Pramesthi, E.A., & Hayashida, T. (2025), Establishment of an appropriate velocity model in West Java to improve the accuracy of automatic hypocenter determination in seismic processing systems, Synopsis of IISEE-GRIPS Master's Thesis, Bulletin of IISEE, 60

ESTABLISHMENT OF AN APPROPRIATE VELOCITY MODEL IN WEST JAVA TO IMPROVE THE ACCURACY OF AUTOMATIC HYPOCENTER DETERMINATION IN SEISMIC PROCESSING SYSTEMS

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ABSTRACT

Accurate automatic hypocenter determination remains a key challenge in seismic processing systems. The Meteorology, Climatology and Geophysics Agency (BMKG) employs SeisComP as its primary seismic processing system. SeisComP utilizes the LOCSAT algorithm to automatically locate earthquake events. The accuracy of LOCSAT strongly depends on the appropriateness of the seismic wave velocity structural model. Currently, BMKG continues to use the global IASP91 velocity model for seismic processing. However, several detected events have shown hypocenter locations significantly deviating from the actual source. West Java was selected as a case study due to its dense and evenly distributed seismic network (31 seismic stations) and high seismic activity. The complex subsurface structure in West Java makes global models less suitable, highlighting the need for a region-specific velocity model. An updated velocity model was developed using the coupled velocity-hypocenter method. Model performance was assessed through waveform playback using three criteria: low RMS error, consistency with the earthquake source, and matched with BMKG's fourth-stage quality-controlled hypocenter locations. Among the tested models, the updated shallow model based on AK135 showed the best overall performance. It successfully detected all earthquake events in September 2024 without false locations. In contrast, the IASP91 model failed to accurately detect an event. The updated model also reduced RMS errors and yielded hypocenter locations more consistent with slab depth and the final validated results.

Keywords: Automatic hypocenter determination, velocity model, SeisComP, LOCSAT, waveform playback.

1. INTRODUCTION

West Java is one of the provinces in Indonesia with high seismic activity. This region is located at the convergence of the Eurasian and the Indo-Australian plates. The subduction process has led to the formation of overlapping mountain ranges and rock deformation, which in turn has created numerous fault zone structures across West Java. Seismic sources in this region include the subduction zone, active

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Approved as Master Paper of DMP by BRI/GRIPS

fault, and volcanic activity. Shallow inland earthquakes are often associated with active faults such as Cimandiri, Lembang, Garut, Bogor, and Baribis faults (Supendi et al, 2018).

Countries with high seismic activity operate seismic processing systems to support earthquake and tsunami disaster mitigation. These systems analyze seismic waveforms recorded by sensors to determine earthquake parameters. Accurate earthquake parameters are especially critical for tsunami early warning systems, where they are used as input for tsunami modelling. In Indonesia, the Meteorology, Climatology and Geophysics Agency (BMKG) is responsible for seismic monitoring and issuance of tsunami warnings. BMKG faces the challenge of disseminating earthquake and tsunami information within three minutes after an event occurs. The accuracy of the initial hypocenter location, which is often determined automatically, is crucial for timely and reliable warnings. Previous studies have shown that using a suitable seismic velocity structure significantly improves hypocenter accuracy (Widya et al., 2021). This study aims to identify the most suitable velocity model for the West Java region to enhance the accuracy of automatic hypocenter determination within BMKG's seismic processing system (SeisComP).

2. DATA

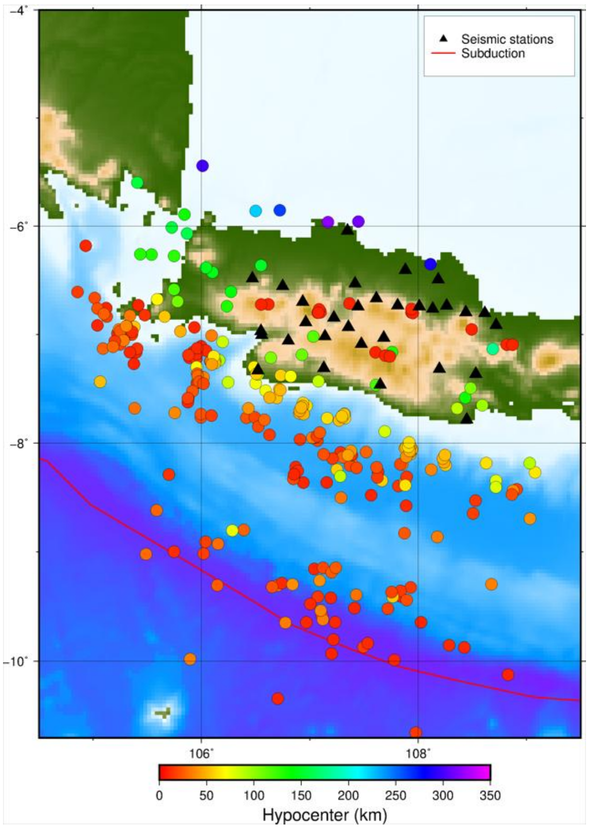

Figure 1. Seismicity of West Java in 2021-2024 (BMKG, 2024).

This study developed an updated velocity model using 289 earthquake events that occurred in West Java between January 1, 2021, and December 31, 2024. The selected events met the criteria of having a magnitude greater than 4 (M≥4) and more than five recorded phases to ensure data quality. Data from 31 seismic stations in West Java, such as longitude, latitude, and elevation, were used to calculate travel times. A total of 9,545 manually picked P- and S-wave arrival times were used in the analysis.

Three different velocity models were tested to initialize the inversion: the local model by Sakti et al. (2012), and two global models, IASP91 (Kennett et al., 1991), and AK135 (Kennett et al., 1995). Among them, AK135 is characterized by faster seismic velocities in the shallow crust, which affects the estimation of the Mohorovičić discontinuity.

The waveform data from September 2024 were used for playback in the SeisComP system to evaluate model performance. The BMKG earthquake catalog, which has undergone fourth-stage quality control by expert analysts, served as the validation reference for comparing automatic hypocenter results by each velocity model.

3. METHODOLOGY

3.1. Coupled velocity-hypocenter method

The coupled velocity-hypocenter method simultaneously calculates both the hypocenter location and the velocity model (Kissling et al., 1994). The time residual is defined by Equation 1, where *tobs* is the observed arrival time, s represents station coordinates, h denotes hypocenter parameter (origin time, longitude, latitude, and depth), and m is the velocity field.

$$t_{res} = t_{obs} - t_{calc} = \sum_{k=1,4} \frac{\partial f}{\partial m_i} \Delta h_k + \sum_{i=1,n} \frac{\partial f}{\partial m_i} \Delta m_i + e \quad (1)$$

This method is implemented using the VELEST program to develop an updated velocity model. Seismic ray path analysis shows that the dataset used in this study has limited sensitivity to events deeper than 60 km. Due to this limitation, two modeling scenarios are applied. The first scenario uses three initial velocity models to generate deep models down to 300km. The second scenario focuses on shallower structures up to a depth of 60km. The most suitable models from each scenario are then compared with the global velocity model currently used by BMKG.

3.2. Automatic hypocenter determination in SeisComP

BMKG's SeisComP system uses LOCSAT as its automatic hypocenter locator. LOCSAT determines origin time and hypocenter using a travel-time interface that considers pick times, back azimuth, slowness, and phase-specific travel-time tables. The updated velocity models generated by VELEST are used to create new travel-time tables for LOCSAT. These travel-time tables are computed using the TauP toolkit (Crotwell et al., 1999). Once the updated velocity models are integrated into the LOCSAT locator, waveform playback is conducted to test their performance. Waveform playback simulates real-time detection by replaying archived seismic waveforms, allowing the system to automatically locate events using the updated models.

3.3. Validating velocity models

The most appropriate velocity model is selected based on two criteria: the lowest Root Mean Square Error (RMSE), and the closeness of the resulting hypocenter locations to the BMKG catalog, which has undergone fourth-stage quality control by BMKG experts. The hypocenter results from the updated velocity models, as well as from the IASP91 global velocity model currently used by BMKG, are compared against the validated BMKG catalog to assess improvements in automatic hypocenter determination accuracy by SeisComP. RMSE is used to quantify model performance; a higher RMSE indicates greater uncertainty. The RMSE is calculated using Eq.(2).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (t_{cal} - t_{obs})^2} \quad (2)$$

In Eq.(2), n is the number of phase arrival times, t_{cal} is the arrival time calculated based on the velocity model, and t_{obs} is the observed arrival time recorded at the seismic stations.

4. RESULTS AND DISCUSSION

The output of the VELEST inversion includes station corrections, expressed as delay time values for each seismic station. The delay times, calculated for P- and S-wave arrivals, were used to infer the geological characteristics beneath each station. A negative delay time indicates that seismic waves arrive faster than at the reference station, possibly

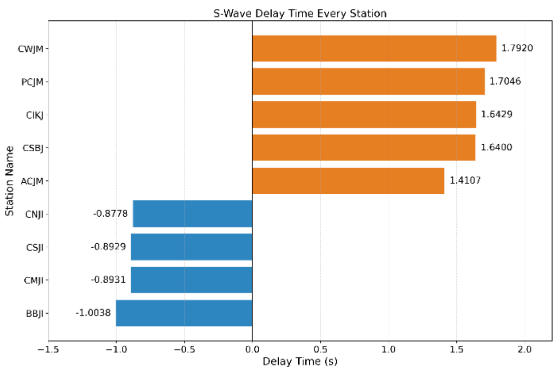

Figure 2. S-wave delay time every station.

due to the presence of hard rock. Conversely, a positive delay time suggests slower wave propagation, typically associated with soft rocks such as sediment, sand, or clay.

The delay patterns for both P- and S-waves were consistent, showing similar distributions of positive and negative values. Stations with large negative delay times (e.g., CMJI, CNJI, BBJI, and CSJI; see Figure 2) are located in the southern part of West Java, an old mountainous zone dominated by hard rock. In contrast, stations with high positive delay times (e.g., PCJM, ACJM, CIKJ, CSBJ, and CWJM; see Figure 2) are situated in the northern coastal region, which is characterized by alluvial plains and soft sediments.

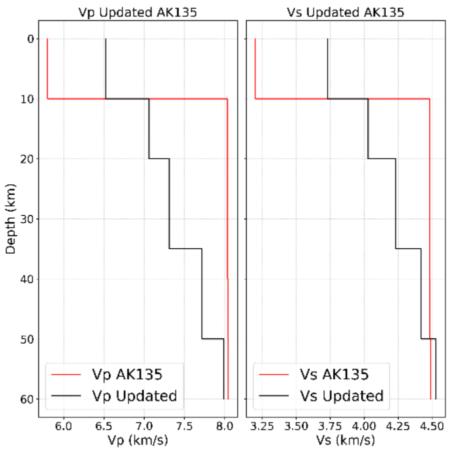

Figure 3. The updated AK135 shallow velocity model.

From the two modeling scenarios (deep and shallow), six updated velocity models were generated. Among them, the updated AK135 shallow model performed best for the West Java region (Figure 3). The updated IASP91 shallow velocity model yielded the highest RMS error, with 35 events exceeding an RMS of 1. In comparison, both the updated AK135 and Sakti shallow models had RMS values ≤1 for all events, indicating better relocation accuracy in VELEST.

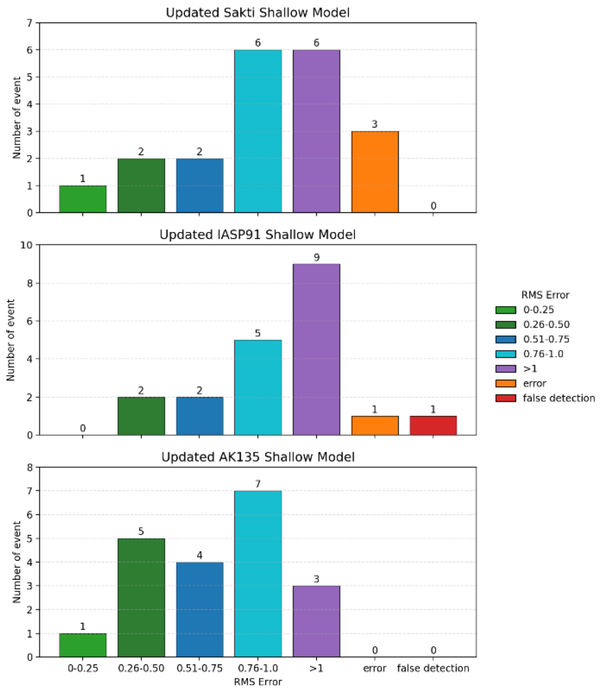

Figure 4. RMS error range for updated shallow velocity model of IASP91, AK135, and Sakti using waveform playback.

Model suitability was further assessed using waveform playback. The playback tests confirmed that the updated AK135 shallow model was the most appropriate. It successfully detected all events without false hypocenter locations and produced the lowest RMS error among the shallow models. In contrast, the updated IASP91 model failed to detect one event and mislocated another (Figure 4). The updated Sakti model also failed to detect three events automatically. Additionally, the updated AK135 model indicated that the Mohorovičić discontinuity is located at a depth of 35–40 km (Figure 3), which aligned with the tomographic results of Rosalia et al. (2019).

Hypocenter locations from automatic determinations were validated against known seismic sources in the region. RMS values are insufficient for evaluating model suitability if the hypocenter locations do not align with the regional seismotectonic. The final hypocenter results from BMKG, which has undergone fourth-stage quality control, were used for validation (Figure 5a). Figures 5b and 5c represent hypocenter distributions derived from the IASP91 and the updated AK135 shallow velocity model, respectively.

Twenty automatically detected events were analyzed to compare the performance of the IASP91 and the updated AK135 shallow model. The color contour lines on the map represent slab depth from PUSGEN (2024). The automatic detection of event A using the IASP91 velocity model (Figure 5b) indicated a shallow depth of 10 km. However, the slab depth in that region exceeds 100 km, making it impossible for shallow earthquakes to be related to the subduction. While a local fault could be the source of a shallow earthquake, the location was distant from the fault. In contrast, the final validated hypocenter was located within the fault zone, as shown in Figure 5a. The automatic hypocenter determined using the updated velocity model (Figure 5c) closely matched the final hypocenter.

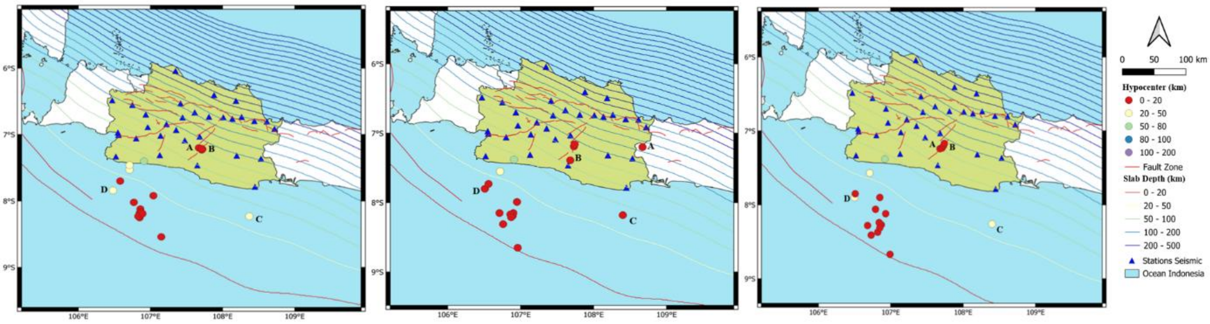

Figure 5. (a) Validation of the hypocenter determination, (b) Automatic hypocenter determination using IASP91, and (c) Automatic hypocenter determination using the updated velocity model.

The hypocenter of event B based on the IASP91 velocity model (Figure 5b) was located farther from the local fault zone. The updated velocity model placed it directly on the fault, coincident with the validated hypocenter (Figure 5a). Both events A and B were attributed to the Garsela fault, which was the source of the damaging earthquake on September 18, 2024. The focal mechanism was a normal fault, consistent with the characteristics of the Garsela fault (Supendi et al., 2018).

The hypocenter depths of events C and D also differed between the velocity structure models used. Results from the IASP91 model consistently assigned a fixed depth of 10 km. The updated AK135 shallow velocity model estimated events C at 34 km depth, consistent with the 20–50 km slab depth indicated by contour lines in Figure 5a.

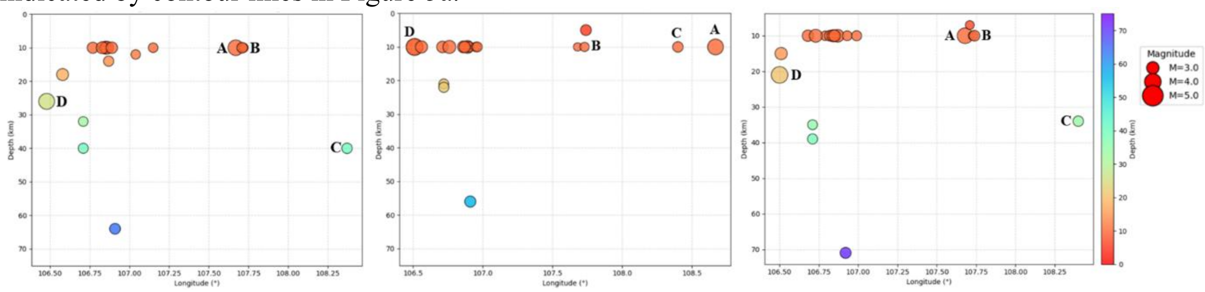

Figure 6. (a) Vertical plot of hypocenter determination for validation, (b) Vertical plot of automatic hypocenter determination using IASP91, and (c) Vertical plot of automatic hypocenter determination using the updated velocity model.

For event D, the updated velocity model estimated a hypocenter depth of 21 km, while IASP91 located 10 km, and the validated depth was 27 km. The hypocenter distribution of the vertical cross-section is shown in Figure 6. These results demonstrate that the updated velocity model improves automatic hypocenter determination by finding depths and locations more consistent with the validated hypocenter locations.

5. CONCLUSIONS

This study demonstrates that the velocity model plays a critical role in automatic hypocenter determination. The updated velocity model developed for West Java significantly improved the performance of SeisComP in locating earthquake events, yielding more reliable hypocenter estimates than the IASP91 global velocity model currently used by BMKG. In waveform playback tests of 20 events in September 2024, the updated velocity model consistently showed lower RMS errors in automatic detection. Notably, one event that was undetected by the IASP91 velocity model was successfully detected using the updated model.

Furthermore, the accuracy of hypocenter locations improved with the updated velocity model. Four automatically determined events using IASP91 did not correspond with known seismic sources, while the updated velocity model showed results that aligned with both the BMKG validated hypocenters and the regional seismotectonic conditions. The findings highlight the importance of using a region-specific velocity structure model in the seismic processing system. As BMKG continues to use the IASP91 global velocity model across Indonesia, there is a clear need to develop localized velocity structure models that reflect the seismotectonic characteristics of each region to enhance the accuracy of automatic earthquake monitoring.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Dr. Takumi Hayashida, for his valuable support and experience, which helped me to complete my research successfully.

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