Unveiling the potential: preliminary result on an AI-based on-site earthquake early warning system deployment in Denpasar City

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Abstract. Due to Indonesia's geographical location within the Pacific Ring of Fire, it is susceptible to earthquake occurrences. Therefore, the implementation of an Earthquake Early Warning (EEW) System is crucial to mitigate the impact of earthquakes. This study focused on deploying an on-site EEW system on Bali Island, an Indonesian region known for its elevated seismic activity. The study evaluated the system's performance over five months in 2023. Throughout this observation period, the AI-based on-site EEW system successfully detected the earthquake's P-wave before the occurrence of stronger seismic waves, such as the peak ground acceleration (PGA). It provided a warning time of up to 75 seconds and accurately predicted the intensity of the impending earthquake. These outcomes meet the fundamental requirements for an effective EEW system. The results obtained from the deployed AI-based on-site EEW system demonstrate the potential for wider implementation of such systems across Indonesia.

1 Introduction

An effective Earthquake Early Warning System (EEWS) can be achieved through the implementation of an artificial intelligence (AI) based methodology, resulting in the development of AI-based EEWS. The Taiwan National Center for Research in Earthquake Engineering (NCREE) has been developing AI-based EEWS since 2009. Unlike the regional system deployed by the Taiwan Central Weather Bureau (CWB), the AI-based EEWS developed by the NCREE uses on-site methodology, which allow for a faster deployment since the on-site methodology does not require the construction of a dense ground motion monitoring station and at the same time, able to offer a faster early warning capability. The NCREE on-site AI EEWS system, now maintained by P-Waver Inc., utilizes artificial neural network technology to detect the earthquake P-wave and accurately predict the intensity and peak ground acceleration (PGA) of the earthquake based on the first 3 seconds of the earthquake acceleration record following the arrival of the P-wave [1].

Compared to the regional EEW system that is being built by Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), also known as Indonesia Meteorology, Climatology, and Geophysical Agency, the on-site AI EEWS provides a significant advantage in terms of early warning time. Its ability to rapidly detect the earthquake P-wave and promptly assess the earthquake's characteristics enables it to deliver timely alerts to affected areas, allowing residents and authorities to take immediate precautionary measures. Overall, the on-site AI EEW developed by NCREE and the P-Waver has proven to be a valuable asset in earthquake early warning efforts. Its ability to swiftly detect and assess earthquakes offers a crucial advantage in minimizing the potential impacts of seismic events. Continual advancements in AI-based systems like the on-site EEWS contribute to the ongoing improvement of earthquake preparedness and response strategies.

To assess the effectiveness of the on-site AI EEW system in Indonesia, trial installations have been established through a collaborative effort between the P-Waver team and BMKG. The island of Bali was selected as the trial location due to its significant seismic activity, dense population, and socioeconomic importance to Indonesia. Bali Island is a tectonically part of the Lesser Sunda Islands, a group of numerous tiny volcanic islands situated between Java and the Banda Arc. This group of islands resulted from subduction, collision, and volcanism [2]. Bali Island has been the scene of sixteen catastrophic earthquakes since 1821 [3]. In Indonesian tourism, Bali plays an important role and holds the key to the development of this sector in the future. In 2023, TripAdvisor recognized Bali as the second winner of its annual Travelers Choice awards for worldwide locations. Following closely behind were London and Paris [4]. According to the Travel and Leisure site, the most frequently asked travel question on Google in 2016 was

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"Where is Bali?" [5]. That question may come from tourists who read about Bali on lists of the top tourist spots in the world but are unaware of the island's location. They probably aren't aware of its earthquake risks if they don't know where it is. Therefore, the installation of the EEW system in Bali is very important. In 2022, two monitoring stations were installed to facilitate the evaluation of the AI EEWS system. The first station, named S10035, was set up at the BMKG Sanglah station in Denpasar. The second station, referred to as S10036, was established at the BMKG Bali Regional Station in Kuta. The precise locations of these stations can be observed in Figure 1.

This study focuses on examining the performance of the AI EEWS system during the period from January to May 2023. By analyzing the data collected from the trial installations in Sanglah station in Denpasar, valuable insights can be gained regarding the system's ability to detect and issue timely warnings for seismic events in the region. The trial period provides an opportunity to assess the system's accuracy, reliability, and effectiveness in providing early warnings to mitigate the potential impact of earthquakes on the island. The findings of this study will contribute to a comprehensive understanding of the AI EEWS system's performance and its suitability for broader implementation across Indonesia. By evaluating its effectiveness in a high-risk area like Bali, valuable lessons can be learned to further enhance and optimize the system's capabilities for earthquake early warning purposes.

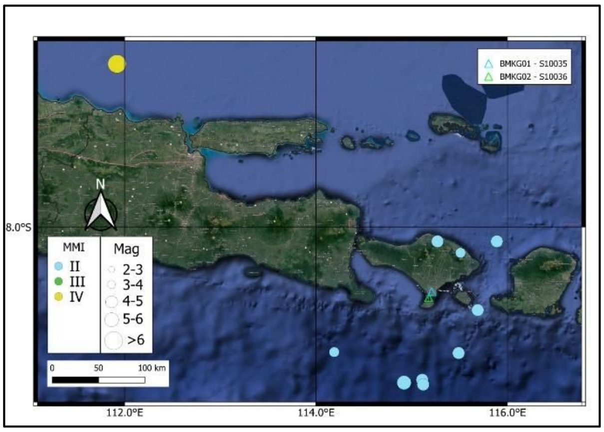

Fig. 1. List of earthquake events used in this study and EEW station's location.

2 On-site AI EEWS

The on-site AI-based EEWS used in this study was originally developed by NCREE in 2008 and is now maintained by P-Waver Inc., an NCREE spin-off company. As of 2023, the on-site AI EEWS has been applied at more than one hundred locations in Taiwan. Figure 2 shows the developed procedure diagram of on-site AI EEWS. The development of the AI used in the onsite EEWS leverages the 200,000 historic earthquake data from Taiwan CWB in the past 30 years. To build the on-site AI EEWS, four stages of work need to be done. The first stage, that is data preparation, requires each earthquake data of the training sets to be pre-processed to identify the measured PGA and six P-wave features from the first three seconds of P-wave. After the data is pre-processed, the data is then used for the second stage, that is the AI training. The AI model used for the on-site EEWS is an artificial neural network (ANN). The six P-wave features were used as inputs and the measured PGA was used as output. In the second stage, thousands of ANN models are trained, and thus in the third stage of the AI-based EEWS, selection of the best ANN model is conducted. The best ANN model is selected based on its ability to provide an accurate and stable prediction. The selected ANN model is then tested again using data from the validation set, and if the performance of the ANN model is found to be unsatisfactory on the validation set, the selection stage 3rd stage) is repeated. The final ANN model check with the validation data constitutes the 4th stage.

In a real application of on-site AI EEWS, it will detect the P-wave all the time. When the on-site AI EEWS detected the P-wave, it used the first three seconds of P-wave data to predict the peak ground acceleration (PGA), and MMI intensity of the following strong shake of the earthquake. The on-site AI EEWS has been shown to have an excellent performance during the 2016 Meinong Earthquake, the 2018 Hualien Earthquake, and the 2019 Hualien Earthquake [6-8].

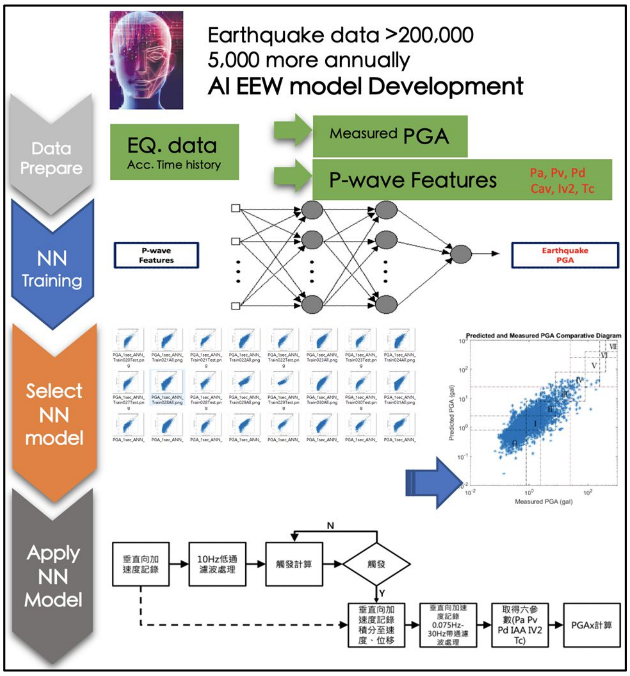

Fig. 2. Development procedure diagram of the AI EEWS.

Figure 3 shows the time history response of the real performance of on-site AI EEWS. This case was recorded in the 2016 Meinong earthquake, the on-site AI EEWS station was located 38 km away from the epicenter, which was very close, hazardous, and hard to have an early alarm. The AI EEWS detected P-wave at time tag "10s" and three seconds later raised the alarm at "13s" with the "predicted PGA=178 gals". 5.34 seconds later, the peak ground acceleration (PGA) of 242 gals was measured. At the time of the alarm, the vibration was tiny, which means people still had some time to do something to minimize the seismic loss. Even for the region close to the epicenter, the on-site AI EEWS still can provide some crucial warning (lead) time. For the other on-site AI EEWS, which was 100km away from the epicenter, normally about 15 seconds of warning (lead) time can be expected.

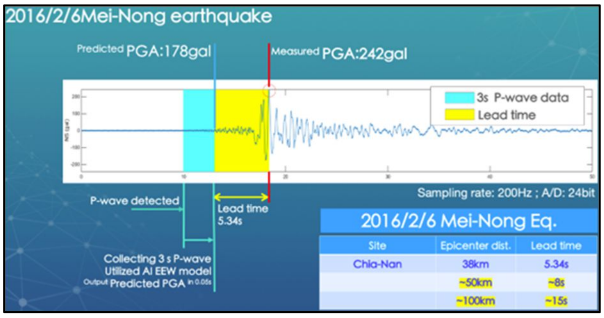

Fig. 3. Illustration of the real performance of the on-site AI EEWS in the 2016 Mei-Nong earthquake.

Figure 4 shows the comparison of the on-site AI EEWS with the conventional, regional EEWS, with each point representing the prediction of a single station. The X-axis shows the measured PGA, and the Y-axis represents the predicted PGA. For convenience, an intensity scale is also drawn in the graph. The performance of the onsite AI EEWS is comparable with the prediction given by the regional EEWS.

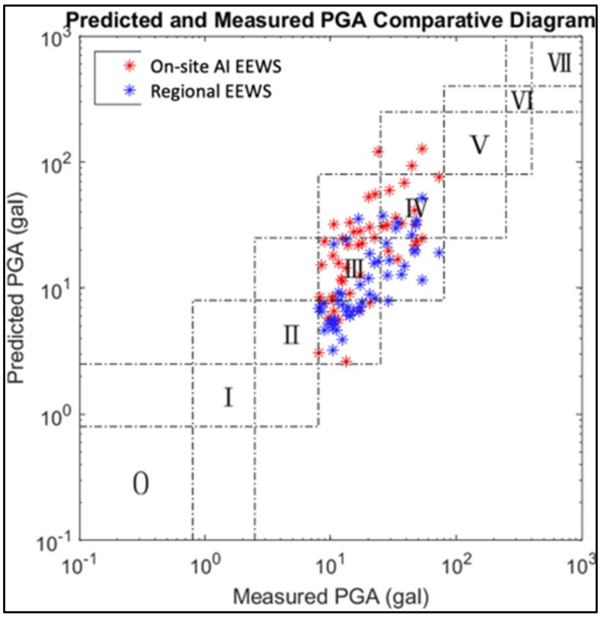

Fig. 4. Comparison of the prediction accuracy between on-site EEWS and regional EEWS during the 2016 Meinong earthquake

3 Performance of the On-site AI EEWS in Denpasar City

The performance of the on-site AI EEWS is measured by its prediction accuracy and the warning time given by the system. To measure the prediction accuracy, the intensity prediction accuracy ratio (IPAR) is adopted from previous studies [8]. A station is said to provide accurate prediction if the predicted intensity is located within plus minus one scale from the measured intensity. In a previous study by Hsu [8], the IPAR is measured only when the predicted intensity or the measured intensity is larger than 4 (using the CWB intensity scale). The CWB intensity scale of 4 roughly corresponds to level 4 at the MMI scale used by BMKG.

Aside from IPAR, the time difference between the time the on-site AI EEWS station issues a prediction and the time the earthquake PGA is measured is taken as the warning time. A larger warning time would mean more time for the impacted area to prepare for the coming S-wave, thus reducing the probability of earthquake casualties and damage. Note that in this study, the on-site AI EEWS requires three seconds of data to predict PGA and MMI intensity and issue an alarm since P-wave is first detected, as the 3 seconds ANN model was used. An ANN model that only requires one second for predicting the earthquake PGA is also available, providing two seconds additional warning time, at the cost of lower accuracy.

3.1 Observed Earthquake at Sanglah Station (S10035)

The Sanglah station in Denpasar City was originally equipped with two ground motion sensors, Nanometrics Titan-Open a Force balance accelerometer (FBA) type, and SanLien PAlert+ Micro Electro Mechanical Systems (MEMS) accelerometer type. During the observation period of this study, at least 10 earthquakes were recorded at the Sanglah station. Table 1 shows the earthquake parameters of the event measured by the Sanglah station, and Table 2 shows the corresponding measured PGA from both Sanglah ground motion sensors and on-site AI EEWS sensor. Due to some technical problem, there is no measured PGA from the FBA sensor during earthquake event numbers 1 and 8.

Due to the difference in the sensor measurement characteristic and signal processing, all three sensor measurements have a slight difference. For example, for the May 24 earthquake, the FBA sensor recorded a maximum single-axis PGA of 5.0 gal, while the MEMS sensor measured a maximum single-axis PGA of 4.27 gal. Furthermore, in general, the P-Waver sensor, which uses the FBA type sensor, shows a good agreement with the Nanometric Titan Open sensor measurement compared with the MEMS one. A visual comparison of all the maximum single-axis PGA can be seen in Figure 5.

Table 1. List of Earthquake felt at BMKG Sanglah Station

Eq. No.	Date and Time	Mag.	Depth (km)
1	1/8/2023 0:40:31	3.5	11
2	1/16/2023 13:10:04	4.6	69
3	2/18/2023 0:03:49	4.9	10
4	4/3/2022 18:26:48	4.6	74
5	4/10/2023 0:37:29	4.9	49
6	4/14/2023 9:55:44	6.6	632
7	4/19/2023 16:42:18	4.5	12
8	5/2/2023 17:56:44	4.6	10
9	5/23/2023 17:41:50	4.4	10
10	5/24/2023 19:57:22	5	10

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Table 2. List of Earthquakes felt at BMKG Sanglah Station (Cont.).

Eq. No.	Date and Time	Depth (km)	Dist. (km)
1	1/8/2023 0:40:31	11	56
2	1/16/2023 13:10:04	69	78
3	2/18/2023 0:03:49	10	95
4	4/3/2022 18:26:48	74	57
5	4/10/2023 0:37:29	49	103
6	4/14/2023 9:55:44	632	449
7	4/19/2023 16:42:18	12	109
8	5/2/2023 17:56:44	10	132
9	5/23/2023 17:41:50	10	59
10	5/24/2023 19:57:22	10	111

Table 3. Measured PGA at BMKG Sanglah Station Sensors.

Nanometrics Titan Open PGA (gals)					
Eq. No.	Component			Max. Resultant Hor. Comp. PGA	Maximum Uniaxial PGA
	Z	N	E		
1					
2	2.22	3.94	2.55	4.69	3.94
3	2.38	4.25	4.45	6.16	4.45
4	2.85	4.86	3.52	6	4.86
5					
6	9.68	28.99	28.31	40.52	28.99
7	1.4	2.38	1.97	3.09	2.38
8					
9	1.6	3.21	2.22	3.9	3.21
10	2.63	5	4.4	6.65	5

SanLien PAlert+ PGA (gals)					
Eq. No.	Component			Max. Resultant Hor. Comp. PGA	Maximum Uniaxial PGA
	Z	N	E		
1	0.82	0.61	0.99	1.16	0.99
2	1.9	2.7	2.21	3.48	2.7
3	2.23	3.46	3.16	4.69	3.46
4	3.47	3.53	3.11	4.7	3.53
5	2.03	4.31	2.69	5.08	4.31
6	12.98	29.24	22.19	36.71	29.24
7	1.14	1.79	1.67	2.45	1.79
8	0.89	1.2	0.96	1.54	1.2
9	1.6	1.89	2.66	3.26	2.66
10	1.67	3.53	2.4	4.27	3.53

P-Waver EEWS PGA (gals)					
Eq. No.	Component			Max. Resultant Hor. PGA	Maximum Uniaxial PGA
	Z	N	E		
1	1.09	1.41	1.01	1.48	1.41
2	2.4	4.23	2.78	5.03	4.23
3	2.68	4.65	5.19	5.75	5.19
4	3.24	4.93	4.08	6.17	4.93
5	3.07	3.72	4.19	5.17	4.19
6	11.22	30.41	23.1	37.27	30.41
7	1.67	2.65	2.19	3.28	2.65
8	1.03	1.92	1.64	2.17	1.92
9	1.67	3.47	2.53	3.55	3.47
10	2.83	5.02	4.92	5.35	5.02

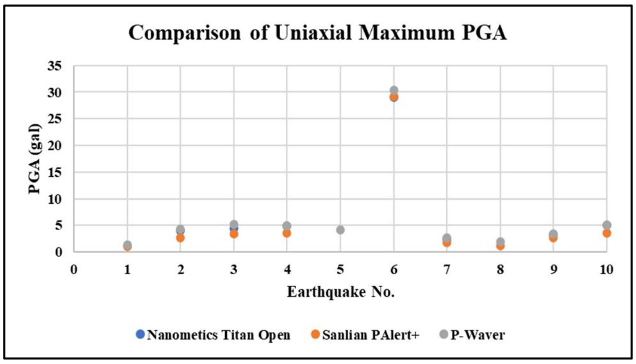

Fig. 5. Comparison of maximum PGA from Nanometrics, SanLien, and P-Waver sensor.

Note that in the data presented in Table 2, the calculation for the maximum resultant PGA is different for the Nanometrics and SanLien sensors. For the P-Waver sensor, the maximum resultant PGA is taken from the largest resultant of all three-axis PGA in a timestep, while for Nanometrics and SanLien results, the maximum resultant PGA is only consider the horizontal component (that is, north-south and east-west axis PGA) and instead of calculating the resultant from each timestep, the maximum uniaxial component PGA of each component is taken and the maximum resultant PGA is calculated from each axis maximum PGA.

3.2 Comparison between On-site AI EEWS results with the observation

The performance of the on-site AI EEWS during the observation period can be seen in Table 3 and presented visually in Figure 6. For convenience, Figure 6 is marked with the MMI scale used by BMKG, with bounded box marking plus minus one intensity scale. In Table 3, the predicted PGA issued by the ANN is the resultant of all three-axis PGA. Furthermore, in Figure 6 the Measured PGA is taken from the sensor maximum resultant PGA. The methodology to calculate the maximum resultant PGA is as mentioned in the previous section. The on-site AI EEWS managed to give early warning to 8 out of 10 recorded earthquakes, with two earthquakes having a negative warning time. However, in the two earthquakes in that the on-site AI EEWS provides negative warning time, the recorded PGA is relatively small (around 1 to 2 gal). Since the PGA is small, the earthquake P-wave is also small and thus, hard to differentiate from the ambient vibration. However, at the same time, since the earthquake is also small, there is no need for an earthquake early warning alarm.

If only an earthquake with a resultant PGA larger than 5 gal is considered (based on P-Waver accelerometer measurement, that is earthquake No. 3,4,6,10). The on-site AI EEWS managed to give early warning to all four earthquakes and provide a warning time of at least 10 seconds. Furthermore, onsite AI EEWS managed to predict the intensity accurately in 7 of 8 earthquakes that have an official BMKG intensity report, and 10 out of 10 earthquakes when the predicted intensity is compared with the measured intensity by the P-Waver accelerometer.

Table 4. On-site EEWS performance at BMKG Sanglah Station.

Eq. No.	P-Waver Max. Comp PGA (gal)	Predicted PGA (gal)	P-Waver Measured Intensity	P-Waver Predicted Intensity
1	1.41	3.47	2	3
2	4.23	1.32	3	2
3	5.19	2.33	3	2
4	4.93	9.52	3	3
5	4.19	3.36	3	3
6	30.41	9.28	4	3
7	2.65	7.05	2	3
8	1.92	3.78	2	3
9	3.47	1.65	3	2
10	5.02	2.55	3	2

Table 5. On site EEWS performance at BMKG Sanglah Station (Cont.).

Eq. No.	Warning Time
1	-0.8
2	10.2
3	13.3
4	12.4
5	18.1

Eq. No.	Warning Time
6	75.7
7	-0.5
8	2.2
9	22.2
10	11

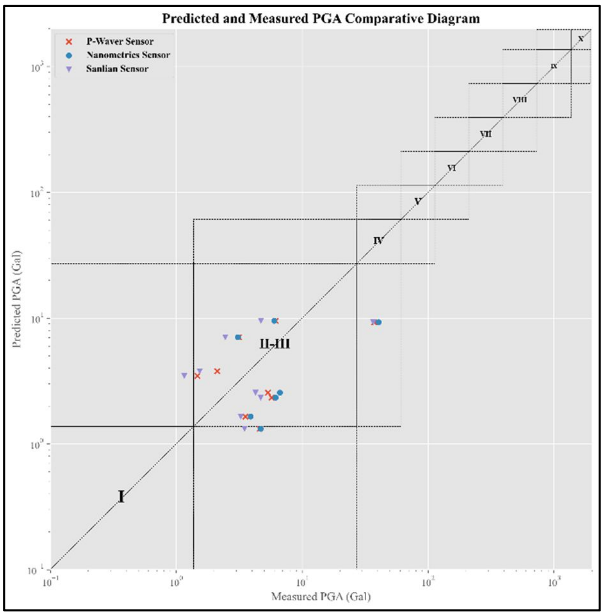

Fig. 6. Comparison of measured maximum PGA from all sensors with the predicted PGA.

During the largest earthquake event during the observation period, the on-site AI EEWS managed to provide an impressive warning time of 75.7 seconds. Compared to other earthquakes during the observation period, only the 14 April earthquake has a measured PGA larger than 25 gals (Corresponding to the CWB Intensity scale of 4, the minimum intensity used by the previous study to measure the IPAR). It was during this earthquake that the EEWS provided the best performance compared to the previous, smaller earthquake. Better performance during a larger earthquake is caused by the fact that the signal-to-noise ratio is higher when the PGA is higher. And the most important thing is that only the hazard earthquake like 14 April needs to be an alarm.

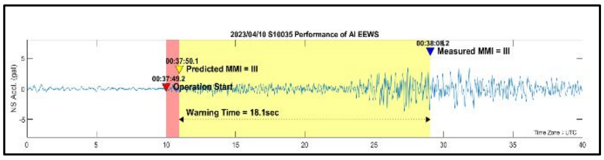

Fig. 7. Ground motion acceleration record from P-Waver accelerometer during the 10 April Earthquake, annotated with EEWS warning.

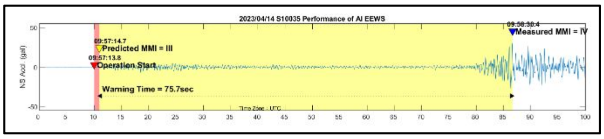

Fig. 8. Ground motion acceleration record from P-Waver accelerometer during the 14 April Earthquake, annotated with EEWS warning.

3.3 Dissemination of the EEW

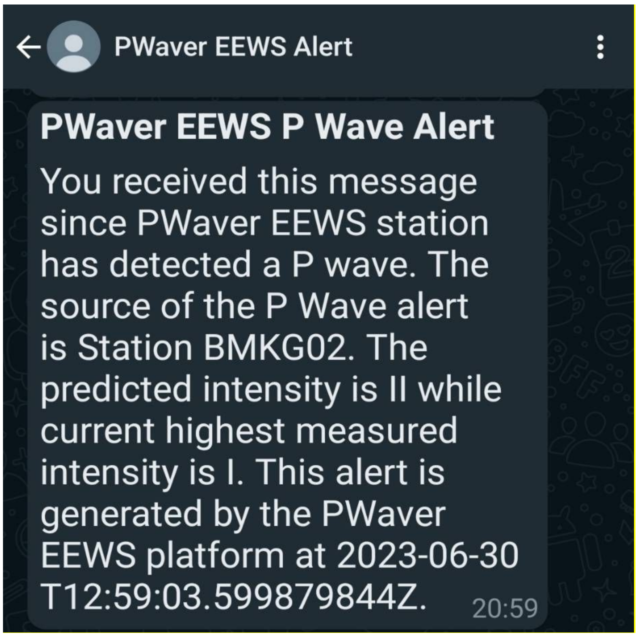

Fig. 9. Automatic EEW message in WhatsApp.

Fig. 10. Documentation of warning light triggered by demo EEW.

Aside from detecting the P-wave and providing the earthquake intensity prediction, an important part of the EEWS is the dissemination of the EEW. Currently, the EEWS deployed in Bali can disseminate the EEW through WhatsApp messaging service (for the machine to human communication) and through a cloud platform, which allows machine-to-machine communication. The advantage of having a dissemination system that can directly communicate from machine to machine is that during a large earthquake, an automatic shutdown of sensitive equipment, elevators, gas valve, and other important systems can be done automatically without human intervention. A sample message of the EEWS WhatsApp broadcast system, taken during a real earthquake on 30 June 2023 in Bantul (which is not discussed in this study) is shown in Figure 9. Note that the 30 June Bantul Earthquake epicenter is located hundreds of kilometers from Sanglah station, yet the EEWS deployed at Sanglah can detect the P-wave and issue an EEW alert before a national alert is issued by the station closer to the epicenter. Figure 10 shows an example of a warning light automatically triggered by the EEW cloud platform. Note that different from Figure 9, which is a real example of a real earthquake, Figure 10 is taken during a trial EEW demonstration.

4 Conclusions

Despite being trained exclusively using earthquake acceleration time histories from Taiwan, the on-site AI EEWS exhibits a good performance when deployed in Bali. It should be noted that Indonesian earthquake ground motion possesses distinct behaviors that may or may not be encapsulated within the original ground motion dataset used for training. Hence, it is plausible to anticipate a significant improvement in the performance of the on-site AI EEWS upon retraining the AI model with ground motion data specific to Indonesia.

Since each on-site AI EEWS can provide earthquake early warning independently without the need for a seismic network, it can be installed in high earthquake risk areas and immediately provide the earthquake early warning service for the neighborhood area and provide an accurate prediction of intensity for a radius of 15 km. Furthermore, the independent nature of the on-site AI EEWS provides some benefits, such as no need to maintain high-quality data and time synchronization between seismic stations. These benefits make the deployment of on-site AI EEWS in Indonesia, where some parts of the country lack high-speed and low-latency internet connection, an attractive proposition. Compared to regional-based EEWS, the deployment of on-site AI EEWS could be done quicker and more easily.

In conclusion, the study provides important insights into the performance of the on-site AI EEWS deployed in Bali, Indonesia, demonstrating its potential to provide early warning for earthquakes, thereby potentially mitigating the loss of life and property damage.

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