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Original Research

Enhancement of P-Wave Detection for Earthquake Early Warning in Western Java Region

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Abstract

In recent decades, earthquake early warning (EEW) has become an option in many countries to reduce the vulnerability to earthquake hazards. For onsite-type EEW systems, P-wave detection or P-wave picking is key in successfully providing warnings for destructive earthquakes. Furthermore, the accuracy of P-wave picking will affect the accuracy of ground shaking in the warnings issued by the EEW system. P-wave picking under noisy circumstances is a challenge and requires a suitable method. We employed the initial power of P-wave (IPP) method and compared it with other techniques. Compared to several other methods, Short Time/Long Time Average (STA/LTA), Integrated Skewness-Kurtosis (InTeg), and EQTransformer model, the IPP gives a more accurate P-wave arrival time. From the investigation of 485 earthquake events in western Java that occurred during 2009-2023, Indonesia, with various magnitudes and various Signal-to-Noise Ratio (SNR), showed the mean deviation of IPP was 0.066 seconds, EQTranformer was 0.266 seconds, STA/LTA was 0.310 seconds, and InTeg was 0.316 seconds. The IPP method was shown to have better accuracy than other methods because of the ability to reduce the background noise without misjudgment and missing rates. The accuracy of P-wave picking makes the IPP method potentially applicable to the EEW systems.

Keywords Earthquake Early Warning, P-wave, Arrival Time, Mean Deviation

1. Introduction

Western Java is a seismically active zone and part of a very active arc and active arc seismotectonic unit with complex geological conditions resulting from the convergence of the Indo-Australian and Eurasian plates. Convergence is the subduction of the Indo-Australian plate to the Eurasian plate, which moves at a speed of 70 cm/year (Abdurrachman and Yamamoto, 2023). The existence of active faults, such as the Cimandiri fault (Aribowo et al., 2022), the Lembang fault (Daryono et al., 2018), the Cipamingkis fault (Gunawan and Widiyantoro, 2019), the Garut fault (Supendi et al., 2018), and the Baribis Fault, located not far from Jakarta (Damanik et al., 2021), makes western Java an area that is very vulnerable to destructive earthquake events.

EEW systems aim to predict ground shaking using the initial phase of P waves before the more destructive S waves shake the target area. Therefore, determining P-wave arrival time or P-wave picking is the key to the EEW system currently being built by the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) in the western Java region. One approach in EEW systems in some countries that have implemented EEW is to use the first 3 seconds of the initial phase of the P wave for ground shaking estimation (Wu et al., 2007; Hsu et al., 2013; Kumar et al., 2020; Chamoli et al., 2021). The accuracy of a single P-wave pick affects the location results; for example, 0.01 seconds of error in determining P-wave arrivals can translate to tens of meters of error in location (Mousavi et al., 2020). Errors in determining the arrival time of P waves in the context of EEW will make estimates EEW parameters such as dominant period and maximum amplitude of the initial phase of wave P (τ_c and Pd) inaccurate and have an impact on Peak Ground Acceleration (PGA) prediction errors which are then used as an output of the system for end users (buildings, highways, trains, gas pipeline, factories, and urban communities), (Yang et al., 2022; Claudio et al., 2010; Alizadeh et al., 2022; Karaca, 2022).

P-wave picking under noise circumstances from most signals received by earthquake stations is a challenging task and requires a suitable method. Many P-wave picking methods have been shown to fail in determining P-wave arrival times due to the influence of noise. We compared the IPP method results of the P-wave picking calculation with frequently used methods, such as STA/LTA, integrated skewness-kurtosis (InTeg) made by BMKG researchers, and the EQTransformer deep learning model (Gunawan et al., 2013; Mousavi et al., 2020; (Zhu et al., 2022); Chen et al., 2023). Two criteria are used to assess the ability of these methods to successfully detect the P-wave arrival time: the misjudgment rate and the missing rate. The misjudgment rate refers to the proportion of events with incorrect detection results, and the missing rate refers to the proportion of seismic events that are not detected.

An investigation of accelerometer signals from 485 earthquake events in the western Java region was recorded at 228 sensors with M ≥ 4, which occurred in West Java from 2009 to 2023. With various SNR (Fig. 1) using IPP, STA/LTA, InTeg, and EQTransformer methods, we wanted to find the best P-wave arrival time determination method supporting the EEW currently built by BMKG, Indonesia. The number of seismic signals used in this investigation is 4.482, with SNR of less than 10 dB to SNR with low noise. Two accelerometers, MEMS (Micro Electro Mechanical Systems) and FBA (Force Balance Accelerometer), are used, and the sampling rate is 100 samples per second.

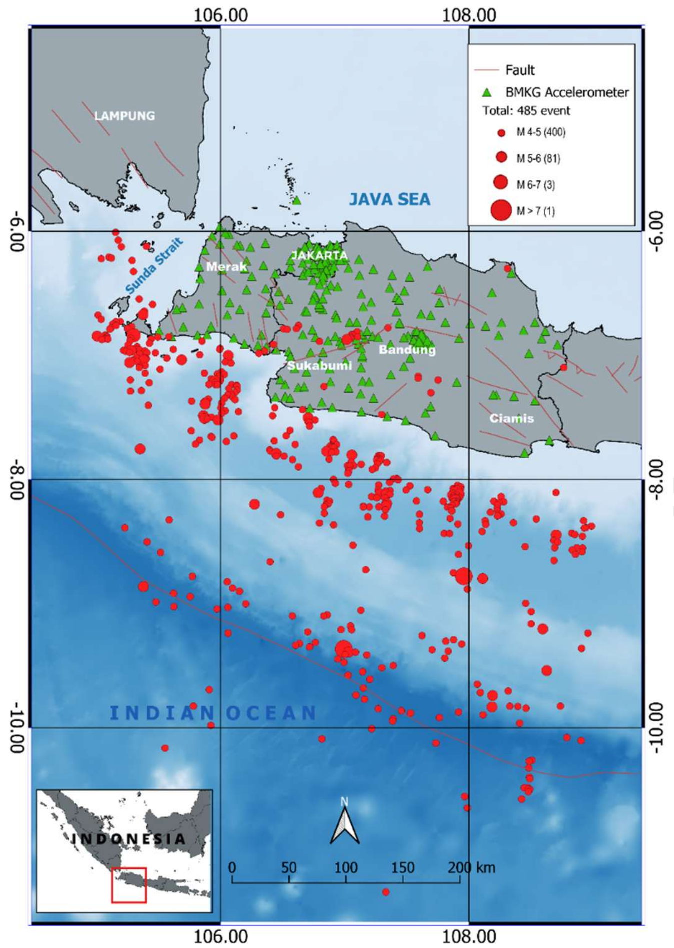

Figure 1. The distribution of the BMKG accelerometer sensor and earthquake epicenter with M 4.1 - M 7.3 occurred in Western Java from 2009 to 2023 and was used in the study.

2. Methods And Materials

The technique of determining the arrival time of the P wave using the IPP method is explained in more detail in Fig. 2. IPP consists of a short-time window and a long-time window, with the position of the short-time window at the end of the long-time window. The IPP calculation of the accelerometer signal is formulated by equations 1-4 (Zhang et al., 2023). In digital signals, the energy is formulated by equation 1, the sum of squares of the amplitudes at each point (relative power, P). P_S, P_L, P_P, and P_n are the relative power of the short, long-time, P wave, and noise. P_S is the window containing the P wave, while P_L is the window containing the noise. Before the P wave arrives, the short- and long-time windows are filled with noise, so the IPP will be zero. When the P wave arrives, the noise elimination is effectively represented by P_S- P_L and the wave calculated using the IPP method is free from the influence of noise. The calculated value of IPP will significantly increase when the P wave arrives and passes the specified threshold.

$$P = \frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N} \quad (1)$$

$$P_S = P_P + P_n \quad (2)$$

$$P_L = \frac{S}{L} \times P_P + P_n \quad (3)$$

$$IPP = P_P = \frac{(P_S - P_L) \times L}{L - S} \quad (4)$$

Where x_i is the signal value, $\bar{x}$ is the signal mean value, and N is the length of the signal. S and L are the lengths of the short and long windows.

The signal was filtered using a Butterworth highpass filter at a cutoff frequency of 0.075 Hz to eliminate the drift effects of low-frequency (Wu et al., 2007; Shieh et al., 2011). The performance of the P-wave arrival time calculation using IPP was then compared with the STA/LTA, InTeg, EQTransformer model and manual calculation. The STA/LTA method is the most commonly used in determining the arrival time of P waves, and this method calculates the ratio of the moving average of wave amplitudes of short and long windows (Chen et al., 2023). Equation 5 shows the mathematical equation for calculating STA/LTA.

$$STA/LTA = \frac{\sum_{i=1}^{N} X(i)/N}{\sum_{j=1}^{M} Y(j)/M} \quad (5)$$

X(i) is the signal amplitude in the short-time window, and *Y(j)* is the signal amplitude data in the long-time window. *M* and *N* represent the number of samples in the long-time and short-time windows, respectively.

BMKG researchers used the kurtosis and skewness algorithm and its combination with differential skewness and kurtosis, InTeg (Gunawan et al., 2013) with equation 6. Determination of P-wave arrival times using the deep learning algorithm EQTransformer, with global STEAD (Stanford Earthquake Dataset) data is also used to compare the accuracy of the IPP method. The EQTransformer model performs earthquake detection and P and S wave arrival time picking simultaneously under noise-filled signal conditions. The best P-wave picking method is the method with the smallest mean deviation or the calculation result closer to the actual arrival time of wave P. The analyst's manual calculation is a reference for testing the four methods discussed. The mean deviation is a statistical measure used to calculate the average deviation from the mean value of the given data set.

$$\text{InTeg} = |Skewness * Kurtosis| \times \left|\frac{dSkewness}{dt} * \frac{dKurtosis}{dt}\right| \quad (6)$$

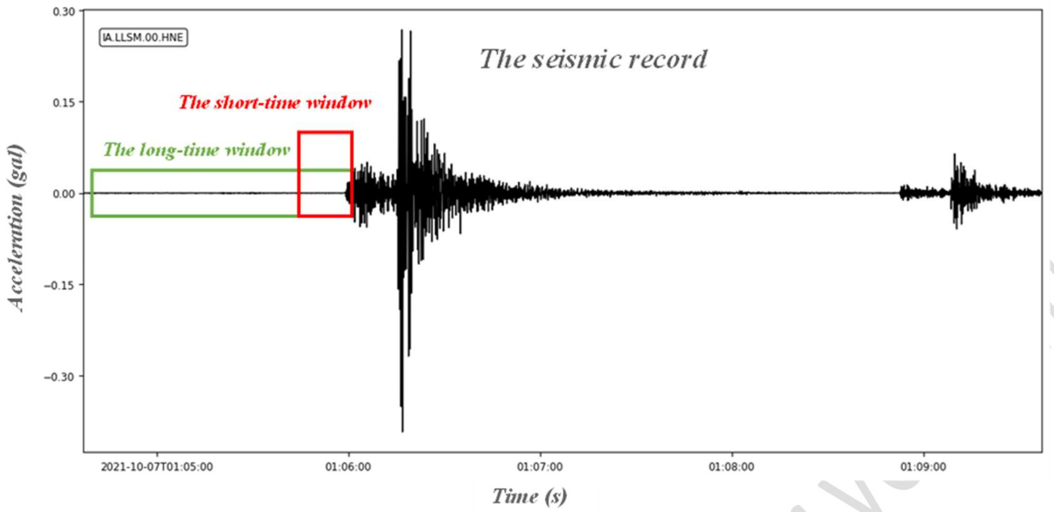

Figure 2. The diagram of Picking P Wave using the IPP Method. The red and green rectangles are, respectively, the short and long-time windows.

3. Result And Analysis

Detecting P-waves is important in EEW and is the first step before estimating earthquake ground shaking. The threshold selection in IPP and STA/LTA determines the accuracy, and the selection depends on the condition of the arriving signal. From data processing experience, the IPP and STA/LTA calculation will give good results if the length of the long-time window is 10x that of the short-time window and for the signals. The selection of the long- and short-time windows' lengths also influences the accuracy of IPP detection; for example, when the short-time windows are 0.3 s, the longer the long-time window must be set to 3 s. For SNR less than 10 dB, the IPP threshold must be chosen with a much smaller value of <0.0001 to read the arrival of the P wave correctly. The signals with a large SNR have less difficulty picking because noise does not interfere much with the P wave. Meanwhile, the STA/LTA threshold can be set at 5 for signals with a small SNR. A comparison of P wave picking using the IPP method and STA/LTA method from signals with M 4 and SNR 10.4 dB is shown in Fig. 3. The difference between IPP and STA/LTA in reducing noise is visible, as in the response signal below the threshold (red dotted line). The manual calculation is done by an experienced operator/seismologist so that it becomes a reference in calculating IPP and STA/LTA. The signal response on the IPP is relatively clean before the arrival of the P wave. This ability to suppress noise on the IPP will provide a precise reading of the P wave arrival. At ±280 seconds, for example, the noise is recorded as a P wave on STA/LTA, while IPP does not record it as a P wave arrival because it does not pass the threshold (Fig. 3b and Fig. 3c).

The calculation results in the InTeg method provide pretty good results, but the InTeg method does not require a threshold like the IPP and STA/LTA methods. The skewness and kurtosis algorithms can directly give the value of when the P wave arrives. However, for signals with small SNR, the

InTeg value is not single, which makes it challenging to choose the arrival time of the P wave. At the same time, the deep-learning EQTransformer model is built with significant signal and noise data. This method detects P waves for signals with small SNR or high noise. However, the drawback is that it requires a long window and is unsuitable when applied to EEW systems, which require accuracy and speed in estimating earthquake ground shaking.

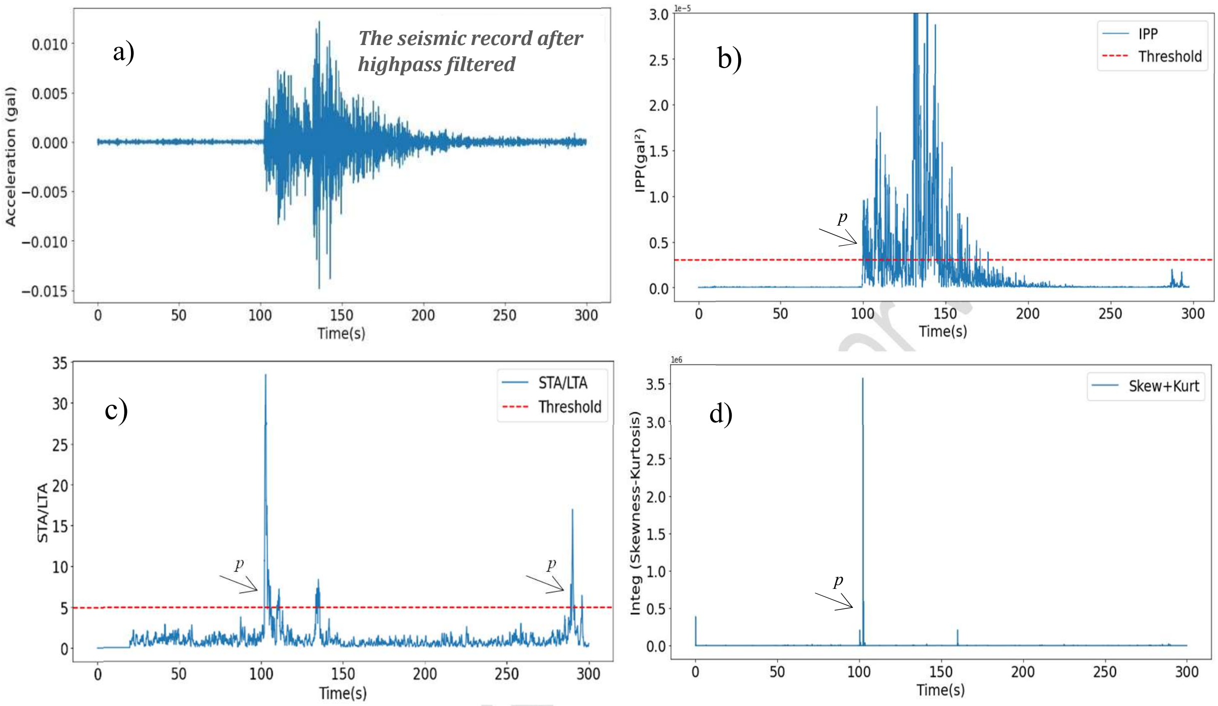

Figure 3. The seismic record after highpass filtering with cutoff frequency 0.075 Hz (a), IPP calculation (b) and STA/LTA calculation (c) with the threshold, and the result of picking of P-wave with InTeg method (d).

The mean deviation of the results of the IPP, STA/LTA, InTeg, and EQTransformer for earthquake signals with M 4 to major earthquakes with M 7.3 that occurred in the western Java region is shown in Fig. 4. The IPP calculation results provide a value close to the actual arrival time with a mean deviation of 0.066 seconds, followed by the EQTransformer results with a mean deviation of 0.226 seconds. Meanwhile, the STA/LTA and InTeg accuracy is still below IPP and EQTransfomer, with a mean deviation of 0.310 seconds and 0.316 seconds. The high values of STA/LTA and InTeg in Fig. 4 (a), Fig. 4 (b) and Fig. 4 (c) are entirely due to the failure of the two methods in reducing noise.

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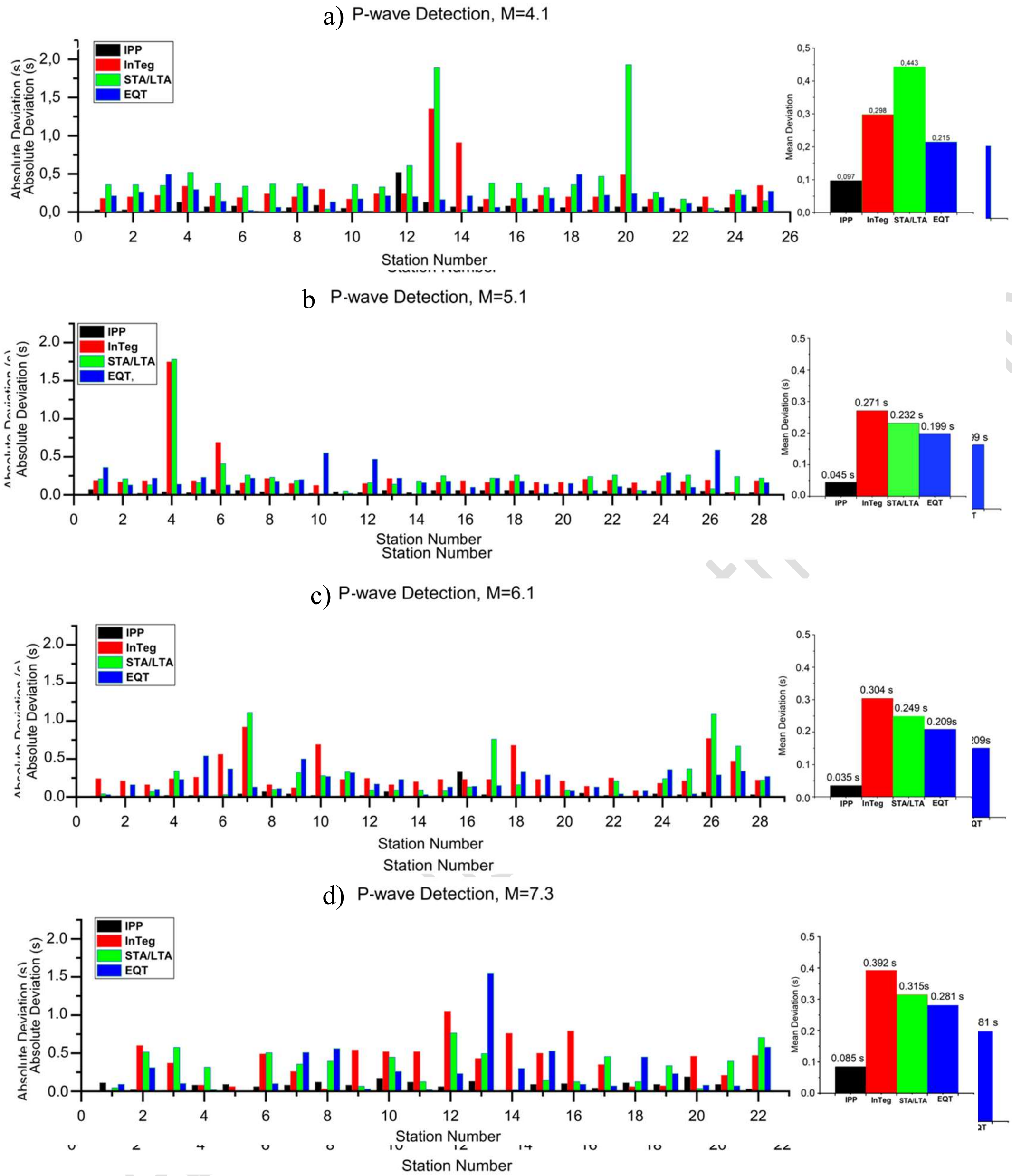

Figure 4. Calculation results of P wave arrival time between IPP, EQTransformer, STA/LTA and InTeg from events sample in West Java with M 4.1 (a), M 5.1 (b), M 6.1 (c), and M 7.3 (d) recorded at each observation station. The right-hand curve shows the mean deviation for the four methods.

Overall, the IPP, EQTransformer, STA/LTA, and InTeg methods can recognize the arrival of P-waves well and with varying degrees of accuracy. IPP has a better accuracy level when compared to other methods, with a level of 4-5 times better (Fig. 5). IPP's ability to reduce noise gives the P-wave picking technique much better accuracy. This noise reduction capability does not occur with the InTeg and STA/LTA methods and requires a high SNR if the P-wave arrival time is to be read. From several events in 2023, we tested the ability of the IPP, STA/LTA, InTeg, and EQT methods from the signals recorded at 228 sensors in western Java with M 4 - M 6. IPP could detect P waves without misjudgment rate and missing rate, while the InTeg method misjudgment rate and missing rate were 2.9% and 1.9%, respectively, STA/LTA was 1.9% and 0%, and EQTransformer was 4.8% and 3.9%. Misjudgment and missing rates for InTeg, STA/LTA, and EQTransformer methods occur in signals with low SNR or significant background noise.

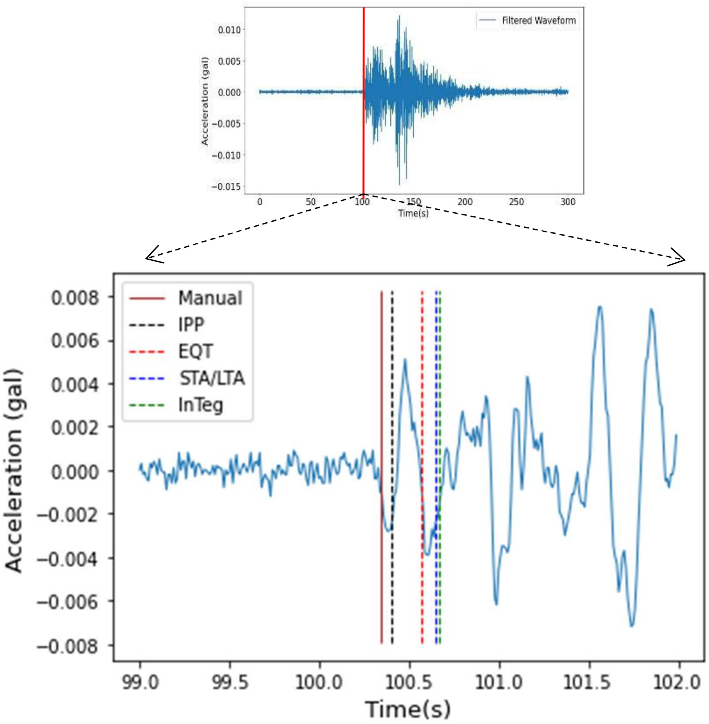

Figure 5. Magnification of P-wave arrival times calculated by IPP, EQTransformer, STA/LTA, and InTeg methods. IPP has the closest arrival time to the actual arrival time with the smallest mean deviation.

4. Discussion

P-wave picking using the IPP method is suitable for the single-station approach in EEW to obtain ground-shaking estimates quickly and immediately issue warnings to the public. In the EEW implementation scenario with the single-station approach (onsite warning), as depicted in Fig. 6, a data processing time of 10 seconds is required after the first trigger by the IPP (Hsu et al., 2013; Rudyanto et al., 2023). 10 seconds is the maximum processing time until the PGA value is obtained and the warning is ready to be issued to the public, or the time from the EEW system detects the P wave until the warning is sent to the public or end users. The same process at nearby sub-sensors will back up signal processing at the main sensor to ensure the accuracy of the warning that will be issued. The arrival time of the P-wave is an important parameter in determining the thresholds (τ_c and *Pd*), including the prediction of the PGA that informs the earthquake-shaking (Wu and Kanamori, 2008; Zollo et al., 2010; Talebi et al., 2022); Kumar et al., 2020). In the western part of Java, previous studies obtained $M = 4.156 + 5.679 \log (\tau_c)$ and $\log PGA = 1.117 \log (Pd) +$

0.728 with respective thresholds for damaging earthquakes τ_c=1,2 seconds and *Pd*=0.5 cm (Gunawan et al., 2013). However, these results require further research because the equations and thresholds generated using the analysis with the data are not too large. If the earthquake originates from the southern megathrust zone of Java, the lead time for warning for the cities of Bandung and Jakarta is 30-40 seconds after the data processing is complete. The lead time for earthquakes that occur near faults will be smaller than for megathrust earthquakes. If the threshold (τ_c and *Pd*) exceeds the value determined for the western Java region, the system will alarm end users as part of the disaster risk reduction system (Wu et al., 2016).

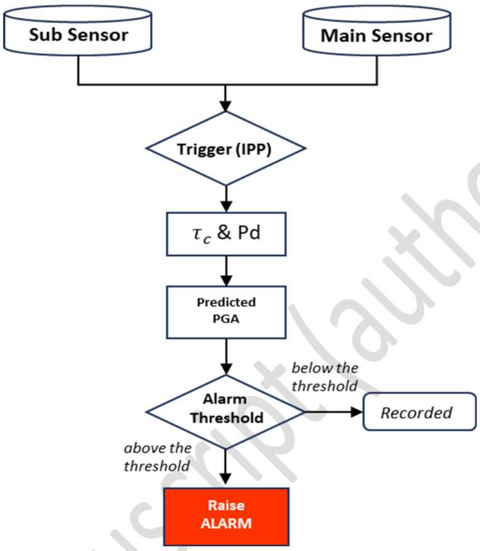

Figure 6. The on-site warning approach in the earthquake early warning system, IPP triggers are key in predicting PGA and issuing alarms for destructive earthquakes.

5. Conclusions

Several points can be concluded from the P-wave arrival time determination investigation using accelerometer signal data from 485 earthquake events in the western Java region during 2009-2023. The IPP method is more accurate than the EQTransformer, STA/LTA, and InTeg methods without misjudgment and missing rates. IPP provides a mean deviation calculation of 0.066 seconds, while EQTransformer is 0.266 seconds, STA/LTA method is almost the same as InTeg, 0.310 seconds and 0.316 seconds. The accuracy value of the IPP method becomes a crucial stage in determining the EEW parameter thresholds (τ_c and *Pd*). It is associated with the decision to provide destructive earthquake warnings to users. Hence, the IPP method is the choice in determining the arrival time of P waves in the EEW system because it is closer to the actual arrival time of the P wave. The ability of IPP to reduce background noise makes this method easy to read P waves well and improves the accuracy of other methods.

What needs to be considered when using the IPP method is the short-time window and long-time window and the determination of the IPP threshold, especially for noisy earthquake signals with SNR less than 10 dB. Determining the length of the short-time window and long-time window, as well as the IPP threshold used, is a success in P-wave picking.

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