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RAPID MAGNITUDE ESTIMATION OF 2019 M6.9 BANTEN EARTHQUAKE USING GNSS 1HZ

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ABSTRACT

Rapid magnitude estimation remains challenging in Indonesia due to the limited evaluation of high-rate Global Navigation Satellite System (GNSS) data and the lack of region-specific validation of existing Peak Ground Displacement (PGD) scaling relations for earthquake early warning applications. This study investigates the performance of high-rate GNSS data (1 Hz) for rapid magnitude estimation of the August 2 2019, Banten earthquake (Mw 6.9). Using 15 InaCORS stations provided by the Geospatial Information Agency of Indonesia, the data were processed using Precise Point Positioning with Ambiguity Resolution (PPP-AR). PGD values were extracted and applied to three empirical scaling relations proposed by Melgar et al. (2015), Crowell et al. (2016), and Ruhl et al. (2019). This study presents a comparative evaluation of multiple PGD scaling models using real Indonesian GNSS data, providing insight into their performance in a tectonic setting that remains underrepresented in previous studies. The results show that all models successfully converged to Mw 6.9, with convergence times ranging from 20 to 160 seconds after the earthquake origin time. However, this study is limited by the analysis of a single earthquake event and the use of global scaling relations that are not specifically calibrated for Indonesian tectonic conditions. These findings demonstrate the potential of high-rate GNSS as a complementary tool to seismic sensors for rapid magnitude estimation. The integration of GNSS into the Indonesia Tsunami Early Warning System (InaTEWS) is therefore recommended to improve the reliability and timeliness of earthquake and tsunami early warning.

Keywords: *earthquake; high-rate GNSS; rapid magnitude estimation*

INTRODUCTION

Earthquakes are natural phenomena that occur due to the release of accumulated stress along faults within the Earth's crust (Fang et al., 2020). On Friday, August 2 2019, an earthquake of magnitude M6.9 occurred at coordinates 7.282° S and 104.791° E, with a depth of 49 km in the Sunda Strait. The epicenter was located approximately 147 km southwest of Sumur, Banten. This event was triggered by the collision between the Indo-Australian Plate and the Sunda Plate (DeMets et al., 2010). The Indo-Australian Plate subducts northeastward beneath the Sunda Plate with a rate of ~20 mm/year, generating tectonic activity (Alif et al., 2024; Anggara et al., 2024). The source mechanism of this earthquake is an intraslab earthquake from an ENE-WSW fault direction (Gunawan et al., 2022). According to BNPB, the earthquake caused six fatalities, damaged more than 100 buildings, and resulted in numerous injuries.

Indonesia has operated the Indonesia Tsunami Early Warning System (InaTEWS) to mitigate the risks of earthquakes and tsunamis (Sakalasuriya et al., 2022; Adityawan et al., 2023). However, its operation still relies primarily on seismometers and accelerometers, with no integration of Global Navigation Satellite System (GNSS) sensors (Hohensinn & Geiger 2018; Melbourne et al., 2021). Seismometers are capable of detecting the arrival of small-amplitude seismic waves, thus contributing to the earthquake warning timeline, even for small or distant events (Hardy et al., 2025; Melgar et al., 2015; Li et al., 2023). Nevertheless, seismometers are limited by their dynamic range, which often prevents them from fully recording strong ground motions with large amplitudes (Goldberg et al., 2019; Melgar et al., 2015; Sha'ameri et al., 2021). These limitations are evident in large-magnitude earthquakes such as the December 26 2004 Aceh earthquake (Fujii et al., 2020) and the 2011 Tohoku-Oki earthquake (Mw 9.0) (Hoshiba et al., 2011; Xu, 2025), where conventional seismic methods experienced magnitude saturation and delayed characterization, leading to underestimation of earthquake size in the early stages and highlighting the need for complementary geodetic observations such as GNSS.

Over the past decade, GNSS has rapidly developed as a geophysical sensor capable of detecting co-seismic deformation. GNSS has been proven to accurately estimate interseismic (Anggara et al., 2026), coseismic (Alif et al., 2021; Anggara et al., 2025), thereby providing faster and more precise earthquake magnitude estimates (Crowell et al., 2013; Meilano et al., 2022; Ruhl et al., 2019), which is consistent with InSAR-based observations of coseismic deformation (Anggara & Alif, 2025). Magnitude and timing estimates can be obtained through the processing of high-rate (1 Hz) GNSS data. Meilano et al. (2022) successfully applied GNSS to estimate the magnitude of the August 5 2018, Lombok earthquake, while Urtiaga et al. (2022) demonstrated the application of GNSS in detecting seismic events such as the 2011 Tohoku earthquake. However, despite these advances, the validation and comparative assessment of existing PGD scaling relations using high-rate GNSS data in the Indonesian tectonic setting remain limited. Most previous studies have focused on individual events or regions outside Indonesia, and the applicability of these models in this region has not been systematically evaluated.

This study aims to estimate the time required to determine the magnitude of the August 2 2019, Banten earthquake (M6.9) using the Peak Ground Displacement (PGD) scaling method (Melgar et al., 2015; Ruhl et al., 2019; Crowell et al., 2016). The results are expected to serve as a scientific reference for the utilization of high-rate GNSS data in rapid magnitude estimation and to contribute to the improvement of the national earthquake early warning system. Furthermore, this study recommends the real-time integration of high-rate (1 Hz) GNSS data in the Indonesian earthquake early warning system.

MATERIALS AND METHODS

In the rapid magnitude estimation using GNSS, the Precise Point Positioning (PPP) method was applied through the PRIDE PPP Ambiguity Resolution (PPP-AR) software (Geng et al., 2019), as shown in **Figure 1**, as it enables high-precision positioning without the need for a reference station and provides improved accuracy and faster convergence compared to conventional PPP approaches (e.g., Paziewski et al., 2023; Fang et al., 2021). The data were provided by the Geospatial Information Agency of Indonesia and consisted of observations from 15 InaCORS stations acquired at a 1 Hz sampling rate (**Figure 2**). The 1 Hz GNSS CORS data were processed using post-processing PPP, incorporating satellite orbit data, satellite clock data, Earth Rotation Parameters (ERP), signal bias information, and quaternions (ORBEX). This study focuses on rapid magnitude estimation using Peak Ground Displacement (PGD) scaling for the epicenter of the Banten earthquake on August 2 2019, Mw 6.9, based on high-rate GNSS data. The Banten earthquake (M6.9) occurred on August 2 2019, approximately ~100 km northeast of the Sunda Trench and about ~140 km offshore of Sumatra Island. In this study, we performed three comparative equation tests to identify the optimal formula for rapid magnitude estimation. The equations applied in this study were adopted from Crowell *et al.* (2016), Melgar *et al.* (2015), and Ruhl *et al.* (2019) for the estimation of Peak Ground Displacement (PGD), as these models are widely used and represent different characteristics in terms of sensitivity to early displacement signals, convergence speed, and stability, enabling a comprehensive comparison of their performance in rapid magnitude estimation.

The earthquake moment magnitude (Mw) can be estimated using Equation 1:

$$\log 10\,(PGD) = A + BMw + CMw\,\log 10\,(R) \quad (1)$$

Where B and C are empirical coefficients derived from regression analyses of earthquakes from previous research (Crowell et al., 2016; Melgar et al., 2015; Ruhl et al., 2019), and R is the distance of the GNSS station from the earthquake epicenter (km). The Peak Ground Displacement (PGD) from unfiltered GNSS data, expressed in centimeters, was calculated from the displacement components in the north, east, and up directions using Equation 2:

$$PGD = \sqrt{dN(t)^2 + dE(t)^2 + dU(t)^2} \quad (2)$$

Where dN represents the north–south displacement, dE represents the east–west displacement, and dU represents the vertical (up–down) displacement.

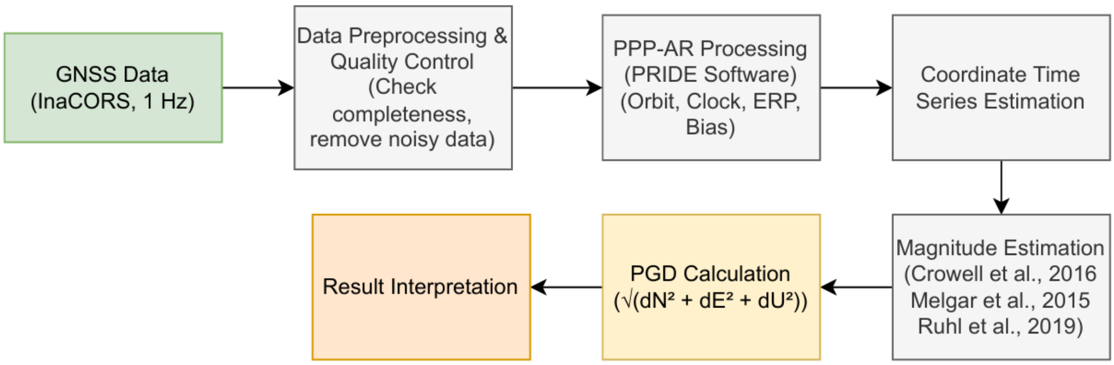

Figure 1. Processing workflow of high-rate GNSS data for PGD Estimation

Source: Developed by the author.

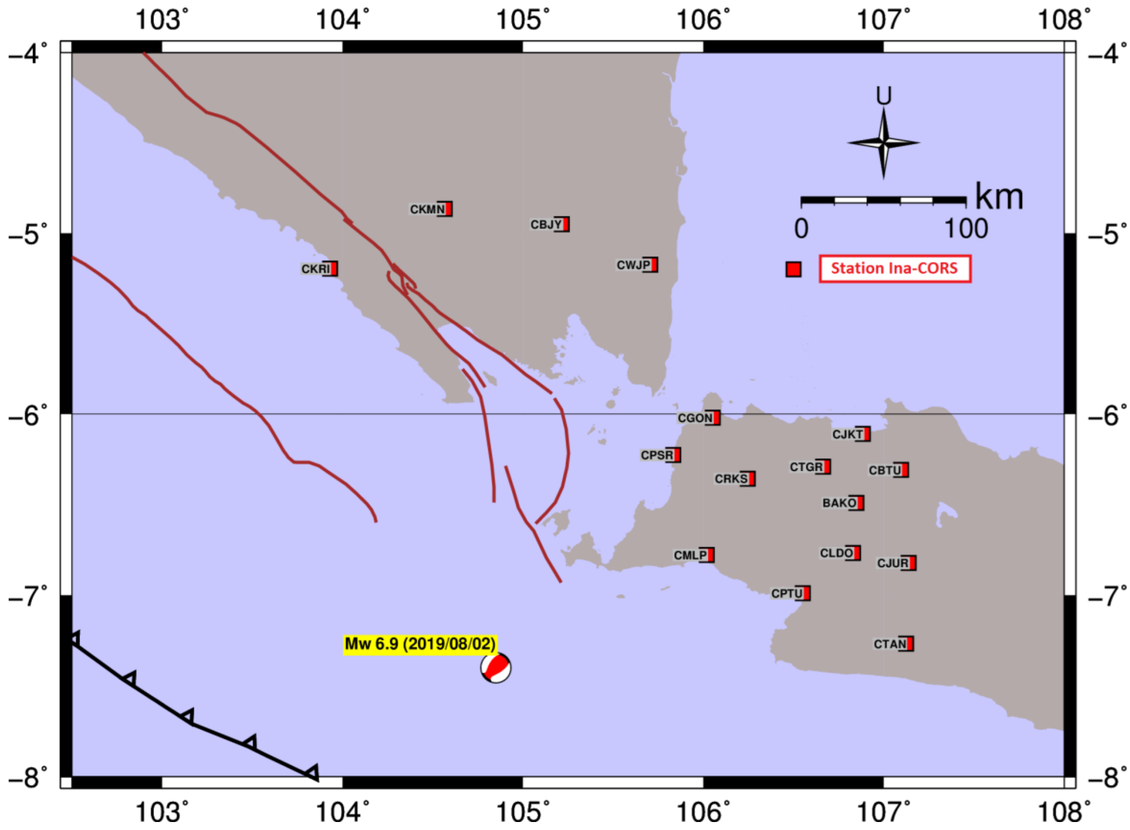

Figure 2. Distribution of GNSS Sites

Source: Developed by the author.

RESULTS AND DISCUSSION

The estimation was carried out using the origin time of the earthquake provided by the United States Geological Survey (USGS). **Figure 3** presents the results of the estimation based on the Equation proposed by Ruhl et al. (2019). The estimation results using the Equation of Ruhl et al. (2019) demonstrate that most GNSS stations consistently converged to the target magnitude of approximately M6.9, albeit with varying convergence times. Stations located relatively close to the epicenter, such as CLDO (232.34 km) and CKRI (249.45 km), showed earlier convergence within less than 100 seconds, suggesting stronger signal detection and more rapid stabilization of displacement data. In contrast, stations such as CPSR (164.02 km), CPTU (197.08 km), CRKS (190.52 km), and CJKT (265.22 km) required longer convergence times of over 150 seconds, indicating that local noise or site-specific conditions may have influenced the delay. However, several stations have long distances (e.g., CBTU at 276.60 km and CJUR at 264.21 km) successfully converged within ~100 seconds, highlighting that distance is not the dominant factor in determining estimation speed. The Ruhl equation produced accurate magnitude values but with noticeable variability in convergence time across stations, ranging from as early as 37 seconds (CLDO) to as late as 196 seconds (CKMN). This variability suggests that while the method is reliable for capturing the optimum magnitude, its timeliness is less consistent compared to other models, potentially limiting its effectiveness in rapid earthquake early warning applications.

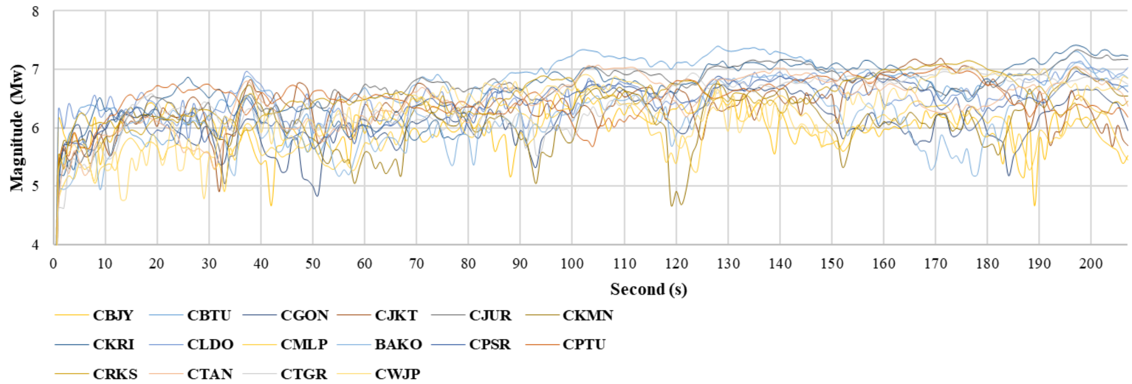

Figure 3. Rapid magnitude estimation using the Equation proposed by Ruhl et al. (2019)

Source: Results from the author.

Figure 4 shows the results of the magnitude estimation based on the Equation proposed by Melgar et al. (2015). Across all analyzed stations, the estimated magnitudes consistently converged to M6.9, which is in close agreement with the reported magnitude from the United States Geological Survey (USGS) of the August 2 2019 Banten earthquake. At station CGON (197.17 km from the epicenter), the magnitude reached M6.9 at 103 seconds after the event. Similarly, station CMLP (146.62 km) produced M6.9 at 104 seconds, and station CPSR (164.02 km) yielded the same magnitude at 87 seconds. Some stations showed much earlier convergence, such as CPTU (197.08 km), which achieved M6.9 as early as 20 seconds, and CKRI (249.45 km) at 24 seconds. Other stations, including CLDO (232.34 km), CBTU (276.60 km), CJKT (265.22 km), CKMN (268.29 km), and CTAN (257.56 km), also exhibited rapid convergence within 36–47 seconds after the event. However, stations located at greater distances, such as BAKO (243.62 km), CTGR (234.19

km), and CBJY (261.98 km), required longer times ranging from 119 to 128 seconds before stabilizing at M6.9. Despite these variations in convergence time, the uniformity of the final magnitude across all stations demonstrates the robustness of the PGD scaling method by Melgar et al. (2015) when applied to high-rate GNSS data.

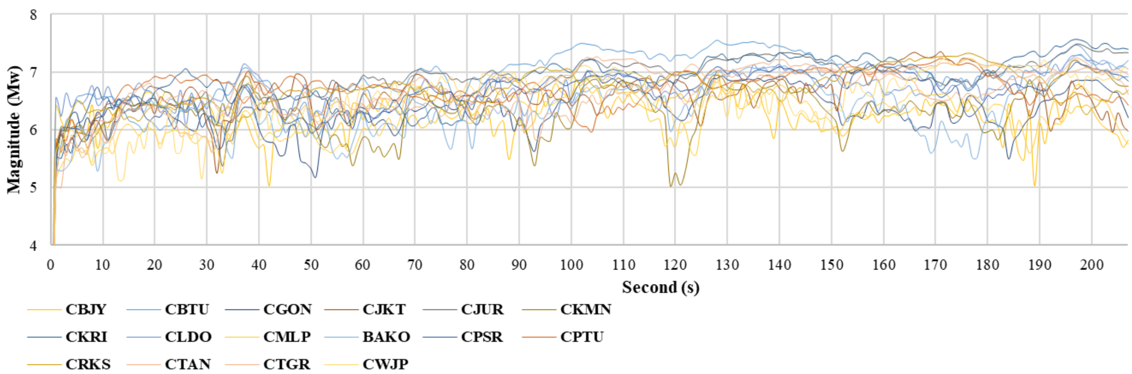

Figure 4. Rapid magnitude estimation using the Equation proposed by Melgar et al. (2015)

Source: Results from the author.

Figure 5 shows the results of magnitude estimation using the Equation proposed by Crowell et al. (2016). Similar to the Melgar et al. (2015) formulation, all stations consistently converged to M6.9, matching the reported magnitude of the August 2 2019, Banten earthquake. However, a notable difference in the origin time, which was significantly faster compared to the Melgar equation results. For instance, several stations detected M6.9 within only a few seconds of the earthquake origin. The earliest convergence was recorded at station CBJY (261.98 km), which reached M6.9 just 1 second after the event. Other stations, including CLDO (232.34 km) and CRKS (190.52 km), also achieved stable magnitude estimates within 4–5 seconds. Stations CGON (197.17 km), CPSR (164.02 km), CKRI (249.45 km), CBTU (276.60 km), CJKT (265.22 km), CJUR (264.21 km), CKMN (268.29 km), and CTAN (257.56 km) showed convergence between 11–15 seconds. Meanwhile, stations BAKO (243.62 km), CTGR (234.19 km), and CWJP (254.05 km) required slightly longer, between 17 - 23 seconds. The latest convergence occurred at CMLP (146.62 km), which stabilized at 72 seconds. These results highlight the robustness of the Crowell et al. (2016) formulation, demonstrating its ability to provide near-real-time magnitude estimation using high-rate GNSS data. The fact that most stations converged to M6.9 within seconds indicates that this method has significant potential for operational earthquake early warning systems. Furthermore, the variation in convergence times across stations suggests that local site conditions, station geometry, and noise levels can influence the rapidity of stable magnitude estimation (e.g., Hardy et al., 2025; Meilano et al., 2022; Susilo et al., 2021).

Figure 6 presents the results of rapid magnitude estimation using the equations proposed by Ruhl et al. (2019), Melgar et al. (2015), and Crowell et al. (2016). Overall, the three methods consistently converge toward the target magnitude of M6.9, but they differ significantly in terms of response time. The Equation by Crowell et al. (2016) provides the fastest magnitude estimation, with several stations (e.g., CBJY, CLDO, CRKS) reaching stable values within 1–20 seconds after the earthquake origin time. This indicates high sensitivity but may also reflect greater dependence on near-field station conditions. In contrast, the Melgar et al. (2015) equation shows intermediate performance, producing stable magnitude estimates within 20–130 seconds at most stations. This balance between timeliness and stability suggests it is robust across a wide range of distances from the epicenter. The Ruhl et al. (2019) equation, while accurate, tends to provide later convergence, often exceeding 150 seconds at stations such as CKMN and CJKT. This delay indicates that the method may require longer observation windows, making it less optimal for real-time applications, though potentially more reliable for post-event validation.

In summary, Crowell et al (2016) equation offers the quickest estimation, Melgar et al. (2015) equation provides a practical compromise between speed and stability, and Ruhl et al. (2019) equation yields consistent results but with longer latency. These findings highlight the trade-off between speed and robustness in rapid GNSS-based magnitude estimation, which is crucial for effective earthquake early warning systems (e.g., Xu et al., 2013; Xu et al., 2021). The finding results that the three existing PGD scaling relations are not optimally in Indonesia, as their development lacks sufficient incorporation of large-magnitude seismic events from this region (Hardy et al., 2025).

To evaluate the accuracy of the magnitude estimation, the results from all stations were compared with the reference magnitude reported by the United States Geological Survey (USGS), Mw 6.9. All PGD scaling relations produced consistent estimates that converged closely to the reference value, with minor deviations during the early stage before stabilization, indicating reliable performance of GNSS-based methods. These findings are consistent with previous studies (e.g., Meilano et al., 2022; Crowell et al., 2013; Ruhl et al., 2019), which demonstrate that PGD scaling provides robust magnitude estimation, although convergence time varies across methods, with the Crowell et al. (2016) model showing faster response. However, this study has several limitations, including the use of a single earthquake event and the application of PGD models not specifically calibrated for the Indonesian tectonic setting, as well as potential influences from station distribution and data quality on estimation consistency and timing.

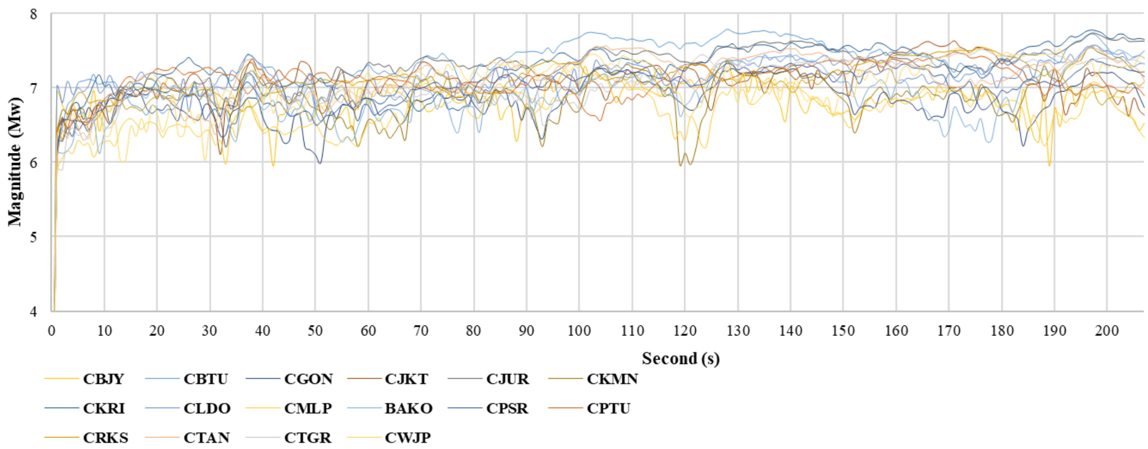

Figure 5. Rapid magnitude estimation using the Equation proposed by Crowell et al. (2016)

Source: Results from the author.

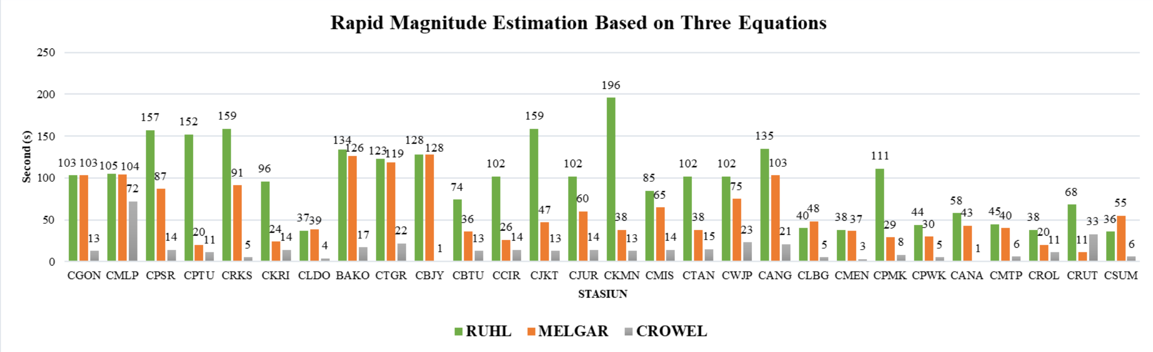

Figure 6. Comparison of the rapid estimation magnitude

Source: Results from the author.

CONCLUSIONS

This study demonstrates that high-rate GNSS (1 Hz) data can reliably estimate the magnitude of the August 2 2019, M6.9 Banten earthquake using PGD scaling relations. All tested models consistently converged to M6.9, confirming the robustness of GNSS-based approaches. However, they differ significantly in response time: Crowell et al. (2016) provide the fastest estimation (1–20 s), Melgar et al. (2015) offer a balance between speed and stability (20–130 s), and Ruhl et al. (2019) show slower convergence (>150 s), limiting its use for real-time applications. Convergence variability is influenced more by site GNSS conditions and network characteristics than by epicentral distance. These results highlight a trade-off between speed and robustness and indicate that existing PGD scaling relations are not yet fully optimized for Indonesian tectonic settings. Future work should focus on developing region-specific models to improve GNSS-based earthquake early warning systems.

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