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Application of 2D Seismic Modeling in Gas Hydrate Reservoir Characterization

Welayaturromadhona[1]*, How-Wei Chen[2]

[1]Petroleum Engineering, Universitas Jember, Jember 68121, Indonesia
[2]College of Earth Sciences, National Central University, Zhongli, 320317, Taiwan

*Corresponding author. Email: wela@unej.ac.id

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Abstract

Gas hydrate reservoirs represent a significant unconventional energy resource with considerable potential for future energy supply and climate-related studies. However, their complex subsurface occurrence requires advanced geophysical methods for accurate detection and characterization. This study presents the application of two-dimensional (2D) seismic modeling to evaluate the seismic response of gas hydrate-bearing sediments and underlying free gas zones. The objective is to assess the reflection coefficients and amplitude variation with offset (AVO) to enhance the interpretation of subsurface features. The synthetic model is constructed using multichannel seismic data and velocity profiles derived from previous studies. Seismic wave propagation is simulated to observe the impedance contrasts across various subsurface layers. Results reveal that the Bottom Simulating Reflector (BSR), a key seismic indicator of gas hydrate presence, exhibits strong negative reflection amplitudes due to the presence of underlying free gas, which significantly reduces seismic velocity. Furthermore, AVO analysis shows that amplitude variations are highly sensitive to the acoustic impedance contrast at the hydrate-gas interface. These findings demonstrate the effectiveness of seismic modeling in improving gas hydrate reservoir characterization and provide a foundation for more accurate exploration strategies. The study contributes to both energy development and environmental monitoring efforts involving gas hydrates.

Keywords: AVO analysis; BSR; gas hydrate; geophysical exploration; seismic modeling.

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Introduction

Under high pressure and low temperature, gas molecules, mostly methane, are encased in a water lattice to form crystalline solids known as gas hydrates (Ruppel & Waite, 2020; Jin et al., 2022). They are usually found in areas with permafrost and marine deposits, where the climate keeps them stable (Ruppel & Kessler, 2017; Zhao, 2020). These hydrates have garnered interest because of their potential to contribute to climate change as a source of energy. Their study is essential for energy security and environmental monitoring since they are large methane reservoirs whose destabilization could result in large greenhouse gas emissions (Yu et al, 2021).

In geophysical terms, seismic techniques are frequently used to detect gas hydrates, and one important indicator is the Bottom Simulating Reflector (BSR). According to Neves et al. (2022) and Zhang et al. (2020), the BSR is a characteristic seismic reflection that happens at the border between hydrate-laden sediments and underlying free gas zones. There is a significant impedance contrast when gas hydrates are present because they change the subsurface elastic characteristics, raising seismic wave velocities, while the free gas zones below lower these speeds

(Wang et al., 2021; Waite et al., 2009). The inability of conventional seismic interpretation methods to distinguish hydrate accumulations from other geological formations, however, can result in reservoir calculation errors (Liu et al., 2021; Xing et al., 2018; Zhang et al., 2020).

To address these challenges, advanced seismic modeling techniques, such as two-dimensional (2D) seismic modeling, have been employed to enhance gas hydrate reservoir characterization. These methods simulate wave propagation through hydrate-bearing sediments and assess key seismic attributes like reflection coefficients and Amplitude Versus Offset (AVO) responses (Ecker et al., 1998; Liang, et al., 2020; Qian, et al., 2022). This approach offers a more detailed understanding of hydrate distribution and their effect on seismic wave behavior, aiding in more accurate reservoir characterization.

This study investigates the application of 2D seismic modeling in characterizing gas hydrate reservoirs, focusing on analyzing reflection amplitude variations and AVO attributes to improve the reliability of seismic interpretation. The findings aim to enhance current gas hydrate exploration techniques and contribute to the development of geophysical methodologies for assessing unconventional resources.

Although research on gas hydrate detection using seismic methods is increasing, there is still a gap in integrating detailed two-dimensional (2D) seismic modeling with amplitude variation with offset (AVO) analysis. Previous studies have often used simplified models or focused only on either seismic modeling or AVO analysis, without fully combining both techniques in a controlled synthetic setting. This study addresses this gap by developing a detailed 2D seismic model of a gas hydrate reservoir and simulating seismic responses to study AVO characteristics, aiming to improve the understanding of gas hydrate indicators such as bottom simulating reflectors (BSRs) and their elastic property contrasts.

The results of this research are crucial for improving gas hydrate detection, which can directly impact future exploration and drilling safety by providing more accurate assessments of reservoir properties and reducing risks associated with gas hydrate-related hazards

Materials and Methods

The wave equation, which comes from Hooke's law of elasticity and Newton's second law of motion, is used to model the propagation of seismic waves. A two-dimensional (2D) seismic model was created for this study to examine the seismic response of sediments that contain gas hydrate. To mimic wave behavior in various subsurface layers, the model includes important elastic parameters such as density (ρ), S-wave velocity (Vs), and P-wave velocity (Vp).

Mathematically, the propagation of seismic waves can be described by solving the wave equation, which is based on two fundamental laws of physics: Newton's second law of motion ($F = m.a$) and Hooke's law of elasticity (related to stress and deformation). Properties of an isotropic elastic medium are described by three spatial-varying parameters: compression-wave velocity $Vp(x_1,x_3)$, shear-wave velocity $Vs(x_1,x_3)$ and density $\rho(x_1,x_3)$. These parameters are functions of the elastic constants and determine the propagation behavior of P-waves and S-waves in the subsurface.

Aki – Richards' approximation explains how seismic amplitudes change with rock qualities and incidence angles, was used to estimate the reflection coefficient. Furthermore, amplitude fluctuations as a function of offset were evaluated using AVO analysis, which shed light on the existence of free gas zones and gas hydrates. Figure 1 shows the layer model, while Table 1 shows the parameters used in the numerical simulation.

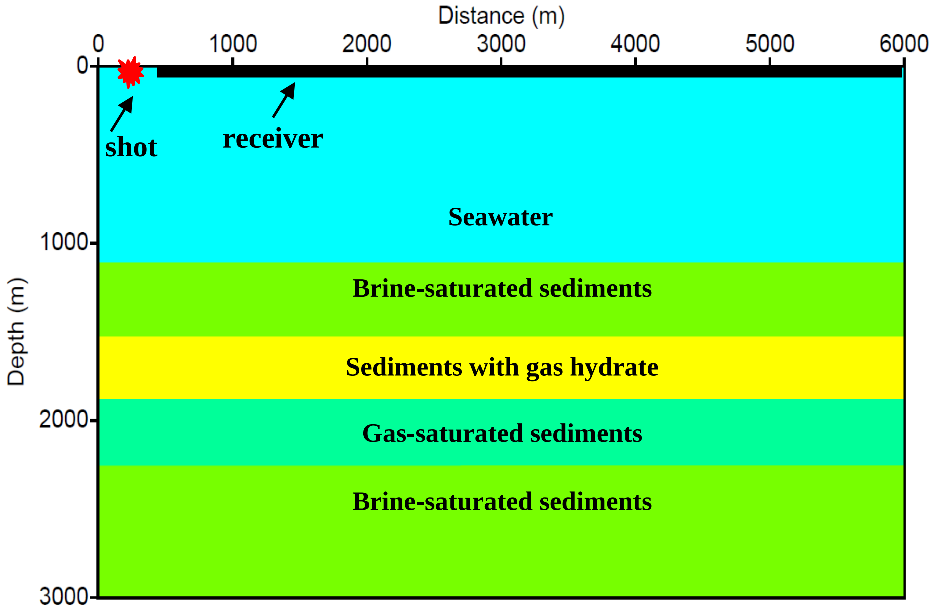

Figure 1: Layer model.

Table 1. The model parameters.

Model parameter	P-wave Vp (km/s)	S-wave Vs (km/s)	Density ρ (g/cm^3)	Poisson's ratio σ
Seawater	1.50	0.00	1.00	0.5
Brine-saturated sediments	2.37	1.10	2.17	0.36
Sediments with gas hydrate	2.70	1.11	2.11	0.39
Gas-saturated sediments	1.74	1.13	2.05	0.13
Brine-saturated sediments	2.37	1.10	2.17	0.36

We modelled the seafloor reflection to provide precise reference calibration. Assuming a seabed velocity of 1.5 km/s, the Poisson's ratio for deep-sea sediments was calculated to be 0.5 using Hamilton's (1979) work and Castagna et al.'s (1985) empirical correlation between Poisson's ratio and P-wave velocity (Vp). While gas-saturated sediments have a velocity of 1.74 km/s, the chosen velocity for sediments carrying gas hydrates is roughly 2.7 km/s. The synthetic seismogram produced for a 6 km receiver streamer with 468 channels separated by 12.5 m is shown in Figure 2. The depths of the source and receiver are 8 and 9 meters, respectively. The overall recorded wave duration is 4 seconds with a sample interval of 2 ms, using a Ricker wavelet with a dominant frequency of 20 Hz.

We analyzed the changes in reflection coefficients by varying Vp and Vs values to determine how gas saturation influences seismic amplitude. This approach provides a quantitative method to characterize gas hydrate reservoirs and distinguish them from surrounding sediments.

Results and Discussion

The border of the hydrate-bearing sediment generates a high-amplitude reflection because changes in elastic impedance (the product of velocity and density) determine the strength of the reflected signal. The BSR is a special kind of seismic reflector that lies parallel to the seafloor and has the opposite polarity from the seafloor reflection.

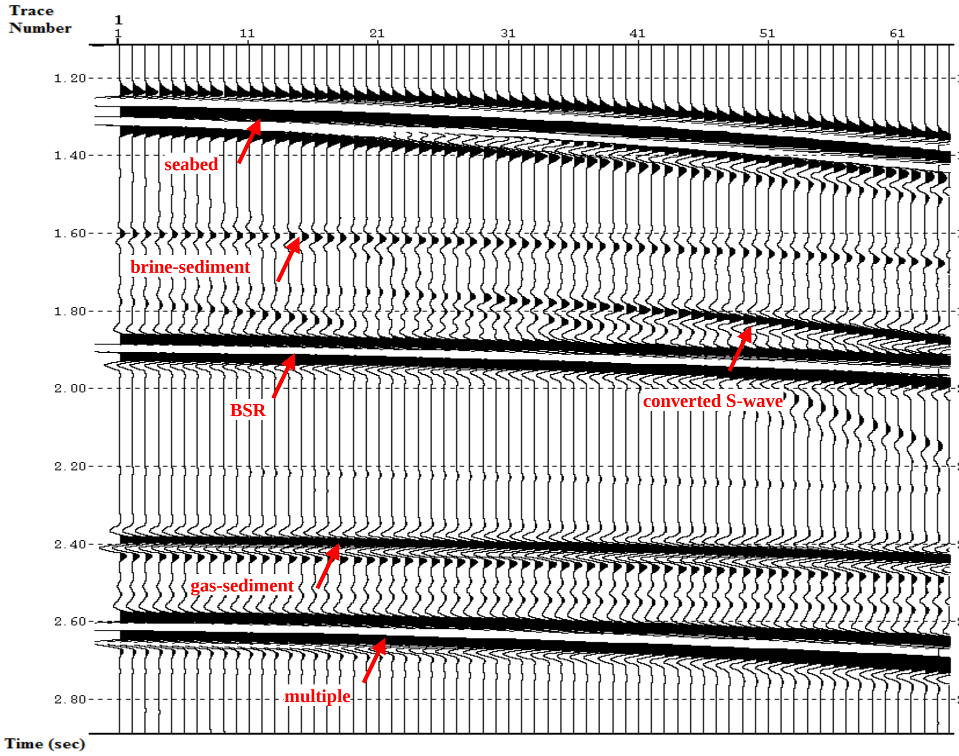

Figure 2. Synthetic seismograms for models with free gas and gas hydrates.

The BSR represents an interface where elastic impedance decreases. A higher P-wave velocity above the BSR and an abnormally low S-wave velocity in comparison to the underlying layer are the causes of this phenomena (Xing et al., 2018; Hakimi et al., 2016, Zhang et al 2015). A substantial velocity contrast is suggested by the large reflection amplitude just under the hydrate layer, which could point to the existence of a free gas layer.

Elastic isotropic circumstances were used to measure and assess the BSR's reflection coefficient to better understand this behavior. For comparison, we also used the Aki and Richards approximation to determine the reflection coefficient, and Figure 3 shows the AVO response for gas-bearing sediments. The findings show that there is an increasing amplitude in the absolute values of the gas-saturated sediment curve. Important markers of free gas at an interface can be found in variations in reflection amplitude with offset or incidence angle (Kim et al., 2020; Ryu & Riedel, 2017).

Reflection amplitudes grow more negative as the incidence angle or offset increases when hydrate-bearing sediments with a normal Poisson's ratio give way to an underlying gas-bearing sediment with a reduced Poisson's ratio (Minshull & White, 1989). Shear velocity (Vs), compressional velocity (Vp), and density distribution all affect the amplitude of BSR reflections as a function of source-receiver offset, but Poisson's ratio contrast is the main determinant of AVO behavior.

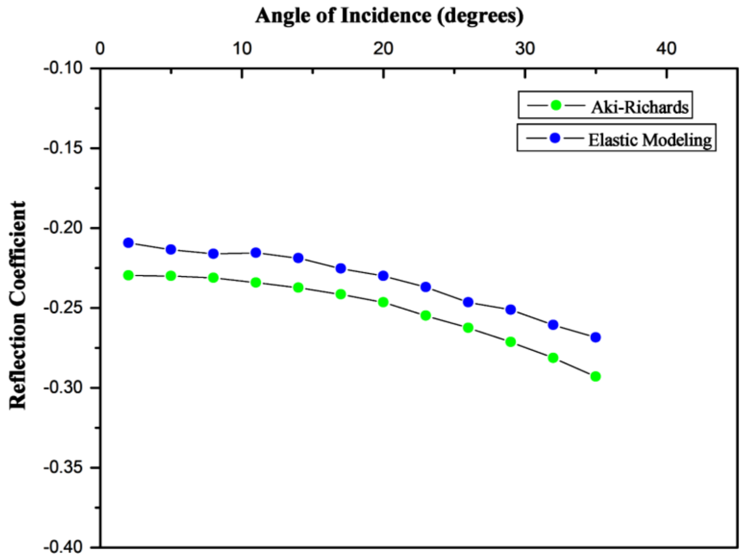

Figure 3. The BSR's reflection coefficients (RC). As the incidence angle rises, the RC shows a downward trend. According to Aki-Richard's theory, the layer-over-half-space model's predicted RC seems to be understated. A 0.02 scaling factor is used.

According to the established model, the P-wave velocity (Vp) of gas-saturated sediment is approximately 1.74 km/s, whereas the Vp of hydrate-bearing sediment is around 2.7 km/s. Above the hydrate layer and below the gas-saturated sediment, the surrounding lithology is composed of brine-saturated sediments with a Vp of approximately 2.37 km/s (Ecker et al., 1998). To examine how velocity variations affect the reflection coefficient, Vp and shear-wave velocity (Vs) were adjusted independently. Initially, Vp was altered by increasing or decreasing it by 5%, 25%, and 65%, and the reflection coefficient was computed using Aki and Richards' approximation. The findings indicate that a rise in Vp results in a lower reflection coefficient, while a reduction in Vp leads to a higher (more negative) reflection coefficient as shown in Figure 4. A comparable pattern emerges when both Vp and Vs are simultaneously adjusted (Figure 5). Increasing Vp and Vs leads to a decrease in the reflection coefficient, whereas decreasing them causes the coefficient to rise (becoming more negative). This analysis helps to understand how variations in Vp and Vs influence reflection coefficients, providing valuable insights for interpreting seismic data related to gas hydrates.

By showing amplitude fluctuations with increasing offset, AVO study provides additional evidence for the identification of gas hydrates and underlying free gas. The hydrate-bearing sediments produce a moderate increase in reflection amplitude, whereas the free gas zone exhibits a strong AVO response, characterized by an increasing amplitude trend with offset. These results are consistent with established AVO classification models for gas-saturated sediments. The strong AVO response confirms that gas hydrate reservoirs can be effectively distinguished using amplitude-based seismic attributes. The observed amplitude variation provides valuable insights into subsurface fluid distribution, supporting the interpretation that free gas accumulations exist beneath the hydrate layer.

These findings highlight the effectiveness of 2D seismic modeling in characterizing gas hydrate reservoirs. The identification of strong BSR reflections and AVO anomalies confirms that seismic attributes serve as reliable indicators for gas hydrate deposits. This is particularly relevant for exploration strategies aimed at assessing gas hydrate potential as an alternative energy resource. Furthermore, distinguishing hydrate-bearing sediments from free gas zones is crucial for risk assessment in offshore drilling operations, as understanding the seismic response of gas hydrates helps mitigate potential hazards associated with gas release and sediment destabilization.

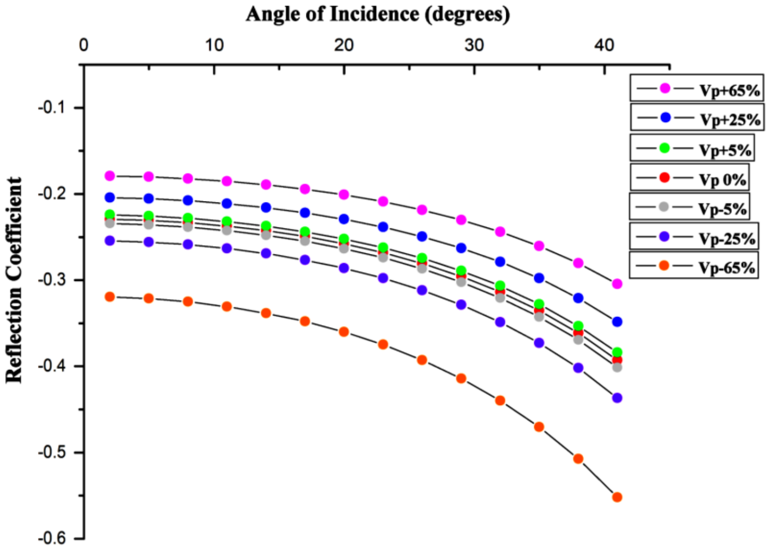

Figure 4. Reflection coefficient values fluctuate in response to variations in P-wave velocity (Vp). The Vp is adjusted by -65%, -25%, -5%, 0%, +5%, +25%, and +65%. An increase in Vp results in a lower reflection coefficient, whereas a decrease in Vp leads to a higher (more negative) reflection coefficient.

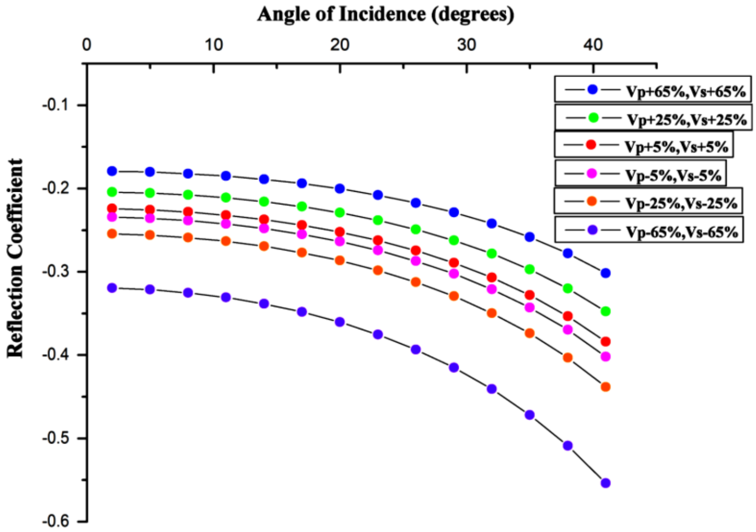

Figure 5. Reflection coefficient values in response to changes in both Vp and Vs. An increase in Vp and Vs results in a lower reflection coefficient, while a decrease in these parameters leads to a higher (more negative) reflection coefficient.

Despite the promising results, some limitations should be acknowledged. The models used in this study assume an idealized layer structure and do not account for heterogeneities in hydrate distribution. Future research should incorporate 3D seismic analysis and field validation using well-log data to improve accuracy. Expanding these methodologies will enhance the reliability of gas hydrate exploration and contribute to a deeper understanding of its potential as an energy resource.

Conclusion

The usefulness of 2D seismic modelling in describing gas hydrate reservoirs and differentiating them from underlying free gas zones is demonstrated in this work. The findings demonstrate that the Bottom Simulating Reflector (BSR), which shows a clear negative amplitude anomaly because of the impedance differential between hydrate-bearing sediments and free gas zones, is a powerful seismic indication of the existence of gas hydrate.

The reflection coefficient analysis shows that increasing P-wave velocity (Vp) reduces the reflection coefficient, while decreasing Vp increases it, making free gas zones more prominent in seismic sections. A similar trend is observed when Vp and S-wave velocity (Vs) are modified together, reinforcing the importance of velocity contrasts in hydrate identification. Additionally, Amplitude Versus Offset (AVO) analysis reveals that hydrate-bearing sediments exhibit moderate amplitude variations, whereas free gas zones produce a strong AVO response, confirming the applicability of AVO attributes in gas hydrate exploration.

These findings highlight the importance of seismic attributes in improving the reliability of gas hydrate detection and reservoir characterization. The ability to differentiate hydrate-bearing sediments from gas-saturated layers is particularly crucial for energy resource assessment and risk mitigation in offshore drilling operations.

Despite the promising results, this study has some limitations. The seismic model assumes an idealized layered structure, which does not fully account for natural heterogeneities in gas hydrate distribution

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Author Contribution

The first author conducted the research, including conceptualization, seismic modeling, data analysis, and manuscript preparation. Field data provided by the second author, made a significant contribution to the interpretation of the results. The authors also received valuable guidance and feedback from supervisors, which helped to improve the study. All aspects of the research and writing were completed independently by the authors.

Conflict of Interest

Regarding this research, the author states that there are no conflicts of interest. The results, analysis, and conclusions of this study have not been impacted by any financial or personal ties to any organizations or people.

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