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Revealing the Subsurface Geometry of the 2023 Sumedang Earthquake Sequence Using Double-Difference Relocation and Cross-Section Analysis

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A B S T R A C T

The Sumedang Regency experienced a significant tectonic earthquake sequence beginning on December 31, 2023, which raised concerns regarding active fault structures in the region. Identifying the precise causative fault geometry was essential for seismic hazard mitigation but remained challenging due to the complex local geology and potential location errors in preliminary data. This study investigated the source mechanism and subsurface geometry of the aftershocks recorded between December 31, 2023, and January 8, 2024. The Double-Difference (HypoDD) method was applied to relocate earthquake hypocenters by minimizing travel-time residuals, utilizing a 1-D velocity model with a variable Vp/Vs ratio. Subsequently, vertical cross-section analysis was conducted to interpret the dip patterns and fault orientation perpendicular to the seismicity trend. The results revealed a significant transformation in the spatial distribution pattern; while initial data exhibited a linear north-south trend, the relocated hypocenters formed a distinct curved cluster extending from the south toward the west. The seismic activity was concentrated at shallow depths ranging from 3 km to 17 km. Cross-section interpretations suggested two potential fault geometries: a near-vertical alignment indicating a strike-slip mechanism potentially associated with the Subang Segment of the Baribis Fault, or an inclined, slab-like structure indicative of a thrust fault system. These findings provided critical constraints for future moment tensor inversion studies.

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1. INTRODUCTION

Indonesia is an archipelagic country with highly complex and dynamic geological conditions because it is located at the convergence of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. The interaction of these three plates places Indonesia within the Pacific Ring of Fire, making the region highly vulnerable to various natural hazards, particularly earthquakes. This high level of tectonic activity results in an earthquake occurrence frequency in Indonesia that is significantly higher than in most other countries worldwide. Based on seismic statistical data, Indonesia is ranked among the top ten countries globally with the highest frequency of earthquakes [1]. Specifically in West Java, the complexity of active onshore fault structures often triggers damaging shallow earthquakes, even when their magnitudes are relatively moderate [2].

An earthquake is defined as a sudden release of energy in the form of seismic waves that propagate throughout the Earth's surface due to disturbances or fractures within the Earth's crust. This natural phenomenon is one of the most feared disasters because it is extremely difficult to predict and can cause destructive impacts, ranging from infrastructure damage and economic losses to loss of life [3]. The initial point within the Earth where energy release begins is referred to as the hypocenter or earthquake focus, while the visual representation of the spatial distribution of such events is known as a seismic map [4]. Accuracy in determining earthquake parameters, particularly hypocenter locations, is crucial for understanding the geometry of the causative fault and for mitigating potential future disaster risks.

To improve the accuracy of earthquake source locations, relocation methods that can minimize errors caused by heterogeneous velocity models are required, one of which is the Double-Difference or HypoDD method. The HypoDD method is an earthquake relocation technique developed to obtain more precise hypocenter positions by minimizing travel-time residuals between pairs of earthquakes [5]. The basic principle of this method involves measuring the differential travel times of seismic waves from two closely spaced earthquake events recorded at the same station, under the assumption that the raypaths traveled are identical [6]. In its implementation, HypoDD performs iterative calculations to update locations and partial derivatives in order to minimize the differences between observed and calculated travel times [7].

The case study in this research focuses on a tectonic earthquake sequence that struck Sumedang Regency, West Java. The mainshock, with a magnitude of M 4.1, occurred on Sunday, 31 December 2023 at 14:35 WIB, followed by a series of aftershocks. The Meteorology, Climatology, and Geophysics Agency (BMKG) reported that the epicenter of the mainshock was located at coordinates 6.85° S and 107.93° E, situated on land approximately 1 km northeast of Sumedang Regency at a depth of 7 km. As of 8 January 2024, a total of 11 aftershocks had been recorded, increasing the urgency for a more detailed analysis of the characteristics of this earthquake source. Therefore, this study aims to compare changes in hypocenter positions before and after relocation and to identify the fault structures triggering the earthquakes in the region through cross-section analysis.

2. RESEARCH METHOD

The primary data used in this study include seismic waveform data, recording station coordinates, and initial earthquake catalog parameters for events that occurred in Sumedang Regency, West Java. The analyzed data span earthquakes recorded from 31 December 2023 to 8 January 2024, obtained from the seismic network of the Meteorology, Climatology, and Geophysics Agency (BMKG). The initial stage of data processing began with the identification and determination of arrival times (picking) of P-wave and S-wave phases from digital seismogram recordings. This picking process was carried out using Linux-based seismic analysis software, namely SAC (Seismic Analysis Code).

The subsequent stage involved hypocenter relocation using the Double-Difference (HypoDD) algorithm, which integrates the picked travel-time data with a seismic velocity model. In this modeling, a P- to S-wave velocity ratio (Vp/Vs) of 1.75 was applied, along with a 1-D velocity model that varies with depth. This specific velocity structure and Vp/Vs ratio were adopted based on the standard regional velocity model utilized by the BMKG, which has been proven reliable for resolving shallow crustal seismicity in the West Java region, including the Sumedang basin [2]. The P-wave velocity was assumed to start at 2.3 km/s at the surface (0.0 km), increase significantly to 5.8 km/s at a depth of 2.0 km, then to 6.3 km/s at 12.0 km depth, 6.9 km/s at 22.0 km depth, and finally reach 8.0 km/s at a depth of 32.0 km. The application of an accurate velocity model in the HypoDD algorithm aims to minimize travel-time residuals between pairs of earthquake events, thereby producing more precise hypocenter locations [8].

After obtaining the relocated hypocenter coordinates, spatial visualization was performed to compare the distribution of earthquakes before and after relocation. The analysis was further extended by constructing cross-sections perpendicular to the trend of earthquake distribution to identify dip patterns and the geometry of subsurface structures. The results of these cross-sections consist of projected hypocenter depth points that assist in interpreting the relationship between seismicity and tectonic activity or the presence of active faults in the study area [9]. All epicenter distribution mapping and cross-section visualizations were generated using GMT (Generic Mapping Tools), which is widely recognized for its reliability in geophysical data processing [10], [11]. The complete sequence of data processing steps in this study is presented in the flowchart shown in Figure 1.

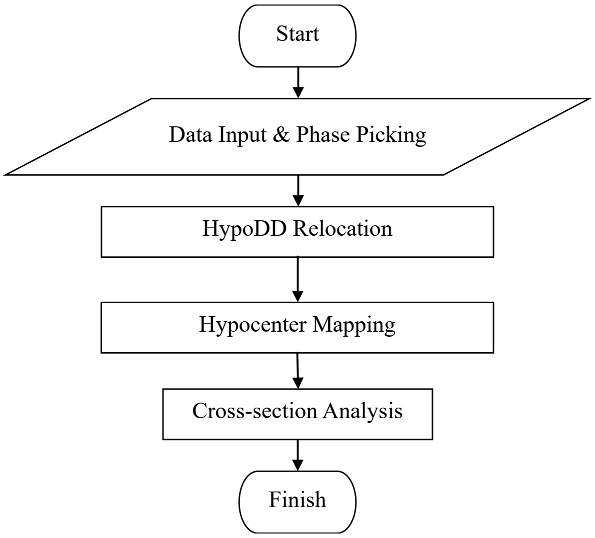

Fig. 1. Research Flowchart

3. RESULTS AND DISCUSSION

3.1. Seismicity and Initial Earthquake Distribution

The pattern of seismicity distribution in West Java during the observation period from 31 December 2023 to 8 January 2024 shows a significant concentration of activity in Sumedang Regency. As illustrated in Figure 2, earthquake epicenters are predominantly concentrated on land and are characterized by shallow depths, generally less than or equal to 20 km. The recorded earthquake magnitudes vary considerably, ranging from small events (M ~3.0) to relatively significant earthquakes approaching M 5.0, indicating energy release associated with local fault activity. Spatially, this earthquake cluster is located very close to the trace of the Baribis Fault, Subang Segment, which has long been identified as one of the main active structures in northern West Java [12]. The proximity of the epicenters to this fault trace suggests an initial hypothesis that the tectonic activity in Sumedang is closely related to the dynamics of the Baribis Fault, which is known to exhibit a relatively active geodetic slip rate [13].

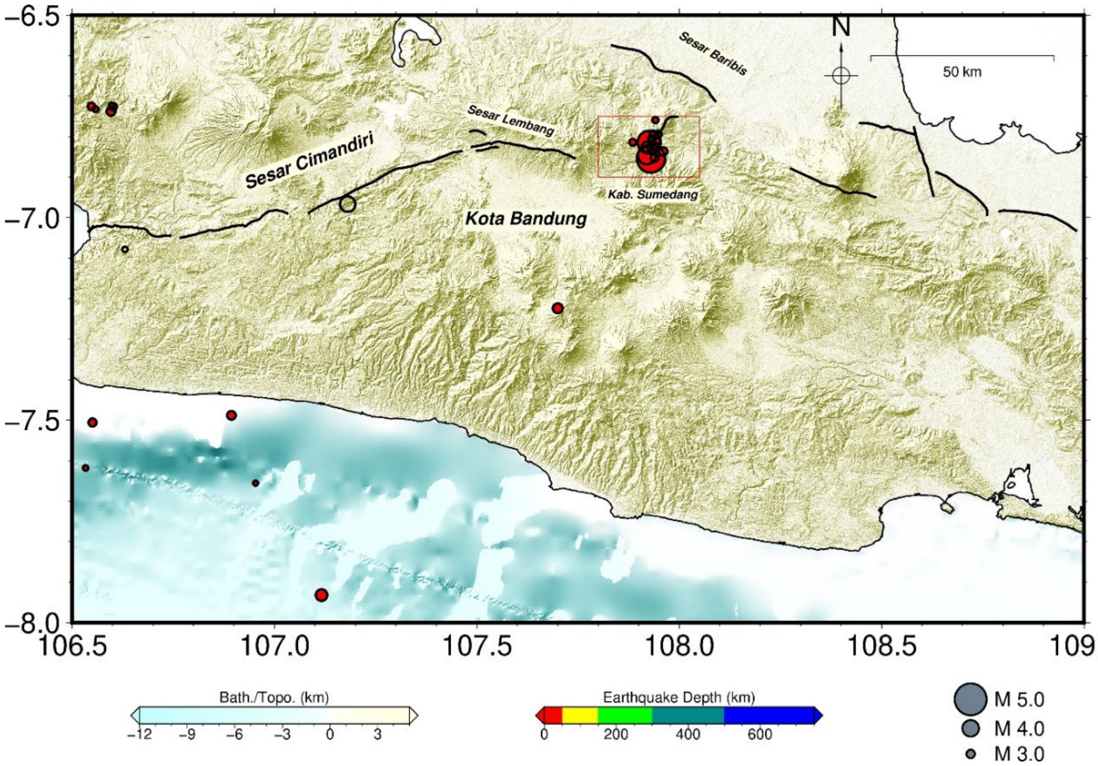

Fig. 2. Earthquake Distribution Map in West Java during 31 December 2023 – 8 January 2024

3.2. Hypocenter Relocation Analysis

To validate the association between earthquake distribution and geological structures, a comparison of hypocenter distributions before and after relocation was conducted. In Figure 3, the initial data (prior to relocation) show an aftershock distribution pattern that tends to be linear with a north–south orientation, which at first glance appears perpendicular to the general trend of regional structures in West Java. However, after relocation using the Double-Difference method, the spatial distribution pattern in Figure 4 changes significantly, with epicenters forming a more curved cluster extending from the south toward the west. Such post-relocation changes in orientation are common, as improvements in travel-time residuals can reveal the complexity of fault geometry that was previously obscured by location errors [14]. Although this curved pattern may indicate a complex fault geometry, the possibility of bias resulting from the sensitivity of P- and S-wave picking within the local station network cannot be ruled out [15].

The stability of the HypoDD algorithm, despite the limited number of events, is demonstrated by the stable convergence of the inversion and a consistent reduction in travel-time residuals. The overall Root Mean Square (RMS) error decreased significantly following the relocation process compared to the initial catalog. This successful convergence confirms the computational reliability of the relocated hypocenter coordinates, proving that the method effectively minimized errors caused by the unmodeled velocity structure.

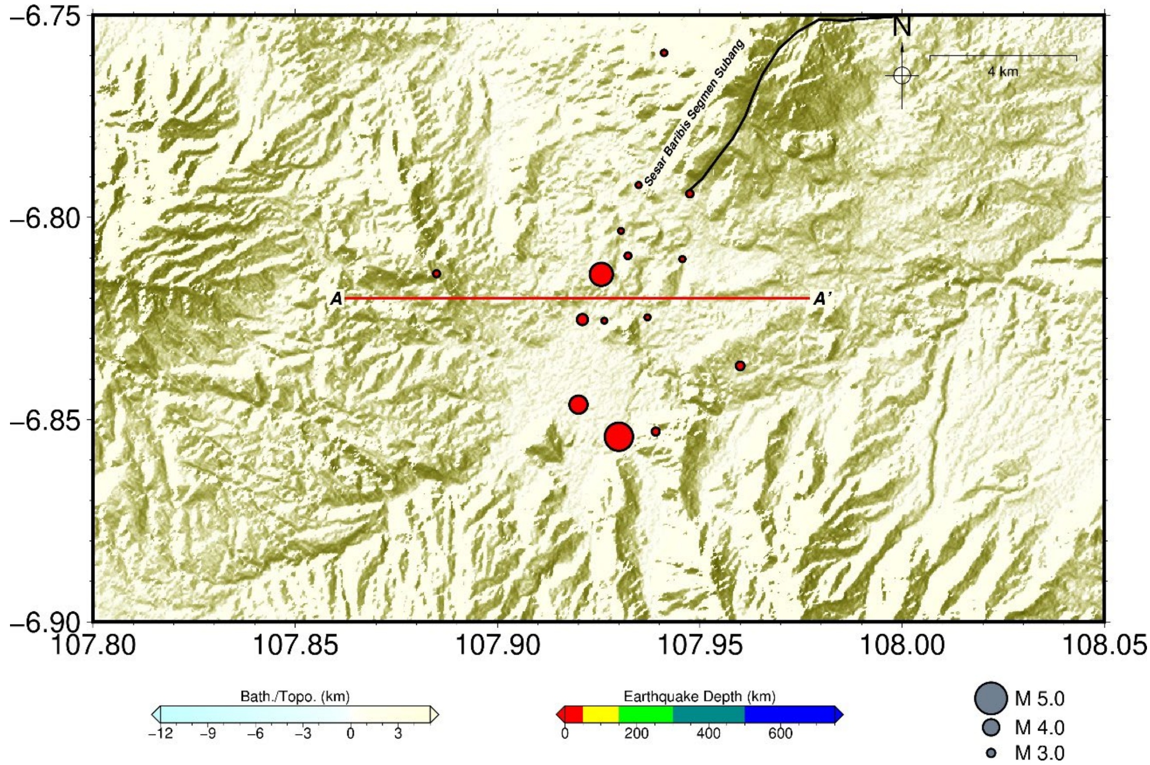

Fig. 3. Distribution map of aftershocks in Sumedang before relocation

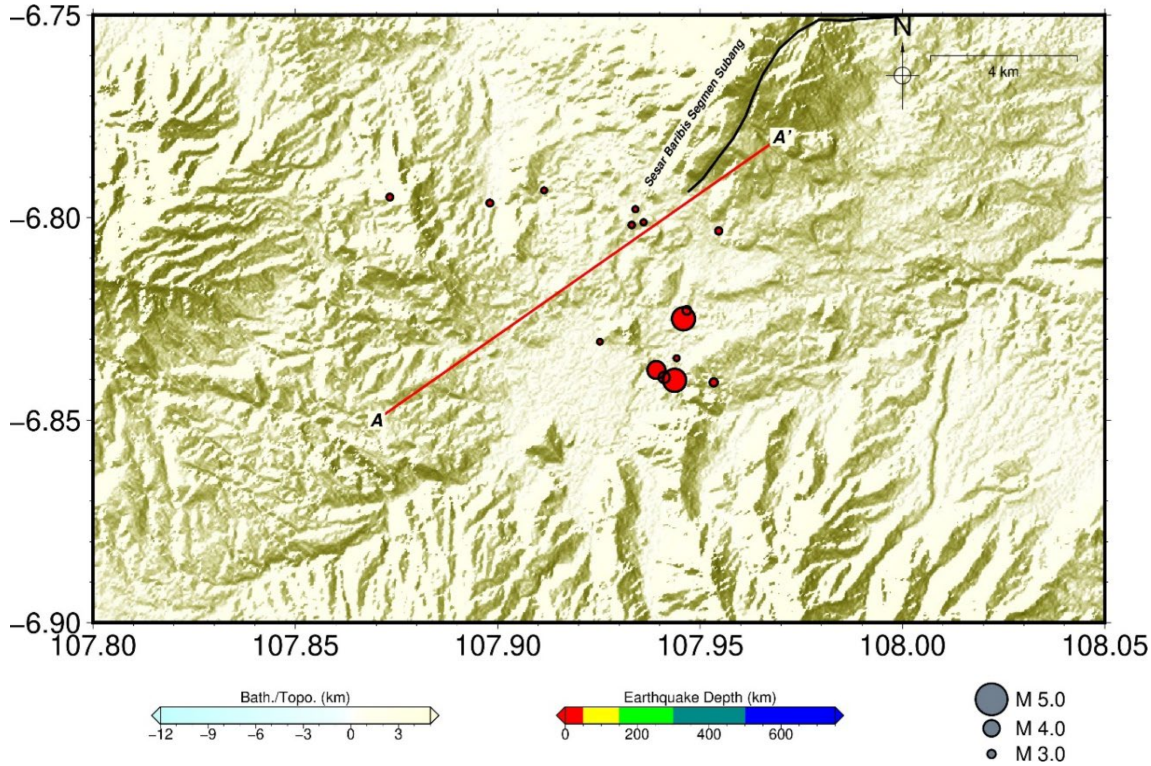

Fig. 4. Distribution map of aftershocks in Sumedang after relocation

3.3. Structural Interpretation Through Cross-Section Analysis

A more detailed analysis was carried out by constructing vertical cross-sections to better understand the subsurface geometry of the earthquake source zone. Based on Figure 5, the vertical section of the initial data shows hypocenter distributions spread over a depth range of approximately 3 km to 17 km, displaying a generally vertical but still diffuse pattern. In contrast, the relocated results shown in Figure 6 exhibit a more focused depth distribution that forms patterns interpretable under two possible source mechanism scenarios. The first possibility is that the nearly vertical alignment observed in the cross-section indicates a strike-slip faulting mechanism, which is consistent with the general characteristics of the Baribis Fault in several of its segments [16].

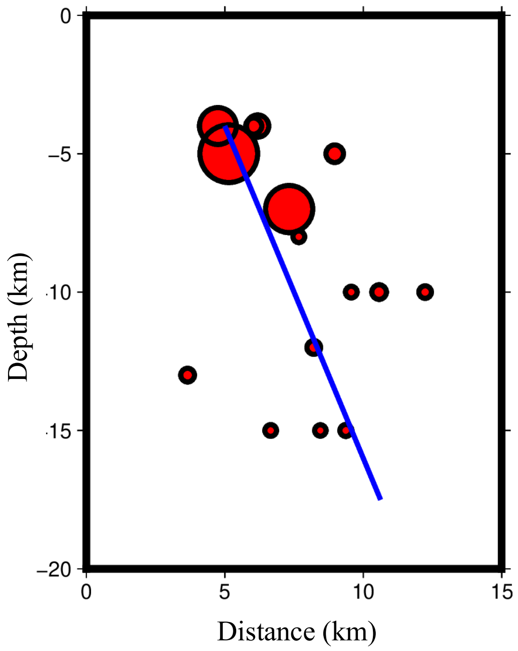

Fig. 5. Vertical cross-section of hypocenter distribution before relocation

On the other hand, the pattern in Figure 6 also shows a tendency toward an inclined geometry resembling a slab or curved fault plane. This feature opens a second possibility, namely the presence of a thrust or normal fault mechanism, which is often associated with shallow crustal deformation in the back-arc region of Java. This complexity suggests that the Baribis Fault, Subang Segment, may exhibit a mixed or oblique geometry at certain depths.

Therefore, although the relocated cross-section analysis provides a clearer depiction of subsurface geometry, definitive identification of the fault kinematics generally requires further analysis, such as moment tensor inversion, to accurately determine the strike, dip, and rake parameters [17]. To resolve the structural ambiguity in this study, we integrated our relocated cross-section with the official focal mechanism solution published by BMKG for the M 4.1 mainshock. The BMKG moment tensor indicates a predominantly strike-slip mechanism. By overlaying this kinematic constraint with the near-vertical alignment observed in Figure 6, it can be conclusively interpreted that the causative structure of the 2023 Sumedang sequence is a strike-slip fault associated with the Baribis Fault system (Subang Segment).

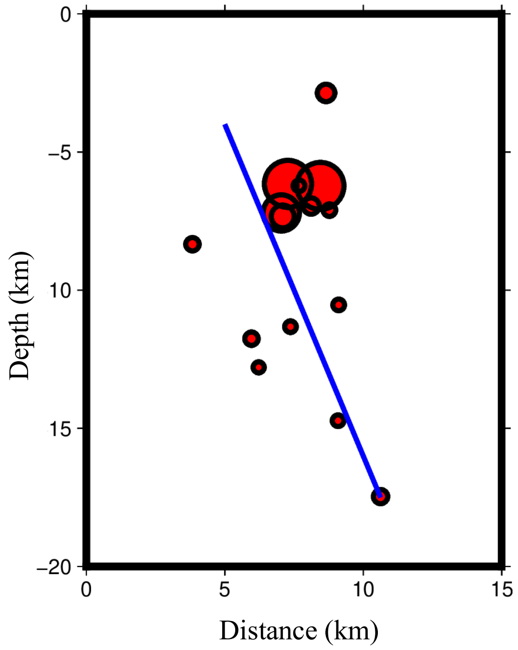

Fig. 6. Vertical cross-section of hypocenter distribution after relocation

4. CONCLUSION

The application of the Double-Difference relocation method to the Sumedang aftershock sequence successfully revealed a significant change in the hypocenter distribution pattern, from an initial north–south trend to a curved orientation toward the southwest. The identified earthquake activity is concentrated at shallow depths ranging from 3 to 17 km. Based on the cross-section analysis and corroborated by the BMKG focal mechanism solution for the mainshock, the causative fault is definitively interpreted as a near-vertical strike-slip structure. This resolves the spatial ambiguity and firmly associates the Sumedang earthquake sequence with the active strike-slip dynamics of the Baribis Fault system.

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