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FORWARD MODELING AND SEISMIC WAVE INVERSION FOR AMPLIFICATION ANALYSIS IN THE JAVA SUBDUCTION ZONE USING PYTHON

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Abstract. This study aims to analyze seismic wave propagation and amplification in the Java subduction zone using a numerical modeling approach. The method integrates forward modeling and seismic inversion within a two-dimensional finite difference framework to simulate wave behavior in heterogeneous subsurface conditions. Secondary data were obtained from BMKG and USGS catalogs, consisting of earthquake events recorded between 2000 and 2024 with magnitudes ranging from Mw 5.0 to 7.5 and depths of 10-300 km. The results show that seismic wave propagation is strongly influenced by variations in subsurface properties. High amplification occurs in regions characterized by low shear-wave velocity and thick sediment layers. Quantitatively, amplification exceeds 2.0 in areas with shear-wave velocity below 2000 m/s, while regions with higher velocity (>3000 m/s) exhibit lower amplification values. Model validation using correlation coefficient (R) and root mean square error (RMSE) indicates good agreement between synthetic and observed data, with correlation values ranging from 0.72 to 0.89 after inversion. The application of multi-parameter inversion improves the resolution of subsurface structures and enhances model accuracy. This study provides a quantitative and dynamic framework for understanding seismic wave behavior and supports seismic hazard assessment in the Java subduction zone.

Keywords: Seismic Wave Propagation, Amplification, Finite Difference Method, Seismic Inversion, Java Subduction Zone.

***Abstrak**. Penelitian ini bertujuan untuk menganalisis perambatan dan amplifikasi gelombang seismik di zona subduksi Jawa menggunakan pendekatan pemodelan numerik. Metode yang digunakan mengintegrasikan pemodelan maju dan inversi seismik dalam kerangka metode beda hingga dua dimensi untuk mensimulasikan perilaku gelombang pada kondisi bawah permukaan yang heterogen. Data sekunder diperoleh dari katalog BMKG dan USGS, yang terdiri dari kejadian gempa bumi pada periode 2000 hingga 2024 dengan magnitudo Mw 5,0-7,5 dan kedalaman 10-300 km. Hasil penelitian menunjukkan bahwa perambatan gelombang seismik sangat dipengaruhi oleh variasi sifat bawah permukaan. Nilai amplifikasi tinggi terjadi pada daerah dengan kecepatan gelombang geser rendah dan lapisan sedimen yang tebal. Secara kuantitatif, nilai amplifikasi melebihi 2,0 pada wilayah dengan kecepatan gelombang geser di bawah 2000 m/s, sedangkan wilayah dengan kecepatan lebih tinggi (>3000 m/s) menunjukkan nilai amplifikasi yang lebih rendah. Validasi model menggunakan* *koefisien korelasi (R) dan root mean square error (RMSE) menunjukkan kesesuaian yang baik antara data sintetis dan data observasi, dengan nilai korelasi berkisar antara 0,72 hingga 0,89 setelah proses inversi. Penerapan inversi multi-parameter meningkatkan resolusi struktur bawah permukaan serta akurasi model. Penelitian ini memberikan kerangka kuantitatif dan dinamis untuk memahami perilaku gelombang seismik serta mendukung kajian bahaya gempa di zona subduksi Jawa.*

Kata kunci: *Perambatan Gelombang Seismik, Amplifikasi, Metode Beda hingga, Inversi Seismik, Zona Subduksi Jawa.*

1. Introduction

Indonesia is located in one of the most seismically active regions in the world due to the convergence of major tectonic plates, namely the Indo-Australian, Eurasian, and Pacific plates [1]. The subduction of the Indo-Australian plate beneath the Eurasian plate along the southern part of Java forms an active tectonic boundary capable of generating large earthquakes and tsunamis [2]. This tectonic interaction controls seismicity and lithospheric dynamics in the region [3]. Therefore, the Java subduction zone is considered one of the most critical areas for seismic hazard assessment in Indonesia [4].

The impact of earthquakes is not solely determined by the characteristics of the seismic source but is also significantly influenced by the propagation of seismic waves through heterogeneous subsurface structures [5]. Variations in seismic velocity, density, and geological layering affect wave behavior such as reflection, refraction, and scattering [6]. The geological complexity of Java, which includes sedimentary basins, volcanic arcs, and active fault systems, leads to significant spatial variability in ground motion response [7]. This variability is further supported by recent studies showing complex subsurface velocity structures beneath Java [8].

One important phenomenon associated with seismic wave propagation is site amplification, where seismic wave amplitudes increase due to local geological conditions [9]. This effect is particularly significant in areas with soft sediment layers overlying bedrock [10]. Amplification commonly occurs in sedimentary basins where low shear-wave velocity contrasts enhance seismic energy trapping [11]. Evidence from the Jakarta Basin shows that thick sediment layers with low shear-wave velocity significantly amplify seismic waves [8].

Previous studies in the Java region have primarily focused on seismic tomography and subsurface velocity imaging to characterize geological structures [12]. These studies identified important features such as high-velocity slabs associated with subduction processes [13]. Other studies also revealed low-velocity zones related to partial melting and tectonic complexity [14]. However, most of these approaches are limited to static representations of subsurface properties and do not explicitly simulate the dynamic propagation of seismic waves [15].

Numerical modeling provides a powerful approach to simulate seismic wave propagation in complex and heterogeneous media [16]. The Finite Difference Method (FDM) is widely used due to its capability to model wavefields with high accuracy under realistic geological conditions [17]. Forward modeling allows simulation of wave propagation based on known physical parameters [18]. Meanwhile, seismic inversion refines subsurface models to better represent actual geological conditions [19]. The integration of these approaches enables a more comprehensive understanding of seismic wave behavior [20]. Recent developments in computational geophysics have enabled efficient implementation of seismic modeling using Python [21]. Scientific libraries support numerical computation and seismic data analysis in modern research [22]. Python-based modeling provides flexibility, reproducibility, and efficient integration of multi-source datasets [23]. This approach is increasingly adopted in computational geophysics studies [24].

Despite these advancements, there is still a significant gap in studies that explicitly link subsurface heterogeneity with seismic wave amplification through dynamic numerical simulation in the Java subduction zone [25]. Most existing research relies on observational approaches without fully capturing the physical processes governing wave propagation [26]. As a result, quantitative information regarding the spatial distribution of seismic amplification remains limited [27]. This limitation affects the accuracy of seismic hazard assessment and risk mitigation strategies [28].

The novelty of this study lies in the integration of forward and inverse seismic wave modeling using a two-dimensional Finite Difference Method (FDM) framework based on Python to explicitly simulate seismic wave propagation and amplification in the Java subduction zone. This study provides a dynamic and quantitative analysis by linking physical parameters such as P-wave velocity (V_p), S-wave velocity (V_s), and density (ρ) with amplification patterns.

Therefore, this study aims to analyze the characteristics of seismic wave propagation and amplification in the Java subduction zone by integrating forward modeling and seismic inversion using secondary data. The results are expected to improve the understanding of seismic wave behavior in heterogeneous media and contribute to seismic hazard assessment and earthquake risk mitigation in Indonesia.

2. Research Methods

2.1 Research Design

This study adopts a quantitative computational approach based on numerical simulation to analyze seismic wave propagation and amplification in the Java subduction zone. The methodology integrates forward modeling and seismic inversion within a two-dimensional (2D) framework using the Finite Difference Method (FDM) [17].

The use of a 2D modeling approach is based on computational efficiency and the assumption that geological variations can be represented along a vertical cross-section. While 3D modeling provides a more realistic representation of subsurface complexity, it requires significantly higher computational resources. The 2D approach is considered valid under the assumption of lateral homogeneity perpendicular to the modeling plane. However, this simplification may limit the ability to capture full three-dimensional heterogeneity and complex wave scattering effects.

To provide a clear overview of the research workflow, the sequence of methodological steps is illustrated in Figure 1. The diagram presents the complete process starting from literature study to final interpretation and conclusions.

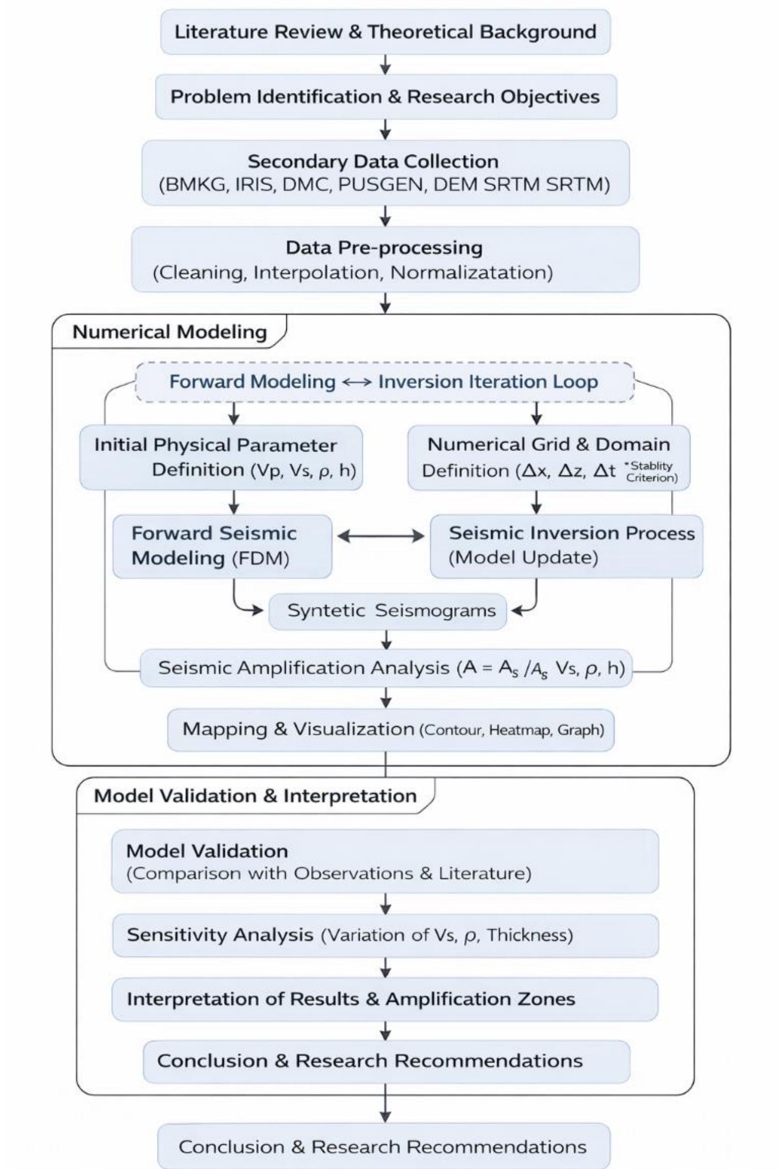

Figure 1. Research Workflow of Seismic Modeling and Amplification Analysis

Figure 1 shows that the research begins with a literature review, problem identification, and formulation of research objectives, followed by the collection of secondary data from sources such as BMKG and USGS. The collected data are then processed through cleaning, interpolation, and normalization before being used in the numerical modeling stage. The modeling process includes the determination of physical parameters (V_p, V_s, ρ, and layer thickness), construction of the numerical grid based on stability criteria, forward seismic modeling to generate synthetic seismograms, and inversion to minimize the misfit between observed and simulated data. The results are then analyzed to evaluate seismic wave amplification, followed by visualization, validation, sensitivity analysis, and final interpretation.

2.2 Data and Study Area

This study focuses on the Java subduction zone, located along the southern part of Java Island. The data used consist of secondary datasets obtained from BMKG and USGS catalogs [26]. The observed seismic data used in the inversion process were selected from earthquake events recorded between 2000 and 2024. The selected events have magnitudes ranging from Mw 5.0 to 7.5 and depths between 10-300 km, representing subduction-related seismicity. Additional datasets include seismic velocity (V_p and V_s), density (ρ), and subsurface structural information derived from previous tomography studies.

2.3 Physical Model and Parameterization

The subsurface model is defined using elastic parameters, namely P-wave velocity (V_p), S-wave velocity (V_s), and density (ρ). These parameters determine the propagation characteristics of seismic waves. The relationship between elastic properties and seismic velocities is expressed in Equation 1 and 2.

$$V_p = \frac{\sqrt{K + \frac{4}{3}\mu}}{\rho} \tag{1}$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \tag{2}$$

Where,

V_p = P-wave velocity (m/s)
V_s = S-wave velocity (m/s)
K = bulk modulus (Pa)
μ = shear modulus (Pa)
ρ = density (kg/m3)

Equation 1 shows that P-wave velocity depends on both bulk modulus and shear modulus, while Equation 2 indicates that S-wave velocity depends only on shear modulus and density. These relationships are used to define the physical properties of each grid cell in the model.

2.4 Finite Difference Method (FDM)

The Finite Difference Method (FDM) is used in this study to numerically solve the elastic wave equation in a discretized spatial domain [16]. This method approximates spatial and temporal derivatives to simulate seismic wave propagation in heterogeneous media. The governing equation used in this study is expressed in Equation 3.

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot \sigma + f \tag{3}$$

Where,
ρ = density (kg/m3)
u = displacement (m)
σ = stress tensor (Pa)
f = body force (N)
t = time (s)

Equation 3 describes the elastic wave equation, where wave propagation is influenced by stress distribution and external forces within the medium. To illustrate the discretization scheme and modeling concept, the numerical approach used in this study is presented in Figure 2.

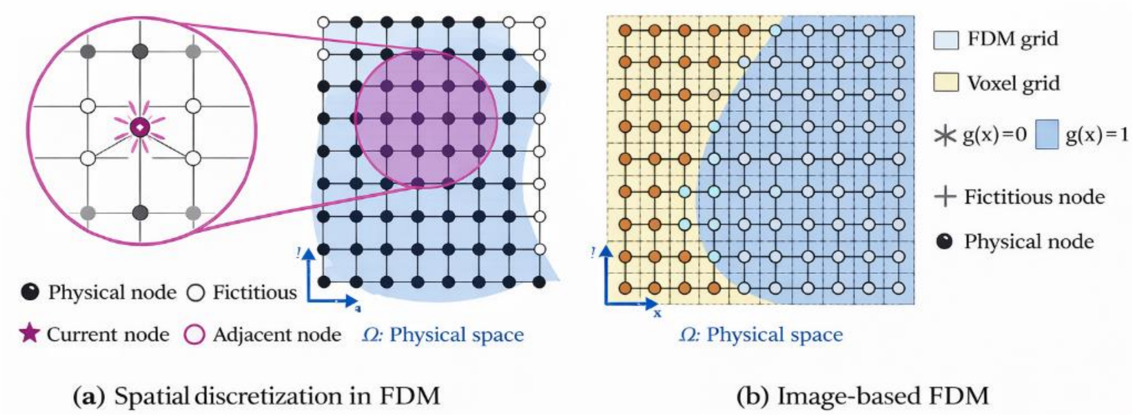

Figure 2. Spatial Discretization Scheme and Numerical Grid Representation in FDM

Figure 2 shows the spatial discretization used in FDM, where the continuous physical domain is transformed into a grid system consisting of physical nodes and fictitious nodes. This discretization allows numerical approximation of wavefield derivatives and enables simulation of wave propagation in a heterogeneous medium.

2.5 Forward and Inversion Modeling

Forward and inversion modeling are essential components in seismic wave analysis to understand wave propagation and subsurface parameter estimation. In this study, forward modeling is used to simulate seismic wave propagation through a predefined velocity model, while inversion is applied to update the model based on the difference between observed and simulated data [20].

Forward modeling is performed to simulate the propagation of seismic waves from a defined source through the subsurface model [18]. The simulation involves assigning physical parameters (V_p, V_s, ρ) to the grid and computing wave propagation over time.

The resulting wavefield provides information about how seismic energy propagates through heterogeneous media and interacts with subsurface structures. These results are used to identify potential amplification zones. Seismic inversion is applied to update subsurface parameters by minimizing the difference between observed and simulated data. The objective function is defined in Equation 4.

$$E = \sum(d_{Obs} - \partial cal)^2 \tag{4}$$

Where,

E = misfit error (dimensionless)
d_{Obs} = observed seismic data
∂cal = calculated (synthetic) seismic data

Equation 4 represents the misfit error between observed and calculated data. The inversion process iteratively adjusts model parameters to minimize this error and improve model accuracy [19]. To illustrate the relationship between forward modeling and inversion processes, a conceptual framework is presented in Figure 3.

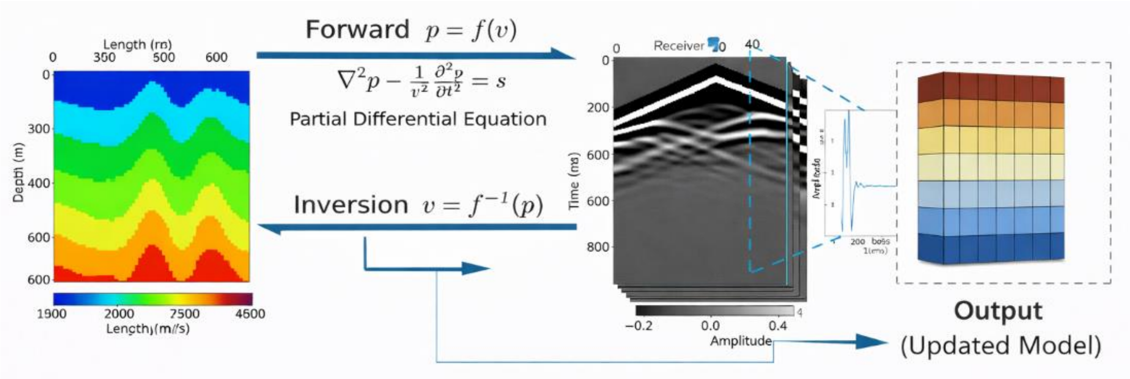

Figure 3. Conceptual Framerowk of Forward and Inversion Modeling in Seismic Analysis

Figure 3 shows that forward modeling computes wave propagation using a velocity model to generate synthetic wavefields, which are then compared with observed data. The inversion process minimizes the difference between the synthetic and observed data by iteratively updating the subsurface model parameters. This iterative process improves the accuracy of the model and provides a better representation of the actual geological conditions.

2.6 Amplification Analysis

Seismic wave amplification is analyzed to evaluate the influence of subsurface heterogeneity on ground motion response. Amplification occurs when seismic waves propagate through layers with contrasting physical properties, particularly low shear-wave velocity (V_s) and high impedance contrast [9]. To quantify this effect, the amplification factor is defined as the ratio between the seismic wave amplitude at the surface and at the bedrock level, as expressed in Equation 5.

$$A = \frac{A_{surface}}{A_{bedrock}} \tag{5}$$

Where,
$A_{surface}$ = amplitude recorded at the surface
$A_{bedrock}$ = amplitude at the reference bedrock level.

Equation 5 indicates that amplification is controlled by subsurface physical parameters, particularly shear-wave velocity (V_s), density (ρ), and layer thickness (h). Lower V_s values and thicker sediment layers tend to produce higher amplification due to energy trapping and resonance effects. The amplification results obtained from numerical simulation are analyzed spatially and represented in the form of contour maps and heatmaps. These visualizations are used to identify zones with high amplification, which are associated with increased seismic hazard potential in the study area.

2.7 Implementation Using Python

All simulations and data processing are implemented using Python. Libraries such as NumPy and SciPy are used for numerical computation, Matplotlib for visualization, and ObsPy for seismic data processing [22]. The Python codes developed in this study are available from the corresponding author upon reasonable request to ensure transparency and reproducibility.

2.8 Modeling Validation

Model validation is performed by comparing synthetic seismograms generated from forward modeling with observed seismic data. The similarity between datasets is evaluated using statistical metrics, including the correlation coefficient (R) and root mean square error (RMSE). The correlation coefficient measures waveform similarity, while RMSE quantifies amplitude differences. Higher correlation values and lower RMSE indicate better agreement between modeled and observed data.

3. Result and Discussion

3.1 Seismic Velocity Model (V_p, V_s, and V_p/V_s Ratio)

The forward modeling results produce seismic velocity distributions of P-wave (V_p) and S-wave (V_s) across the Java subduction zone. These models represent subsurface heterogeneity derived from secondary datasets and numerical simulation.

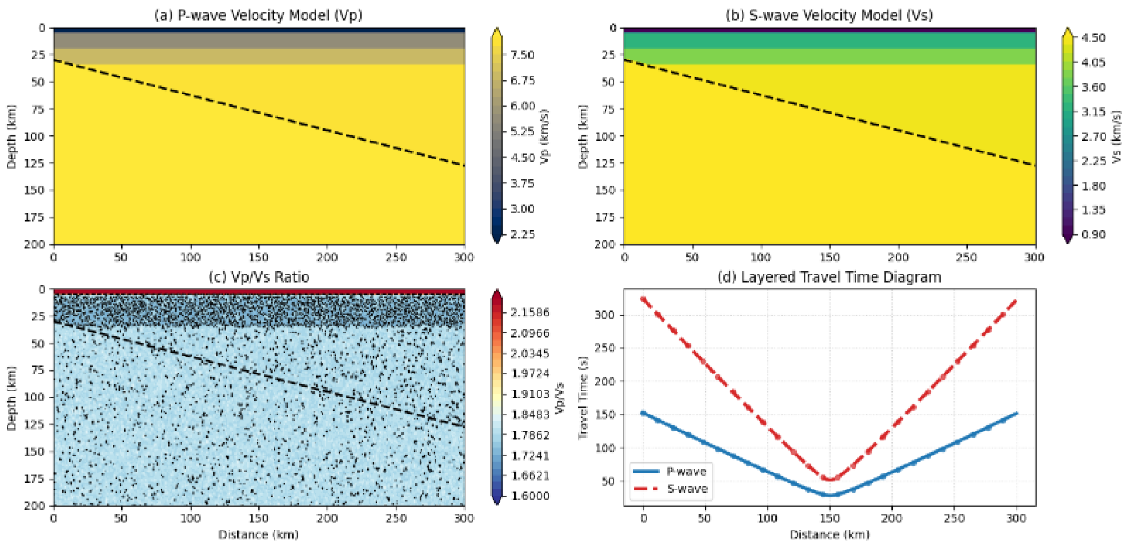

Figure 4. Forward Seismic Velocity Model (V_p, V_s, and V_p/V_s ratio) of the Java Subduction Zone

Based on Figure 4, the V_p and V_s distributions show clear spatial variations associated with different geological structures. The V_p/V_s ratio further indicates variations in lithological properties, where lower ratios are generally associated with more rigid materials, while higher ratios may indicate fluid presence or softer materials. These variations confirm that the subsurface structure in the Java subduction zone is highly heterogeneous and plays an important role in controlling seismic wave propagation.

The speckled pattern observed in the V_p/V_s ratio plot differs from the relatively smooth distributions of V_p and V_s. This effect is primarily attributed to numerical artifacts arising from the division process, particularly in regions where V_s values are relatively low. Small variations in V_s can significantly amplify the ratio, leading to localized fluctuations that appear as noise. Therefore, the observed pattern does not necessarily represent true subsurface heterogeneity but is mainly a consequence of numerical instability in the ratio calculation. Despite this, the overall spatial trend of the V_p/V_s ratio remains consistent with geological expectations and still provides meaningful insight into subsurface properties.

3.2 Seismic Inversion and Subsurface Structure

This section presents the results of seismic inversion, which aims to refine the initial forward model and improve the representation of subsurface structures. Compared to the forward model presented in Section 3.1, the inversion results provide improved resolution of subsurface structures.

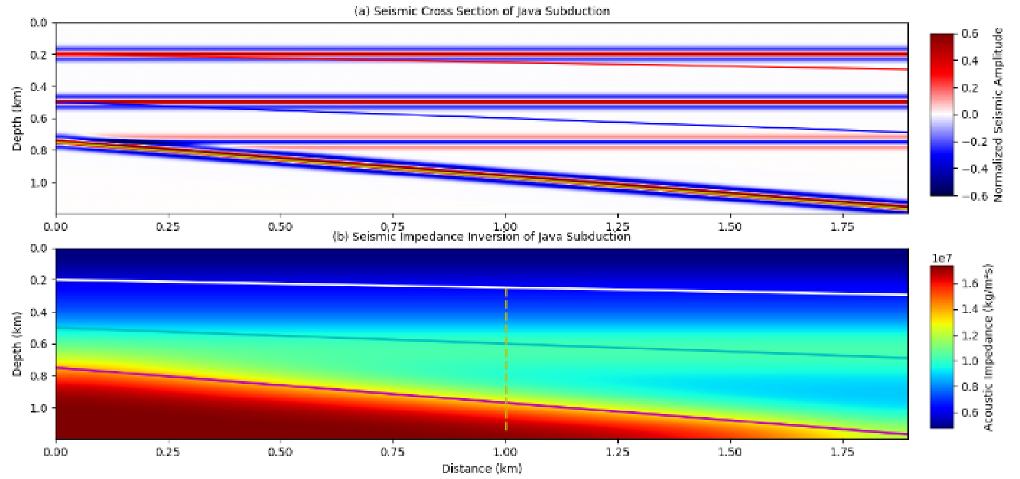

Figure 5. Seismic Impedance and Inversion model of the Java Subduction Zone

The inversion results show enhanced contrast between subsurface layers, particularly in sedimentary and transition zones. Compared to the forward model, the inversion provides sharper structural boundaries and improved parameter resolution. This indicates that the inversion process effectively reduces uncertainty and yields a more realistic representation of subsurface conditions.

3.3 Full Waveform Inversion Multi-Parameter (V_p, V_s, ρ)

Full Waveform Inversion (FWI) is applied to improve the subsurface model by simultaneously updating multiple physical parameters, including P-wave velocity (V_p), S-wave velocity (V_s), and density (ρ). This approach provides a more detailed and physically consistent representation of the subsurface compared to conventional inversion methods.

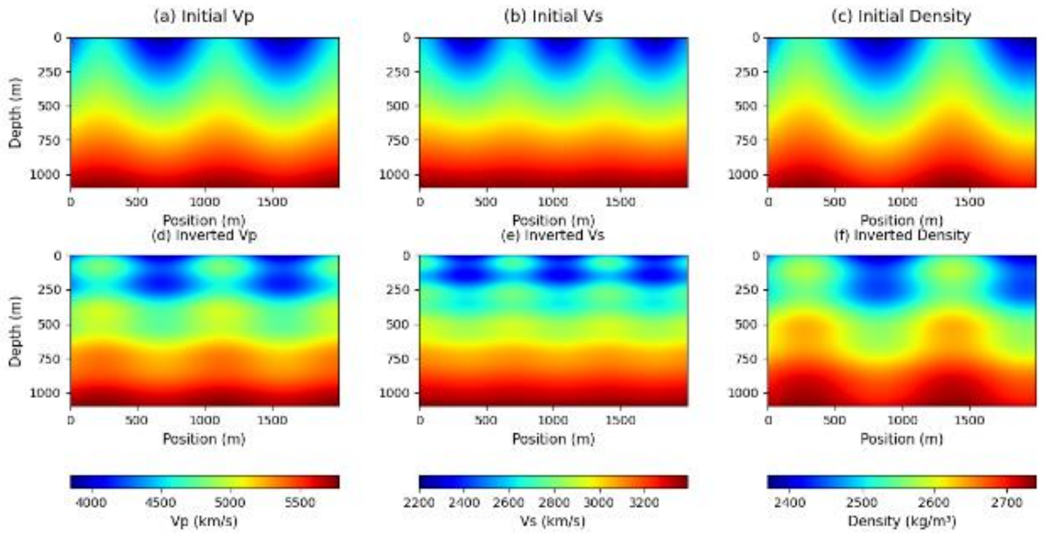

Figure 6. Full Waveform Inversion for Multi-Parameter (V_p, V_s, and ρ) Model

This figure shows that the inversion process produces a more refined and detailed subsurface model, particularly in identifying velocity contrasts and density variations. The updated V_p and V_s distributions exhibit clearer structural boundaries, while density variations provide additional constraints on lithological properties. The multi-parameter inversion enhances the resolution of subsurface heterogeneity, especially in transition zones between sedimentary layers and more rigid geological structures. This improvement indicates that FWI is effective in capturing complex wave–medium interactions and provides a more reliable basis for subsequent analysis of seismic wave propagation and amplification.

The inverted model shows oscillations at shallow depths compared to the initial model. These features are interpreted as cycle-skipping artifacts in Full Waveform Inversion rather than true geological structures. This effect is likely caused by limitations in low-frequency data and dependence on the initial model. Despite this, the inversion improves subsurface resolution at greater depths.

3.4 Seismic Wave Propagation (FDM 2D Simulation)

Seismic wave propagation is simulated using the Finite Difference Method (FDM) to analyze the dynamic behavior of wavefields in a heterogeneous medium. The simulation provides insight into how seismic energy travels through subsurface structures with varying physical properties.

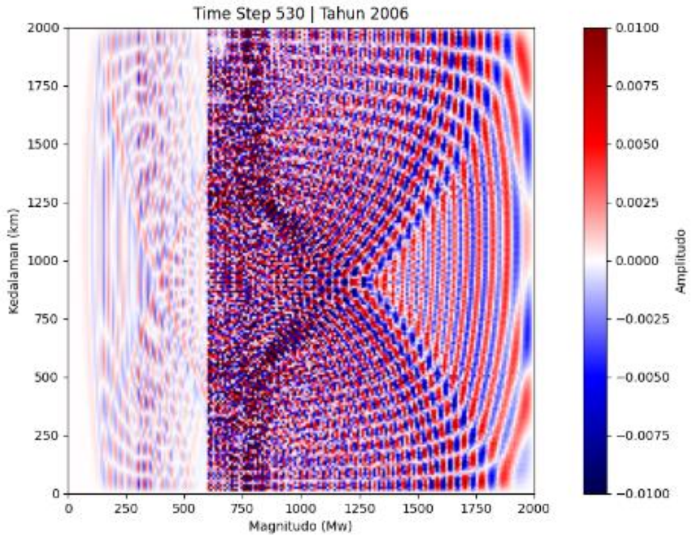

Figure 7. Seismic Wave Propagation using 2D FDM Simulation

Figure 7 shows that seismic waves propagate with varying velocities and amplitudes depending on the subsurface model obtained from inversion. Wavefront distortion, amplitude variation, and phase changes are observed as waves interact with different layers. The simulation reveals that wave energy tends to concentrate in low-velocity zones, while higher velocity regions facilitate faster propagation with lower amplitude amplification. Reflections and refractions at layer boundaries indicate strong impedance contrasts, which significantly influence energy distribution.

3.5 Forward and Inverse Modeling for Amplification Analysis

The integration of forward and inverse modeling is used to analyze seismic wave amplification under realistic subsurface conditions. Forward modeling simulates wave propagation based on the updated velocity model, while inversion minimizes the difference between observed and simulated data to refine model parameters.

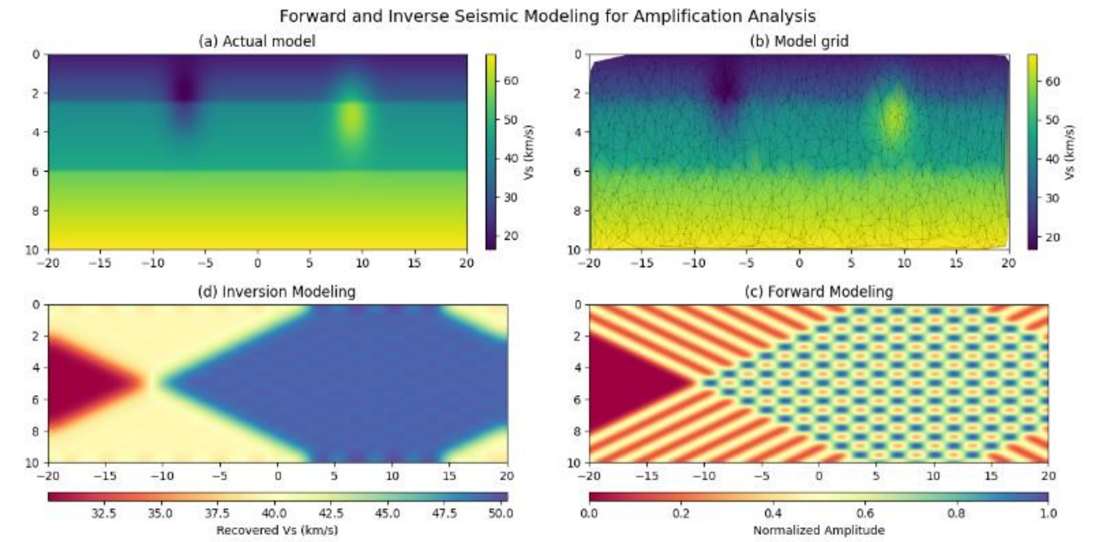

Figure 8. Forward and Inverse Seismic Modeling for Amplification Analysis

Figure 8 shows that the iterative interaction between forward simulation and inversion leads to a more accurate representation of subsurface properties. This process reduces modeling uncertainty and improves the reliability of predicted wave amplitudes. The combined approach allows better identification of amplification-prone zones, as it incorporates both dynamic wave behavior and updated physical parameters. This integration is essential for capturing complex wave–medium interactions in subduction environments.

3.6 Spatial Distribution of Amplification

This section presents the spatial distribution of seismic wave amplification across the study area, based on the results of numerical simulation and inversion. The analysis aims to identify regions with varying levels of amplification and to examine their relationship with subsurface geological conditions.

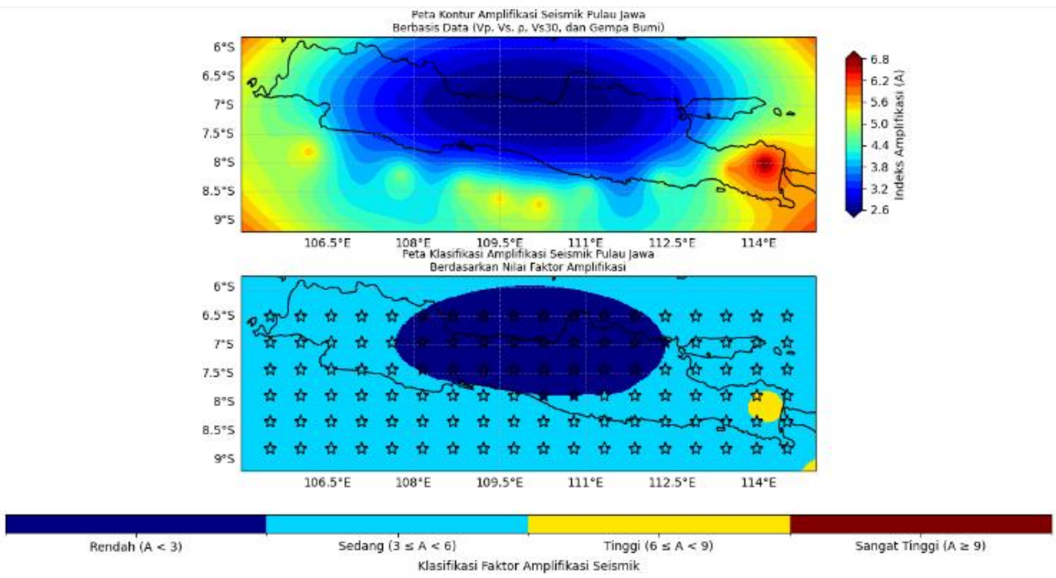

Figure 9. Contour Map of Seismic Amplification Across Java Island

The spatial distribution of amplification is predominantly concentrated in sedimentary basin regions characterized by low shear-wave velocity. Although geological boundaries are not explicitly overlaid, the observed pattern is consistent with known geological structures of Java. High amplification values are associated with thick sediment deposits, while regions with higher velocity materials show lower amplification. This confirms the strong influence of subsurface geological conditions on seismic response.

3.7 Seismic Tomography and Structural Interpretation

Seismic tomography is used to reconstruct the subsurface velocity structure and provide additional insight into geological conditions within the Java subduction zone. The tomography results represent variations in seismic velocity that reflect differences in material properties and structural complexity.

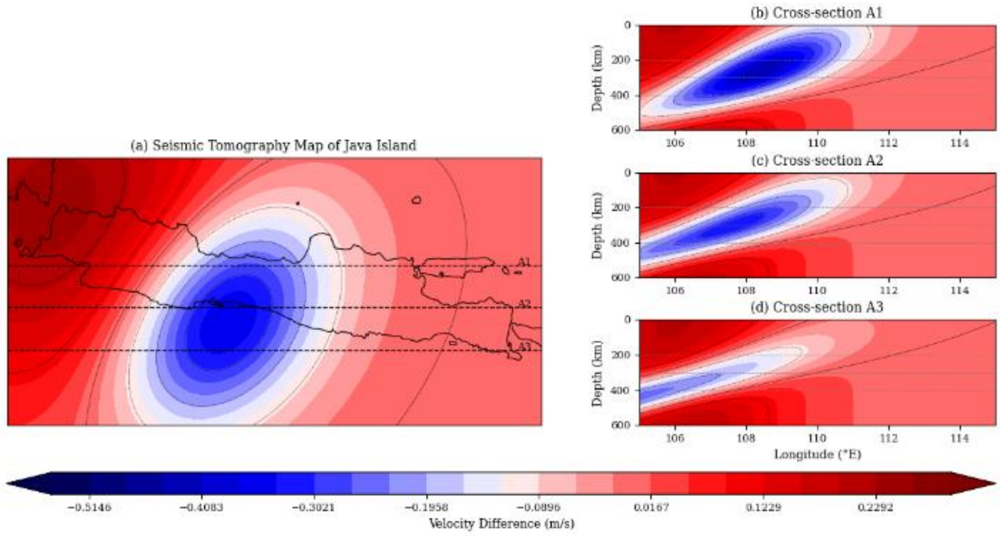

Figure 10. Seismic Tomography of The Java Subduction Zone with Cross-Sections (A1, A2, A3)

Figure 10 shows significant spatial variation in seismic velocity across both lateral and vertical directions. High-velocity zones are associated with denser and more rigid materials, indicating consolidated rock formations at greater depths. In contrast, low-velocity zones are interpreted as softer materials, fractured regions, or sedimentary layers. The tomography results are consistent with the amplification analysis, where low-velocity regions correspond to areas of higher seismic amplification. This relationship confirms that subsurface velocity structure plays a dominant role in controlling seismic wave behavior and ground motion response.

Furthermore, the cross-sectional profiles (A1, A2, A3) reveal variations in layer thickness and structural boundaries, which indicate the complexity of the subduction system. These structural features contribute to wave scattering and energy concentration, further influencing amplification patterns.

3.8 Model Validation Results

The validation results show a significant improvement in the agreement between synthetic and observed seismic data after inversion. The correlation coefficient (R) ranges from 0.72 to 0.89, indicating strong waveform similarity. Meanwhile, RMSE values decrease after inversion, confirming that the updated model better represents the actual subsurface conditions. These results demonstrate that the integration of forward modeling and inversion improves the reliability and accuracy of seismic wave simulation.

4. Conclusion

This study demonstrates that subsurface heterogeneity in the Java subduction zone plays a critical role in controlling seismic wave propagation and amplification. The integration of forward modeling and seismic inversion using a two-dimensional Finite Difference Method (FDM) framework successfully provides a dynamic and quantitative representation of wave behavior in complex geological media.

The results show that variations in seismic parameters, particularly P-wave velocity (V_p), S-wave velocity (V_s), and density (ρ), significantly influence wave propagation patterns and amplification characteristics. High amplification values are consistently observed in low shear-wave velocity zones and thick sedimentary layers, where amplification exceeds 2.0 for V_s values below 2000 m/s. In contrast, regions with higher V_s values (>3000 m/s) exhibit lower amplification ($A < 1.5$), indicating reduced ground motion intensity. The application of Full Waveform Inversion (FWI) multi-parameter enhances the resolution of subsurface structures by simultaneously updating V_p, V_s, and density. This approach improves the accuracy of the velocity model, strengthens the identification of structural boundaries, and provides a more reliable basis for analyzing seismic wave behavior. Furthermore, the integration of forward and inverse modeling reduces uncertainty and increases the robustness of amplification estimation.

The spatial distribution of amplification indicates that high-risk zones are concentrated in sedimentary basins and low-velocity regions, confirming a strong correlation between geological structure and seismic response. Compared to previous studies that primarily rely on static seismic tomography, this study introduces a dynamic simulation-based approach that explicitly captures seismic wave propagation and amplification processes. Overall, this study provides a robust and quantitative framework for linking subsurface physical properties with seismic wave amplification in the Java subduction zone.

The findings contribute to improved seismic hazard assessment and offer a scientific basis for earthquake risk mitigation and urban planning in tectonically active regions. However, this study is limited by the use of a two-dimensional modeling framework and secondary datasets. Future research should consider three-dimensional modeling and the use of real-time seismic data to improve model accuracy and representation of complex geological conditions.

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