies has markedly enhanced the practicality and efficiency of subsurface monitoring, especially in areas that were previously inaccessible or posed significant logistical challenges. This research used the semi-permanent seismic sources namely the Surface Linear Vibrator (SLV) and Surface Orbital Vibrator (SOV) as effective substitutes for conventional Vibroseis systems in time-lapse (4D) seismic applications. A key advantage of SLV and SOV lies in their stationary deployment, which ensures consistent source positioning across repeated surveys. This stability is crucial for maintaining spatial coherence in temporal imaging and directly addresses a major limitation in 4D seismic interpretation, where even slight shifts in source location can lead to substantial errors. Empirical deployments in regions such as Texas and California have demonstrated the operational viability of these systems, particularly for long-term reservoir surveillance. While SLV shares operational principles with Vibroseis, its smaller footprint and reduced signal penetration depth make it more suitable for near-surface monitoring. Furthermore, installation at depths between 3 and 30 meters helps suppress surface noise and environmental variability, including meteorological and human-induced disturbances, thereby improving data integrity. From an operational and economic standpoint, semi-permanent sources offer significant advantages. Unlike mobile Vibroseis units that require extensive logistical coordination and may disrupt local infrastructure, SLV and SOV systems present a low-impact, maintenance-efficient alternative. This approach aligns with the industry's broader commitment to sustainable geophysical practices (Li et al., 2023).

Moreover, when paired with wireless receiver technologies such as STRYDE nodes, the SLV/SOV system represents a transformative shift toward cost-effective and environmentally responsible seismic surveying. Wireless nodes, which are compact and lightweight, streamline deployment by reducing crew size and eliminating the need for cabling. With unit costs ranging from $50 to $100 and deployment expenses estimated at $500 to $2,000 per square kilometer, these receivers offer a scalable solution compared to traditional geophone arrays (Tranter et al., 2022). Although the initial cAmerican petroleum institute tal investment for SLV/SOV systems ranges from $100,000 to $300,000 per unit, and installation costs vary between $10,000 and $50,000 per site, these expenses are offset by long-term operational savings. The fixed-source configuration eliminates repeated mobilization and alignment, thereby reducing labor and logistical overhead. In practice, a 3D survey covering 10 km² using this hybrid approach may cost between $50,000 and $100,000, whereas conventional methods could exceed $150,000 for similar coverage. Additionally, the embedded nature of SLV/SOV sources minimizes surface disruption and mitigates environmental noise, further enhancing data quality. Overall, this integrated methodology supports the industry's transition toward lower-carbon, infrastructure-friendly seismic operations, offering a compelling alternative for repeated and long-duration subsurface monitoring.

The design of seismic surveys for acquisitions depends on numerous input parameters and constraints, making it quite an intricate process. When laying out lines of sources and receivers, one must consider the expected results carefully. A thorough understanding of the necessary geophysical parameters is essential before starting a 4D design project. The seismic acquisition survey must be specifically designed to focus on the CO_2 plume target zone. The ability of the seismic method to identify the CO_2 plume in terms of lateral/horizontal resolution is related to the Fresnel Zone, which is generally one-fourth of the signal wavelength (λ/4). However, since the recorded reflection signal originates from a disk-shaped area with three-dimensional dimensions, the radius of the Fresnel Zone is given by:

$$R_f = \frac{V}{2}\sqrt{\frac{t_0}{f_{dom}}} \quad (1)$$

The frequency and velocity within the target zone will enhance the resolution of the seismic survey. This will notably influence the project's economic viability by determining the selection of parameters for the survey. Factors such as fold, bin size, and offset range must be tailored to address the main target. The distribution of offsets and azimuths is essential and should be carefully evaluated through various proposed templates for three-dimensional seismic design (Triyoso et al., 2023). Additionally, the orientation of major geological features, such as faults or channels, may affect the alignment of the receiver and source lines. In this 4D seismic simulation, three seismic surveys will be conducted. Figure 9 shows the proposed design of the 4D seismic acquisition in Sukowati. The first will serve as a baseline survey, the second will occur five years after the start of injection, and the final survey will take place after twenty years of injection, marking the end of the injection period. The key issue in 4D seismic surveys is the repeatability of the survey design, which refers to how accurately seismic measurements can be replicated (Landro, 2010). In densely populated urban areas that are continuously expanding, achieving ideal survey repeatability can be quite challenging. In this simulation, the number of sources and receivers was strategically varied while keeping them consistently positioned in the same location.

This deliberate approach effectively analyses the impact of these variations on results. The survey acquisition design will differ for each timeframe due to changes in population conditions in the area, as this is a densely populated urban city. For the baseline survey, the conditions are rarely ideal. However, by the five-year mark, placing seismic instruments in the area becomes increasingly challenging, leading us to assume that only 50% of the original number can be utilized. Furthermore, by the conclusion of the twenty-year injection period, the design for the instrument survey is projected to incorporate only 25% of the initial baseline survey design. The seismic source utilized in this survey is a vibroseis mounted on a truck, allowing for easy mobilization and shot point positioning on highways or paved roads. Meanwhile, the receiver, which uses wireless seismic nodes, is placed in areas with soil, primarily in rice fields and pedestrian zones. The number of folds controls the signal-to-noise ratio (S/N). Factors that can impact the quality of 4D seismic include the position (x, y, and z coordinates) of both the source and receiver, as well as noise from surrounding activities, such as human interference.

Table 2. Baseline seismic design

Parameter:	
Source Type	Vibroseis
Source Lines	31
Total Source	759
Source spacing	100 m
Receiver Type	Seismic Node
Receiver Spacing	40
Number of receivers	1,200
Receiver lines	12
Receiver lines spacing	375 m
Bin Width	40 m
Bin Height	40 m
Inline Bin Bearing	30
Max Fold	250
Max Offset	7,580 m

Table 3. Seismic design after 5 years

Parameter:	
Source Type	Vibroseis
Source Lines	31
Total Source	374
Source spacing	200 m
Receiver Type	Seismic Node
Receiver Spacing	80
Number of receivers	600
Receiver lines	12
Receiver lines spacing	375 m
Bin Width	80 m
Bin Height	80 m
Inline Bin Bearing	30
Max Fold	117
Max Offset	7,580 m

Table 4. Seismic design after 20 years

Parameter:	
Source Type	Vibroseis
Source Lines	31
Total Source	374
Source spacing	200 m
Receiver Type	Seismic Node
Receiver Spacing	160
Number of receivers	300
Receiver lines	12
Receiver lines spacing	375 m
Bin Width	80 m
Bin Height	80 m
Inline Bin Bearing	30
Max Fold	115
Max Offset	7,580 m

Figure 9 illustrates each survey's design, with red dots for shot points, light blue crosses for receiver nodes, and a black square polygon in the centre indicating the CO_2 plume target area after 20 years of injection. This Figure illustrates the seismic fold coverage on surface seismic for each design. The colour scale represents the number of folds achieved in each survey, with the target area consistently exceeding 90 folds, more than sufficient for detecting the CO_2 plume. Figure 10 present the illuminations hitmap on the subsurface Tuban Formation for each survey conducted. Additionally, Figure 11 illustrate the azimuth and offset for each survey. This visualization is used in seismic survey design to assess how well seismic waves illuminate subsurface structures. It helps geophysicists to understand the effectiveness of a seismic acquisition setup by showing areas with strong or weak wave coverage. The colour scale indicates the intensity of seismic waves in each survey area, with the red colour representing a maximum of 70 hit seismic waves, which are more effective for detecting the CO_2 plume.

4D seismic modeling and processing

In this study, ray-tracing modelling was conducted within a heterogeneous geological medium using NORSAR modelling software. This advanced tool integrates key parameters such as density, interval velocity, and geological horizon boundaries, enabling a detailed evaluation of subsurface properties. Utilizing the Wave-Front Construction (WFC) method, theoretical seismic waves are generated to propagate through an elastic earth model, employing a three-dimensional seismic acquisition strategy that improves the precision of the simulations. To evaluate the influence of seismic acquisition parameters, ray characteristics, including travel times, amplitudes, and illumination maps, were developed for the target horizon and depth. For every seismic survey shot, we synthesized seismic shot gathers leveraging these ray attributes, effectively simulating how seismic waves would propagate through the varied subsurface layers (Triyoso et al., 2024).

The next phase involved the migration of the post-stack section, achieved by implementing a systematic processing sequence that ensures clarity and precision in our results. This synthetic post-stack migrated section was then critically compared against the post-stack migrated section from a prior survey, as well as the brute stack section from the selected seismic survey, allowing us to identify and analyze differences in subsurface features. The physical properties incorporated within this geological model were derived from the averaging of velocity and density across the various formations, as illustrated in the accompanying data Table 3. In addition, theoretical rock physics models were incorporated, serving a crucial role in time-lapse seismic analysis. Specifically, we estimated changes in seismic velocity induced by CO_2 injection within the target formation, using the Gassmann-Biot (1941) fluid substitution theory as the foundational framework to interpret these variations.

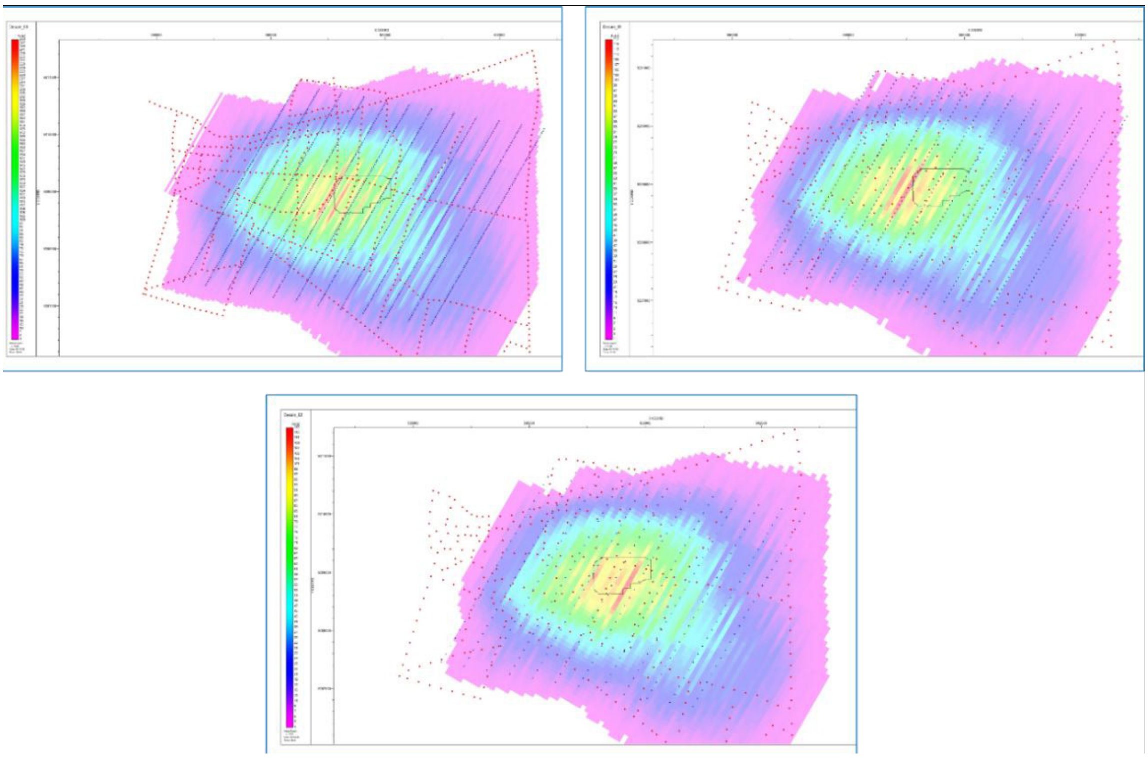

Figure 9. 4D Seismic survey design for each model (a) baseline, (b) 5 years, (c) 20 years injection. The red dots are source locations, and the blue dots are receiver locations.

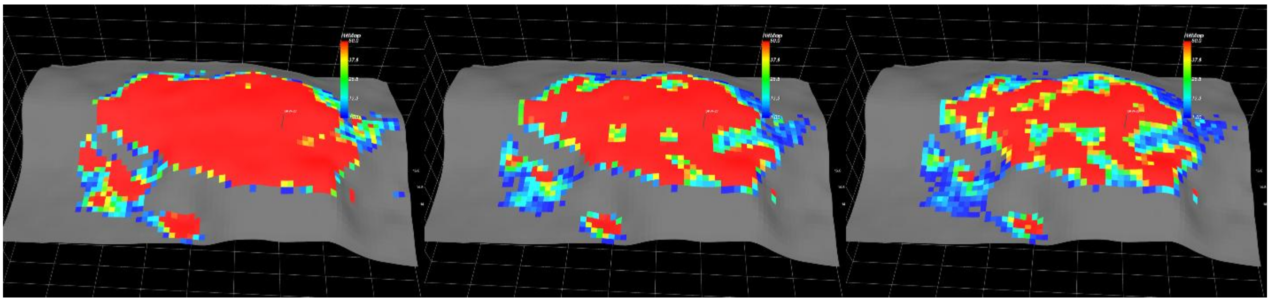

Figure 10. Illumination Hitmap of seismic on target formation (a). Baseline, (b). Design after 5 years, (c). Design after 20 years.

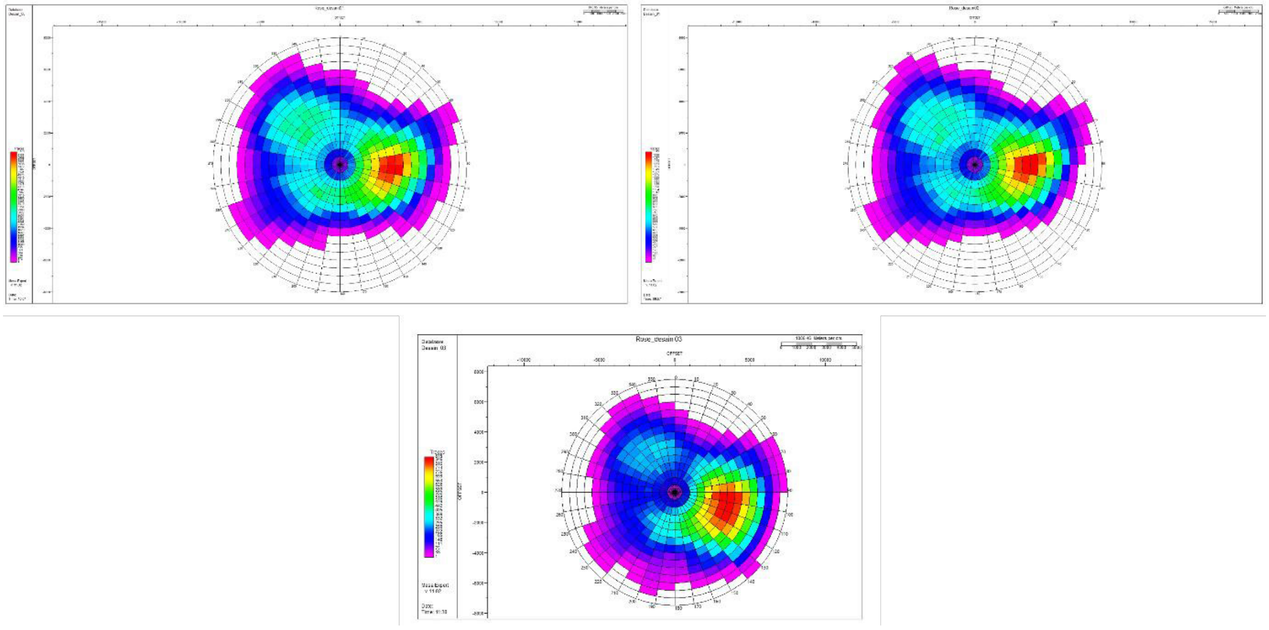

Figure 11. Rose diagram (azimuth and offset distribution) (a). Baseline design, (b). Design after 5 years, (c). Design after 20 years.

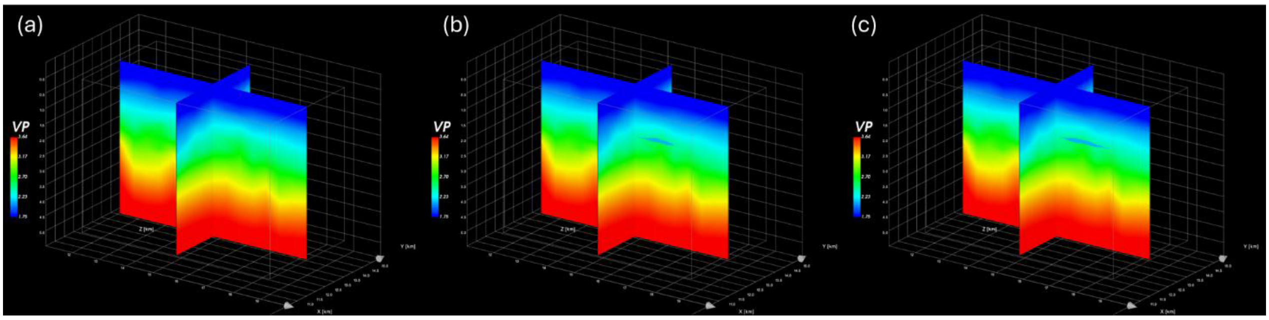

Figure 12. Velocity model of Sukowati oil field (a). Baseline model, (b). CO_2 model after 5 years, (c). CO_2 model after 20 years.

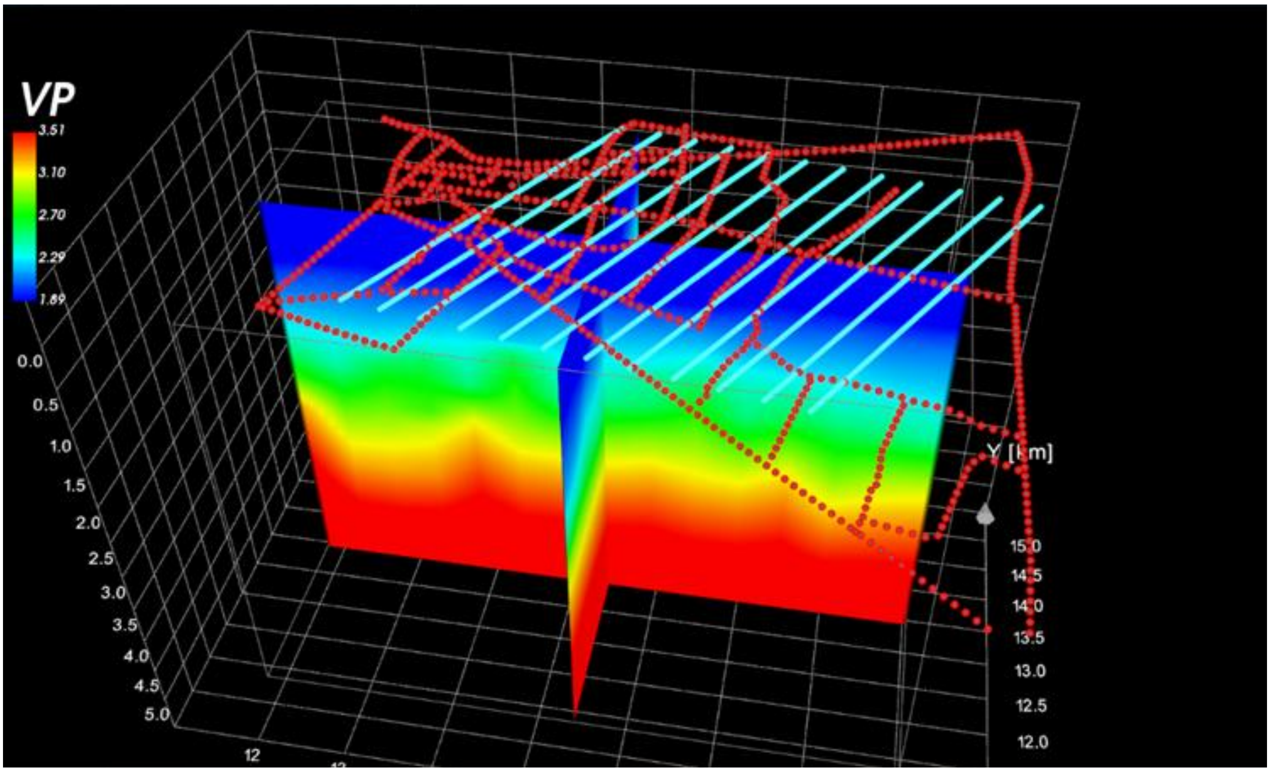

Figure 13. WFC seismic modeling design example (baseline). The red dots are source locations, and the blue lines are receiver locations.

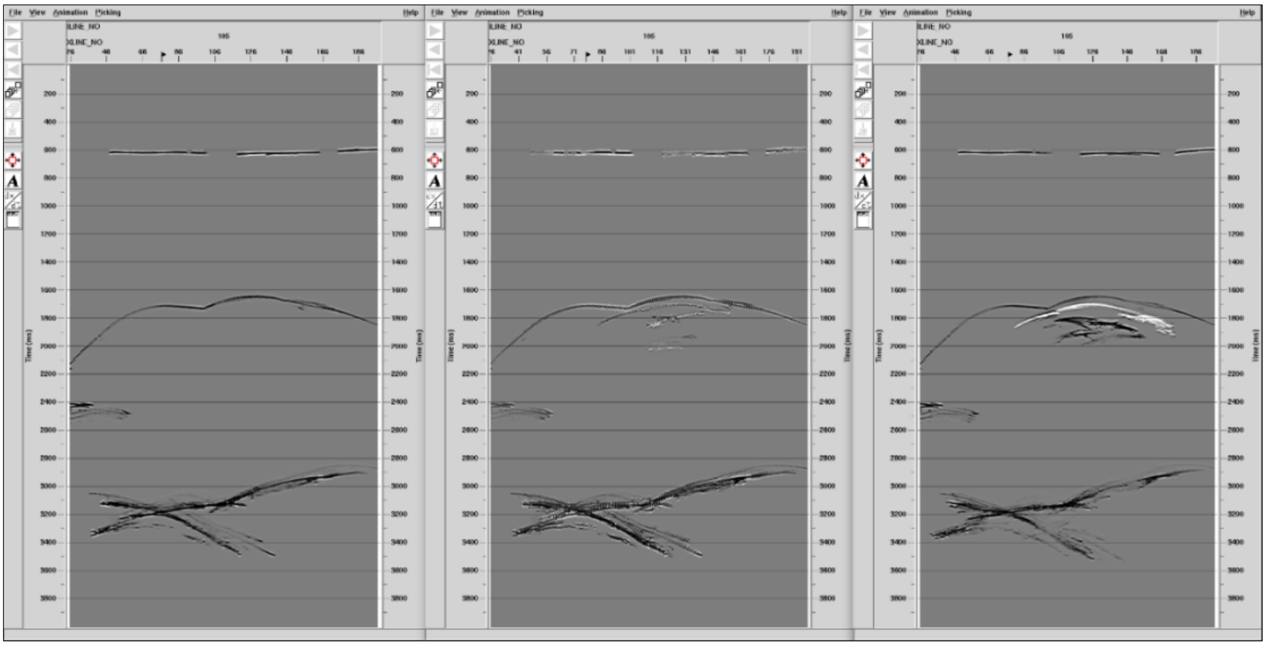

Figure 14. 4D Seismic stack model without noise (a). Baseline, (b). After 5 years, (c). After 20 years

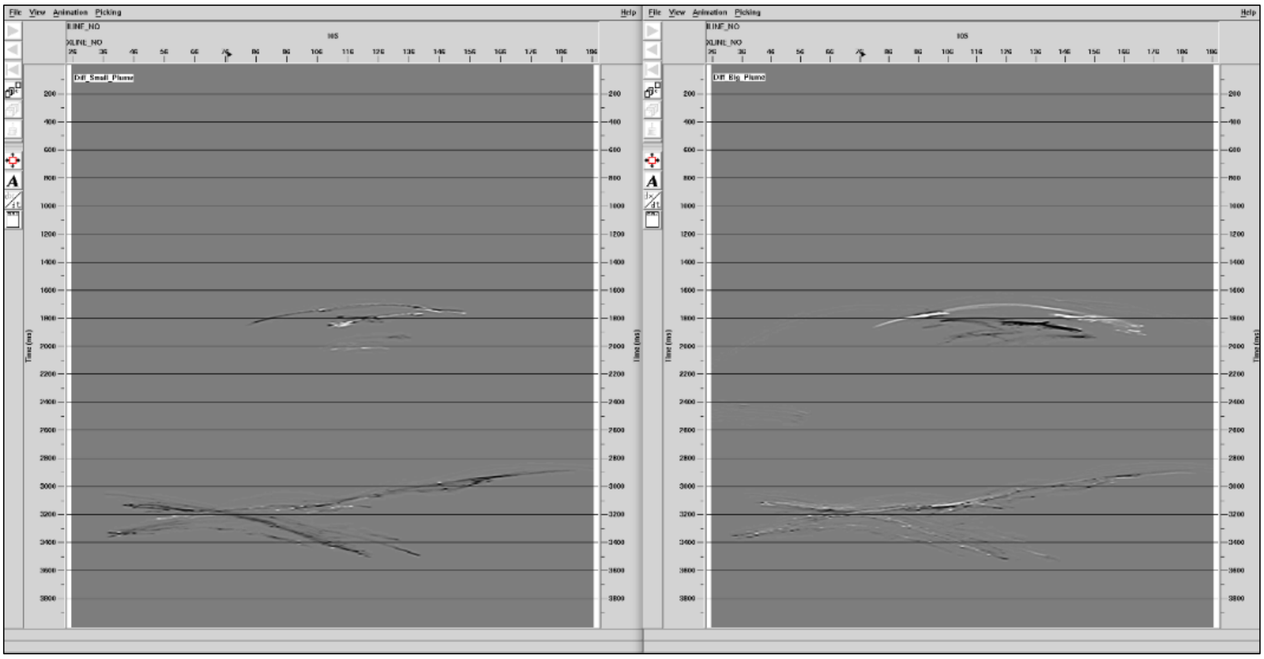

Figure 15. Different Seismic stack models with (a). Baseline vs 5 years, (b). Baseline vs 20 years.

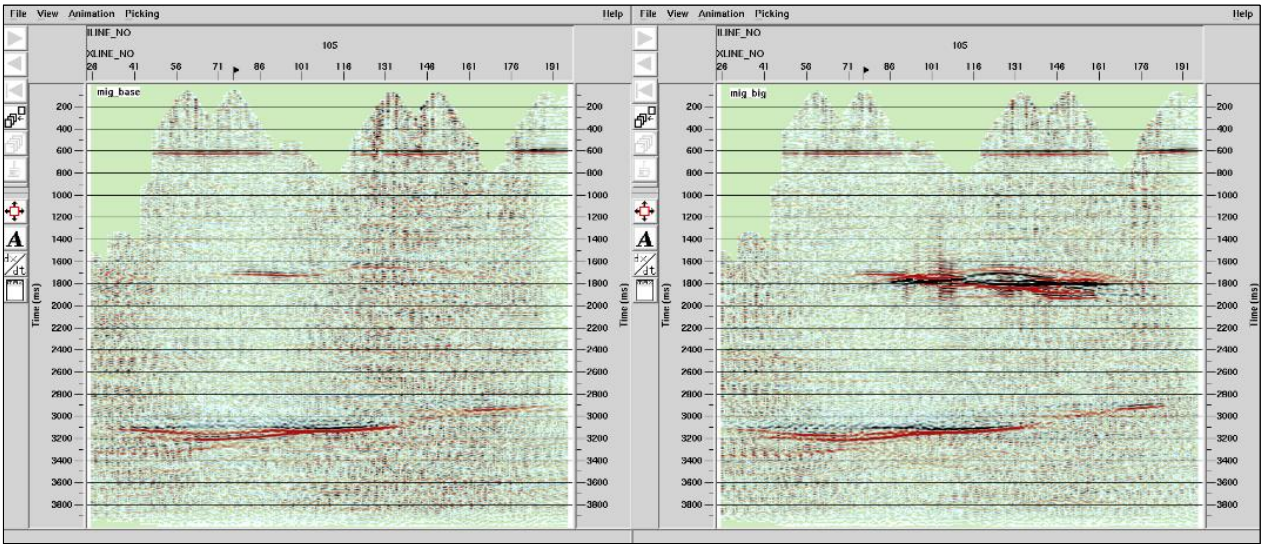

Figure 16. Seismic after migration with random noise (a). Baseline (b). After Injection 20 years.

CONCLUSIONS

The results of 4D seismic modelling provide valuable insights into acquisition design utilizing SLV/SOV and wireless geophones in populated areas. The CO_2 plumes in the target injection zones are clearly identified and can be effectively imaged through 4D seismic methods. Additionally, the costs associated with this type of acquisition can be reduced by 10-30%, while also making the social impact on local residents more acceptable. However, the operation of SLV/SOV may present several challenges, such as noise disturbances from surrounding activities. This issue can be mitigated by employing highly sensitive wireless geophones to record baseline noise levels, allowing for more efficient noise removal during the seismic processing stage. Demonstrating consistency between simulated reservoir performance and monitoring observations is a primary regulatory requirement that must be fulfilled. The effectiveness of simulating reservoir behaviour and analysing monitoring data for conformance assessment is significantly influenced by the specific conditions of the storage site. Understanding these factors is crucial for optimizing performance and ensuring the integrity of the system.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
CCUS	Carbon Capture, Utilization, and Storage	
MBOPD	Thousand Barrels of Oil Per Day	
BSCF	Billion Standard Cubic Feet	
MSTB	Thousands of Stock Tank Barrels	
EOR	Enhanced Oil and Recovery	
EGR	Enhanced Gas and Recovery	
API	American Petroleum Institute	
SLV	Surface Linear Vibrator	
SOV	Surface Orbital Vibrator	
WFC	Wave-Front Construction	

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