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Performance of the *P*-alert real-time shakemaps system and onsite warning during the 2025 M_L6.4 Dapu earthquake

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Abstract
On January 20, 2025, the M_L6.4 Dapu earthquake struck southwestern Taiwan, causing intense shaking in Chiayi County and Tainan City. The *P*-Alert real-time shakemaps system generated detailed shakemaps just 36 s after the earthquake occurred. The areas of strongest shaking were primarily located to the southwest of the epicenter, which corresponds with the observed damage distribution. Based on the epicenter location, the distribution of shaking, and the distribution of aftershocks, it is likely that the rupture propagated southwestward from its initiation point. For this event, the Central Weather Administration (CWA) issued the first report 7.9 s after the earthquake occurred. Considering the average signal transmission delay of approximately 5 s in the Public Warning System (PWS), most individual *P*-Alert devices located within 30 km of the epicenter provided onsite warnings earlier than the CWA's regional warning. These observations underscore the effectiveness of the *P*-Alert system in providing onsite warnings, as well as its significant advantages in disaster response.

Keywords Damage earthquake, Shakemaps, Earthquake early warning, Peak ground acceleration, Peak ground velocity

1 Introduction

Taiwan has been developing earthquake early warning (EEW) technology for over 30 years (Wu et al. 1998, 1999). Over these decades, EEW systems have become a cornerstone of the national disaster mitigation strategy, playing a critical role in enhancing public safety and response. During the recent 2025 Dapu M_L 6.4 earthquake, which occurred on January 20 at 16:17 (UTC), the Central Weather Administration (CWA) issued its first earthquake report within 7.9 s, providing a preliminary magnitude estimate of 6.5. This estimate closely aligns with the officially reported M_L 6.4.

Apart from the CWA's regional EEW system, the *P*-Alert EEW system, developed by National Taiwan University (NTU), also plays a crucial role. The *P*-Alert system instantly transmits peak ground acceleration (PGA) and peak ground velocity (PGV) data to the National Science and Technology Center for Disaster Reduction (NCDR) for damage assessment (Wu 2015; Wu et al. 2016). The *P*-Alert system also generates shakemaps for public reference via social media. Additionally, strong-motion records from *P*-Alert are made available in near real-time for academic research.

During the 2025 Dapu earthquake, the *P*-Alert system reliably generated maps of PGA, PGV, CWA intensity, and spectral acceleration (Sa; Yang et al. 2021) within 36 s

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after the event. This rapid response not only greatly contributed to damage assessment but also aided in determining the rupture direction (Hsieh et al. 2014; Jan et al. 2018). Notably, in areas close to the earthquake epicenter, onsite warnings from each *P*-Alert device can be issued earlier than regional warnings from the CWA, offering a faster alert response. This study will further evaluate the performance of the *P*-Alert system in this earthquake.

2 Real-time shakemaps

The *P*-Alert system, developed by the research team at NTU, has significantly expanded over time. By the time of the 2025 Dapu earthquake, the network comprised nearly 785 stations across Taiwan and its surrounding islands, making it the densest seismic monitoring network in the country.

A core feature of the *P*-Alert system is its ability to generate real-time shakemaps, which provide crucial information about earthquakes shortly after they occur. Since 2014, the system has been capable of producing detailed shakemaps for PGA at one-minute intervals (Hsieh et al. 2014). In 2020, an upgrade (Yang et al. 2021) expanded its capabilities to include real-time maps for PGV, Sa, and the CWA intensity scales. These shakemaps are automatically generated and distributed to key institutions, including the NCDR, ensuring timely information for emergency response and rescue operations (Mittal et al. 2022). Additionally, they are made publicly available on social media platforms such as Facebook and X (formerly Twitter), providing real-time earthquake information to the general public.

Real-time generation of shakemaps occurs when ground shaking triggers five or more stations. The triggering conditions are defined as follows: the maximum acceleration at a station within one second must exceed 1.5 gal, and at least two additional stations within a 30-km radius must record values above 1.5 gal within 6 s. Once triggered, the shakemaps are updated every 30 s, ensuring continuous updates as long as the stations detect ground shaking (Yang et al. 2023).

During the 2025 Dapu earthquake, the *P*-Alert system issued its first shakemaps on Facebook and X approximately 6 s after the earthquake occurred. The first stable report was generated around 36 s after the earthquake occurred, with a total of 486 stations triggered. Figure 1 presents the PGA and PGV shakemaps distributed on social media 36 s after the earthquake occurred. Within 50 km of the epicenter, ground motion did not change

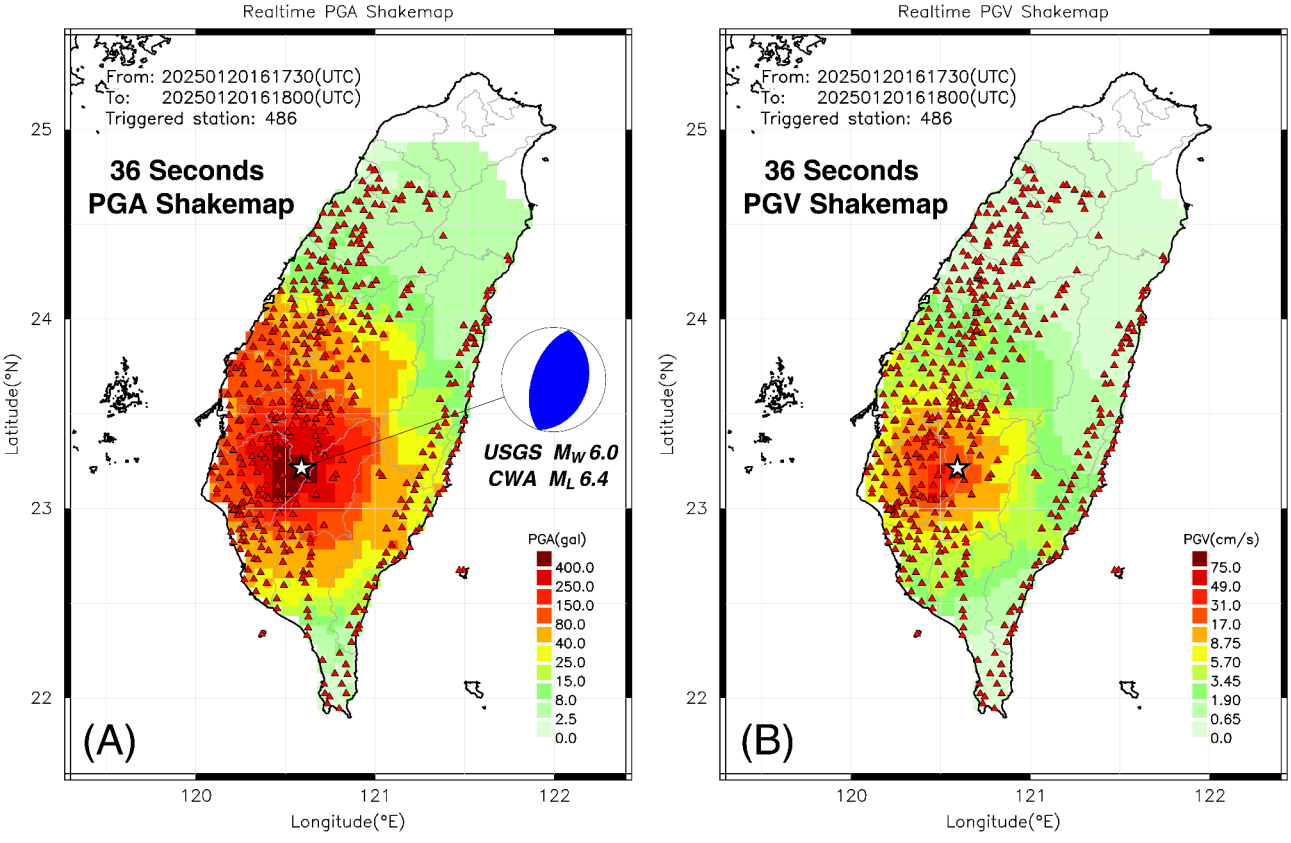

Fig. 1 The (**A**) PGA and (**B**) PGV shakemaps distributed 36 s after the earthquake. The star marks the epicenter of the 2025 Dapu earthquake. The focal mechanism, determined by the U.S. Geological Survey, indicates a pure thrust event with a Mw 6.0. The epicenter and focal mechanism were plotted in this study

significantly compared to the final shakemaps. Areas of high PGA and PGV extended southwest from the epicenter, while the northeastern direction showed a noticeable lack of extension. These detailed shakemaps provided critical insights into the fault rupture and damage assessment.

3 Damage pattern and potential rupture direction

The 2025 Dapu M_L 6.4 earthquake caused confirmed damage to 1,380 buildings, with an additional 367 buildings requiring evaluation, as reported by the National Land Management Agency of the Ministry of the Interior on February 3, 2025. The building damage is categorized as red-tagged (structural damage) and yellow-tagged (repairable damage). Table 1 presents the damage statistics of the 2025 Dapu earthquake.

Most of the damage occurred in Tainan City, particularly in the Nansi and Yujing districts, with some damage also reported in Chiayi County. Nansi was the most severely affected district. Both Nansi and Yujing are located southwest of the epicenter and experienced the strongest shaking during the event, with PGA exceeding 400 gal and PGV exceeding 30 cm/s (Fig. 2). Although this earthquake caused damage to more than one thousand buildings, it resulted in no fatalities.

According to the U.S. Geological Survey (USGS) report, the 2025 Dapu earthquake Mw is 6.0 (USGS, 2025, refer to [https://www.usgs.gov/programs/earthquake-hazards/earthquakes] (https://www.usgs.gov/programs/earthquake-hazards/earthquakes), last accessed on 4 February 2025). The focal mechanism indicates pure thrust faulting with a strike of approximately N15°E (Fig. 2). Figure 2 shows that the highest shaking occurred in the southwest area of the epicenter, along with the most of distribution of aftershocks reported by the CWA updated on February 4, 2025 (CWA 2025, refer to [https://scweb.cwa.gov.tw/en-us/earthquake/data] (https://scweb.cwa.gov.tw/en-us/earthquake/data), last accessed on 4 February 2025). In contrast, stations located northeast of the epicenter recorded relatively lower shaking compared to stations southwest of the epicenter at the same distance. Based on the earthquake's location, aftershock distribution, and the observed high shaking areas, the 2025 Dapu earthquake likely ruptured southwestward from its initiation point.

We further examined PGV attenuation with distance in eight directions from the epicenter. Figure 3A presents the PGV map with eight dashed arrows radiating from the epicenter, each representing a distinct direction. Figure 3B displays PGV values plotted against distance for each of the eight directions, spaced at 45° intervals. As noted by Jan et al. (2018), most PGV profiles show a decreasing trend with distance. However, the S30°W profile exhibits a positive slope, suggesting an increase in PGV with distance. This indicates that S30°W could be the major rupture direction.

Table 1 Confirmed damage statistics of the 2025 Dapu M_L 6.4 earthquake (updated on February 3, 2025, by the National Land Management Agency)

City or County	District	Red-Tagged (Structural damage)	Yellow-Tagged (Repairable damage)
Tainan City	ALL	384	965
Tainan City	Yujing	112	269
Tainan City	Nansi	216	550
Tainan City	Others	56	146
Chiayi County	ALL	6	29

* Additional 367 buildings requiring evaluation

4 Onsite warning

The CWA issued the first report 7.9 s after the earthquake occurred, but the warning was disseminated 2 s later. Under 4G and 5G networks, the Public Warning System (PWS) delivers alerts to end users in roughly 3 s (NCC 2025, refer to [https://www.ncc.gov.tw/chinese/gradation.aspx?site_content_sn=3725] (https://www.ncc.gov.tw/chinese/gradation.aspx?site_content_sn=3725), last accessed on 4 February 2025). This results in a latency that could be critical to in near-source regions, especially within the 30 km of the warning blind zone, where the time difference between P- and S-wave arrivals is only about 3–4 s, the minimum time required for effective warning. To mitigate this delay, onsite warning plays a crucial role (Wu and Kanamori 2008). Each *P*-Alert station functions as an independent onsite warning device, continuously recording data and performing double integration to estimate the peak vertical displacement of *P* waves (Pd). An onsite warning will be triggered once the predefined thresholds (Pd > 0.35 cm or PGA > 80 gal) are exceeded (Wu et al. 2011).

Due to transmission delays, CWA's first report issued at 7.9 s, reached the public approximately 13 s after the earthquake occurred. Figure 4 presents a spatiotemporal analysis, illustrating automatic P-arrival detection and actual alert issuance times for each station. In Fig. 4, a few anomalous stations have been excluded, as these anomalies may have resulted from disconnections, power outages, or inherent station issues. The analysis indicates that onsite warning provided a clear advantage within 30 km of the epicenter, with nearly all alerts issued before the regional warning. Notably, one station located approximately 29 km from the epicenter detected the P-arrival earlier than expected, likely due to a picking error. Overall, the *P*-Alert system performed effectively in providing onsite warnings during the 2025 Dapu earthquake.

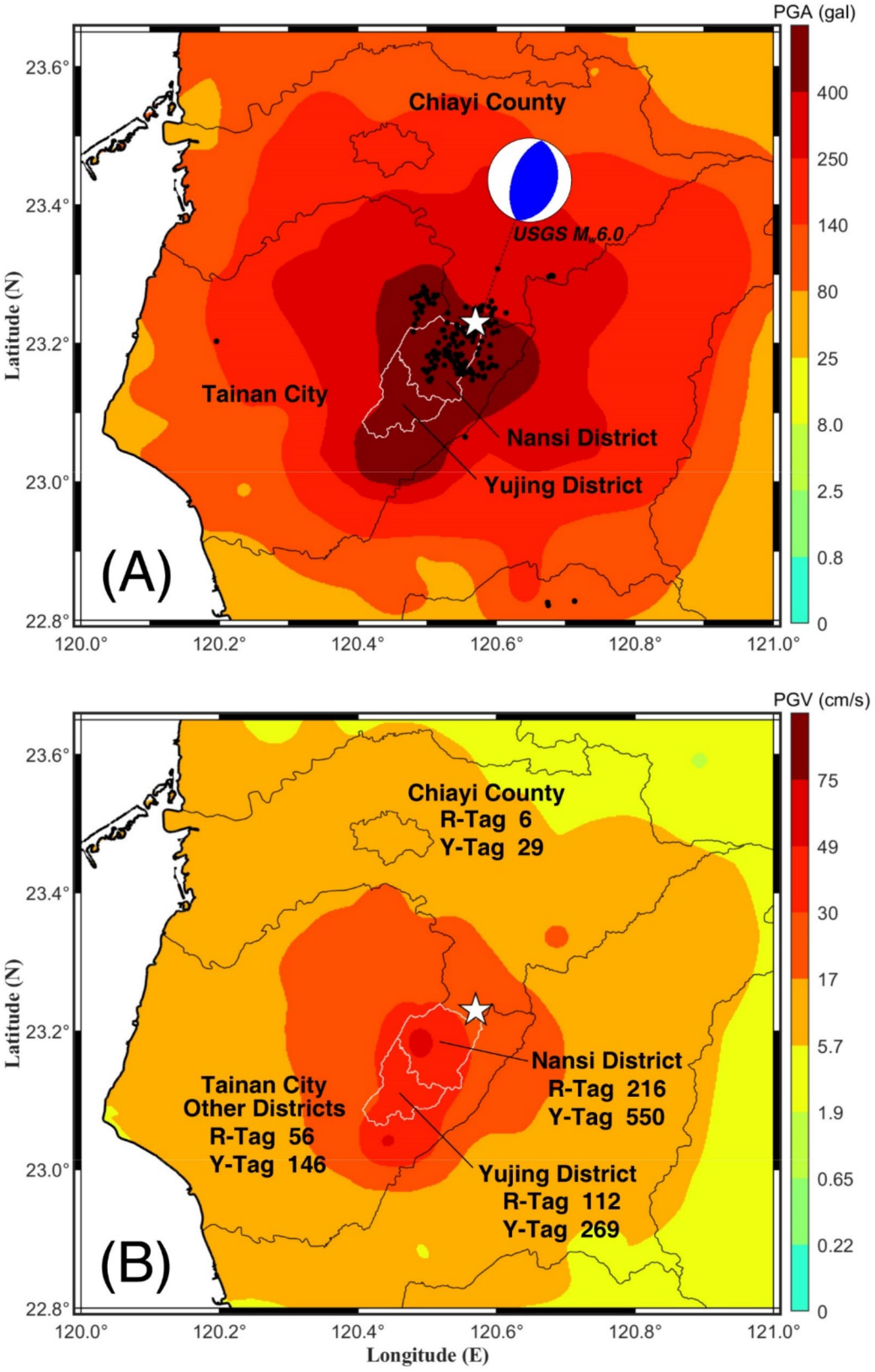

Fig. 2 (**A**) Distribution of PGA and felt aftershocks in southwestern Taiwan Black dots represent felt aftershocks reported by the CWA, updated as of February 4, 2025. (**B**) Distribution of PGV and building damage in southwestern Taiwan. Most of the damage was concentrated in the Nansi and Yujing districts, where PGA exceeded 400 gal and PGV exceeded 30 cm/s. The star indicates the location of the mainshock. R-Tag and Y-Tag represent structural and repairable damage, respectively

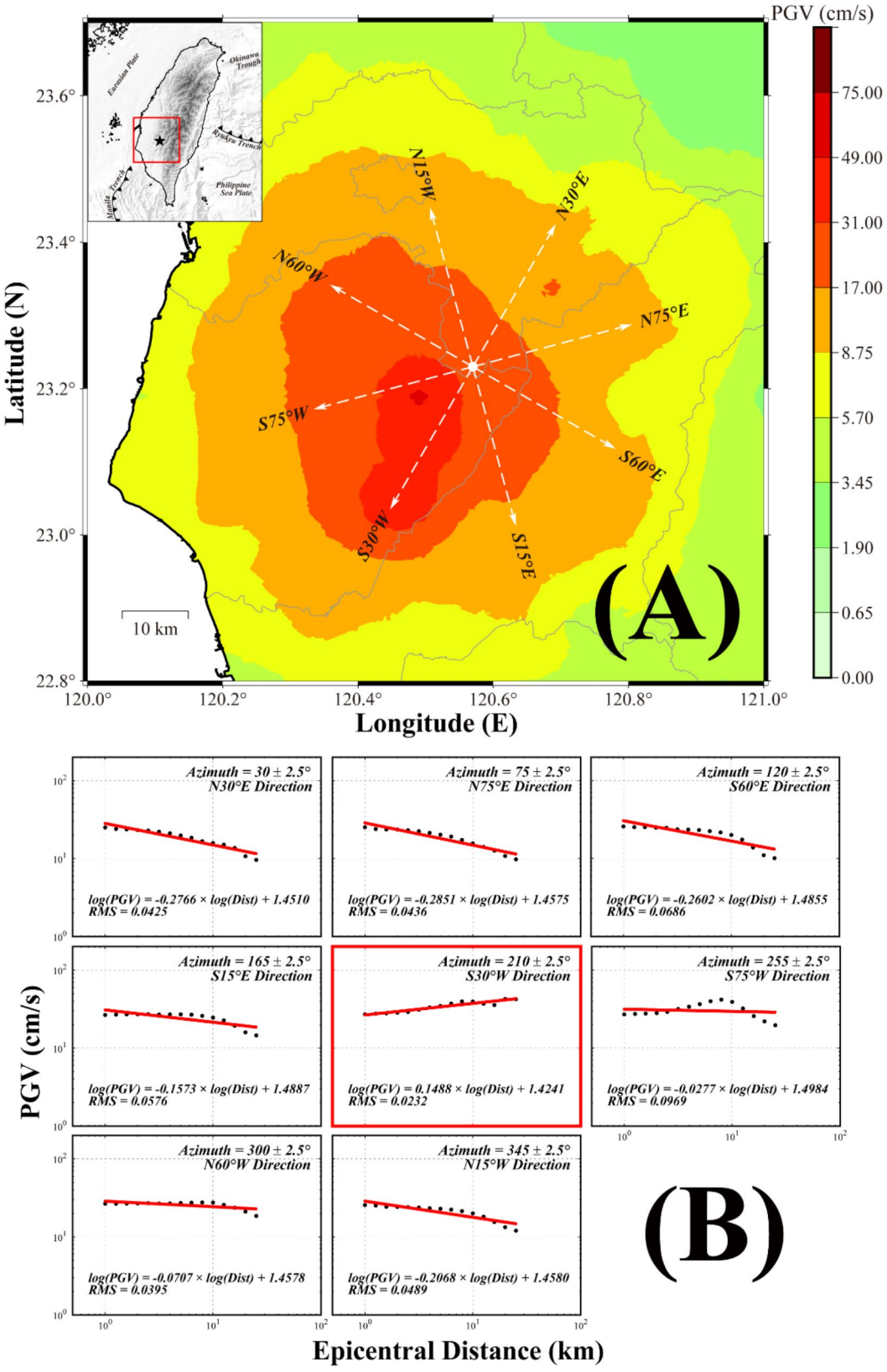

Fig. 3 (**A**) Peak Ground Velocity (PGV) map with eight dashed arrows radiating from the epicenter in distinct directions. The attenuation relationship between epicentral distance and PGV is analyzed along each arrow. (**B**) Regression analysis along 25 km profiles at 45° intervals. Black dots represent data points along each profile, while red lines indicate the regression fits. The profile exhibiting a positive slope is highlighted in red

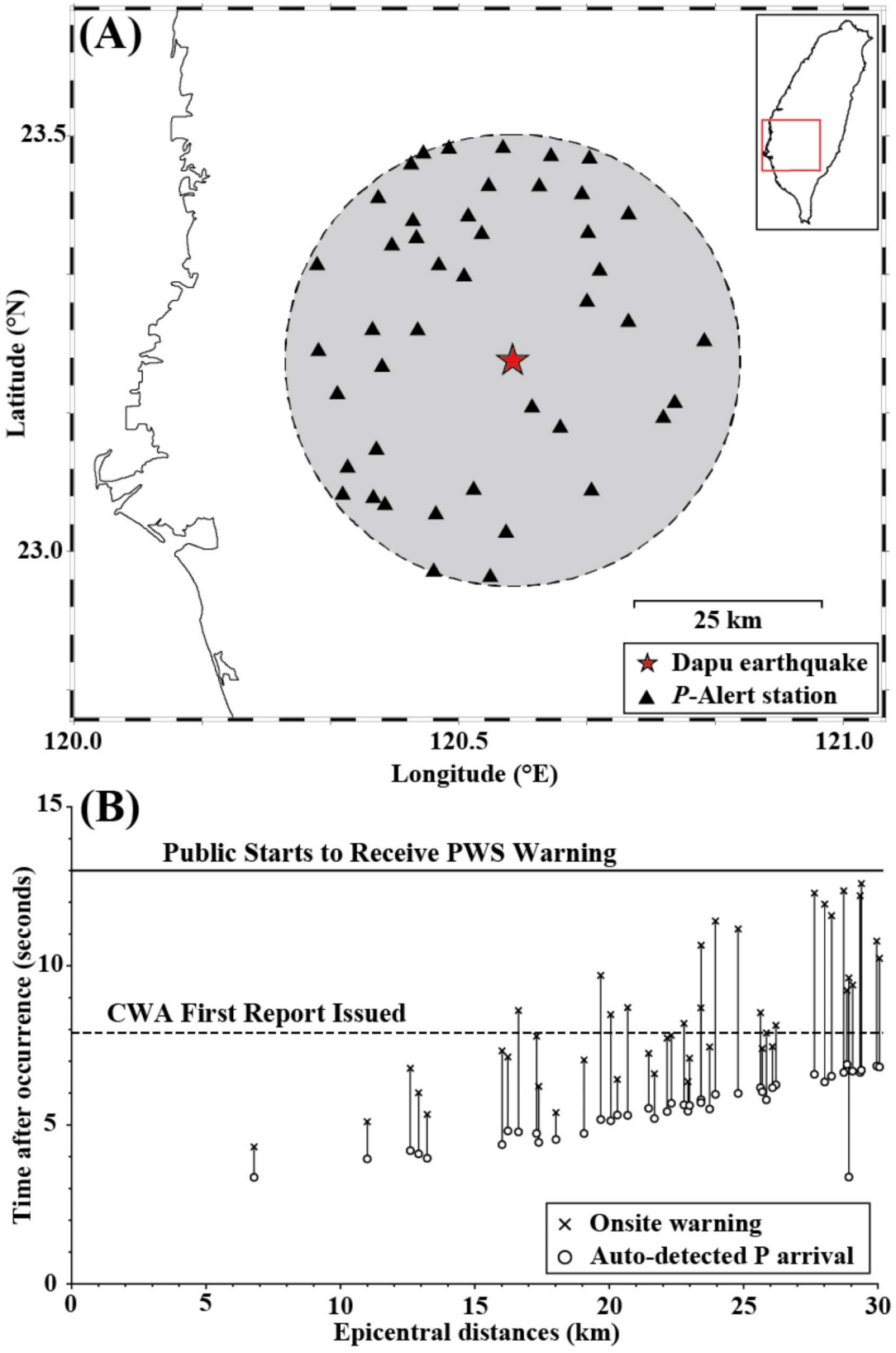

Fig. 4 (**A**) Station distribution within a 30 km radius of the epicenter and the advantage of onsite warning. The red star marks the epicenter, while the gray circle represents the 30 km radius where onsite warning is beneficial. (**B**) Onsite warning effectiveness, the dashed line indicates the time when the CWA issued the first earthquake report, while the solid line represents the average public receipt time via the Public Warning System (PWS). Circles indicate automatically detected P-wave arrivals, while crosses mark the onsite warning activation when Pd > 0.35 cm or PGA > 80 gal at each station

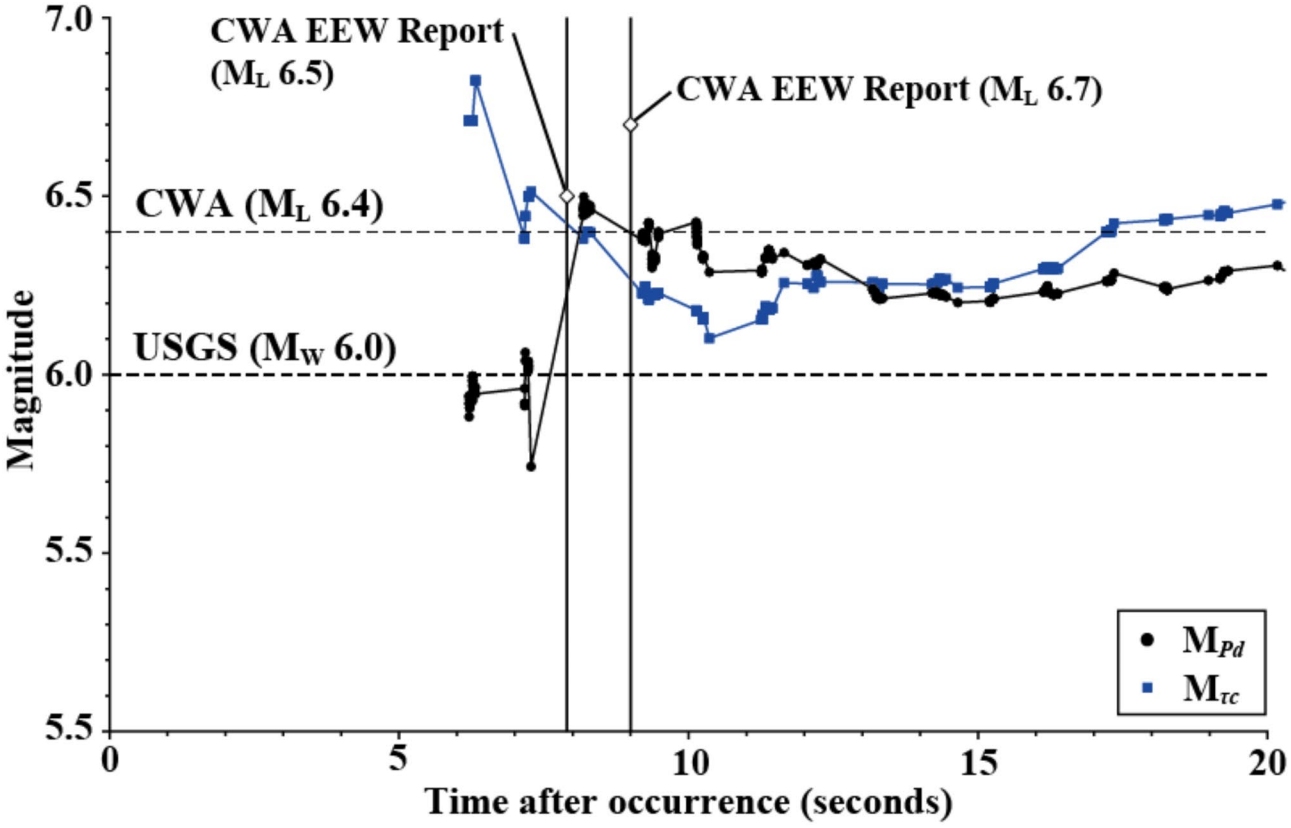

Fig. 5 Quick magnitude estimation for the Dapu earthquake. The black line represents M_{Pd} and the blue line represents $M_{\tau\,c}$ after the earthquake occurred. The vertical lines show the CWA's EEW report magnitude estimation at 7.9 s and 9 s, corresponding the magnitudes of 6.5 and 6.7, respectively. The horizontal lines indicate M_L 6.4 provided by CWA and Mw 6.0 from USGS

During the Dapu earthquake, the CWA's EEW system initially reported a magnitude of 6.5 at 7.9 s, which increased to 6.7 at 9 s. In contrast, the *P*-Alert system utilizes a second-based calculation formula for magnitude estimation (Wu 2024). It provided magnitude estimates of approximately 6.5 for M_{Pd}, and 6.4 for $M_{\tau\,c}$ at around 8 s, with a slight decrease to 6.1 and 6.2 at approximately 10 s. However, these estimates ultimately stabilized at around 6.3 and 6.5, demonstrating the stability of the *P*-Alert system. (Fig. 5)

5 Summary

The 2025 Dapu earthquake caused damage to more than one thousand buildings, with most of the affected structures located in the Nansi and Yujing districts of Tainan City. The *P*-Alert system reliably delivered PGA, PGV, CWA intensity, and Sa shakemaps just 36 s after the earthquake occurred. These real-time shakemaps indicated that Nansi and Yujing districts were located within the highest shaking areas, where PGA exceeded 400 gal and PGV exceeded 30 cm/s. Furthermore, the concentration of both the highest shaking and the majority of aftershocks southwest of the epicenter suggest that the 2025 Dapu earthquake likely ruptured southwestward (S30°W) after its initiation.

The CWA EEW system provided a timely warning for the 2025 Dapu earthquake, with a minimal blind zone where no warning was available. Given the signal latency of the Public Warning System (PWS), onsite warnings from individual *P*-Alert devices were able to provide earlier alerts than the PWS within 30 km of the epicenter.

Regarding onsite warning, the performance of the *P*-Alert system was generally effective. Although individual stations rely on their own data, which can occasionally result in picking errors, these errors do not affect the computation of the predefined thresholds for Pd and PGA. Overall, the *P*-Alert system performed satisfactorily during this earthquake, demonstrating its valuable role in early warning and damage assessment.

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Author contributions
Y.M.W. and Y.H.L. wrote the main manuscript text. Y.M.W., B.M.Y., and S.S.K. prepared Figs. 1, 2 and 3. Y.H.L. prepared Figs. 4 and 5. All authors reviewed the manuscript.

Data availability
Felted earthquake catalog can be downloaded from CWA website at https://scweb.cwa.gov.tw/zh-tw/earthquake/data/. Strong-motion records from P-Alert are freely available for download at https://palert.earth.sinica.edu.tw/database.

Declarations

Competing interests
The authors declare no competing interests.

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