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Case Study of MEMS-Based Earthquake Early Warning With P-ALERT System: A Literature Review

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ABSTRACT

Earthquakes pose significant threats to infrastructure and human life, emphasizing the urgent need for effective Earthquake Early Warning Systems (EEWS). Traditional EEWS are often expensive and inaccessible for many earthquake-prone regions. This paper explores the potential of low-cost EEWS utilizing Micro-Electro-Mechanical Systems (MEMS), focusing on the P-ALERT system developed in Taiwan. Through a literature review, this study analyzes the architecture, performance, limitations, and prospects of MEMS-based EEWS. The findings highlight that P-ALERT, with its affordability, dense sensor network, and rapid response capability, offers a promising solution for localized and regional earthquake warnings. Despite limitations such as lower data quality compared to high-end seismometers and reliance on stable infrastructure, P-ALERT has demonstrated effectiveness during several major earthquakes. This review also provides recommendations for enhancing the system's performance through decentralized processing, improved sensor algorithms, and strengthened network security. Ultimately, this research underscores the viability of low-cost EEWS like P-ALERT as scalable and inclusive tools for seismic risk mitigation, particularly in developing countries.

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1. INTRODUCTION

Earthquakes are natural disasters that often cause significant damage, ranging from infrastructure destruction to loss of human lives. The substantial losses caused by earthquakes have driven the need for effective early warning systems. Earthquake Early Warning Systems (EEWS) aim to provide alerts to the public before the main seismic shaking occurs, allowing them to take mitigation actions to reduce the negative impact. These early warnings are highly valuable as they can provide several seconds to minutes of lead time before strong ground shaking is felt, depending on the distance between the earthquake source and the warning recipients [1].

The development of micro-electro-mechanical systems (MEMS) technology has paved the way for the creation of low-cost EEWS. MEMS sensors, which are small, lightweight, and energy-efficient, enable the construction of dense and widely distributed sensor networks. Such dense sensor networks are crucial for detecting P-waves (primary waves), which arrive before the more damaging S-waves (secondary waves). By detecting P-waves, the system can estimate the earthquake's magnitude and location, and subsequently issue early warnings. Another advantage of MEMS technology is its relatively low production cost, making the implementation of more affordable EEWS feasible, especially in developing countries vulnerable to earthquakes [2].

P-ALERT (Portable Alert) system is a concrete example of a low-cost MEMS-based EEWS. P-ALERT utilizes MEMS accelerometer sensors to detect ground motion caused by earthquakes. Data from these sensors are processed using specialized algorithms to estimate earthquake parameters such as magnitude and distance. Based on these estimations, the system sends early warnings through various communication channels, such as text messages or mobile applications. The advantages of P-ALERT include ease of installation, affordability, and the ability to provide fast and accurate early warnings [3].

A case study of P-ALERT is essential to convey the effectiveness and transparency of this system across various earthquake scenarios. The analysis includes performance metrics in earthquake detection, the characterization of earthquake parameters, and the issuance of early warnings. Additionally, the case study will consider factors such as detection range, response time, and false alarm rate. The primary goal of this case study is to provide a comprehensive understanding of the potential and limitations of P-ALERT as a low-cost EEWS solution and to offer recommendations for system improvement and future development.

2. LITERATURE REVIEW

2.1. Low-Cost Earthquake Early Warning System

EEWS are designed to provide advance alerts several seconds before the arrival of strong ground shaking, allowing people to take protective actions and enabling automated systems to initiate safety measures. However, traditional EEWS can be expensive to implement, often costing hundreds of millions of dollars, making them inaccessible in many at-risk regions [4]. This has driven the development of low-cost EEWS, which utilize affordable sensors and cloud computing to detect earthquakes and issue warnings in near real-time. These systems often employ MEMS-based sensors, which are significantly cheaper than traditional seismometers, enabling the deployment of denser sensor networks. Increased sensor density allows for more accurate event localization, reduces false positives, and shortens the time required to issue warnings—thus providing people with more critical seconds to react.

The effectiveness of low-cost EEWS has been demonstrated in various regions. The P-ALERT system in Taiwan has been operational for nearly a decade, providing both regional and on-site warnings, as well as generating valuable shaking maps [5]. These shaking maps, which visualize the distribution of ground motion parameters, are crucial for assessing damage patterns and rupture directivity, and they support risk mitigation efforts. The MyShake application, developed by the Berkeley Seismology Lab at UC Berkeley, uses smartphone accelerometers to create a global seismic detection network that issues automatic warnings for earthquakes of magnitude 4.5 or greater. Google's Android Earthquake Alerts System utilizes the accelerometers in Android devices to detect earthquakes and issue warnings, demonstrating the potential of crowdsourced EEWS.

2.2. P-ALERT System

The P-ALERT system is a low-cost, MEMS-based EEWS developed by National Taiwan University (NTU) in collaboration with a technology company. It is designed for both on-site and regional EEWS applications, providing crucial seconds of warning before the onset of strong ground shaking. The system uses small, cost-effective, and easily deployable MEMS sensors, making it suitable for dense deployment in seismically active areas. These sensors record high-frequency ground motion data near the earthquake source, which is then processed to estimate earthquake parameters such as magnitude and potential shaking intensity. P-ALERT is especially effective for on-site warnings, offering lead times of several seconds within the "blind zones" of regional warning systems—areas where alerts from the Central Weather Bureau (CWB) may not be available. The system also generates real-time shaking maps, which are extremely useful for damage assessment and understanding rupture directivity [6].

The performance of the P-ALERT system has been validated during several damaging earthquakes in Taiwan, including the 2016 Meinong earthquake and the 2018 Hualien earthquake. During the Dapu earthquake (2025), the P-ALERT system produced a shaking map within 36 seconds of the event, highlighting areas of intense shaking and assisting in damage evaluation. The system's ability to provide rapid warnings and detailed shaking maps makes it a valuable tool for disaster mitigation and emergency response. The success of the P-ALERT system has led to its adoption in several countries around the world, including China, India, and New Zealand, either as a standalone EEWS or integrated into existing networks. Its dual capability for on-site and regional alerts, combined with its cost-effectiveness, makes it a significant advancement in earthquake early warning technology.

3. RESEARCH METHOD

This research methodology will primarily employ a literature review approach to comprehensively analyze existing knowledge and studies related to low-cost EEWS, with a particular focus on MEMS-based sensors and the P-ALERT system. The initial stage will involve a systematic search of academic databases such as IEEE Xplore, ScienceDirect, Google Scholar, and others, using relevant keywords including "earthquake early warning", "MEMS sensors", "P-ALERT", "low-cost EEWS", "performance analysis", and "literature review". The search will be refined by applying inclusion and exclusion criteria to ensure the relevance and quality of the selected studies. Inclusion criteria will prioritize peer-reviewed journal articles, conference papers, and technical reports published within the past 10 years (2015–2025) to capture recent advancements. Exclusion criteria will filter out studies that are not directly related to the research objective, such as those focusing solely on seismic hazard assessment or earthquake prediction.

The next phase will involve detailed analysis and synthesis of the selected literature. This will include extracting key information from each study—such as system architecture, sensor characteristics, data processing algorithms, performance metrics (e.g., alert time, accuracy, reliability), cost analysis, and limitations. Extracted data will be organized and categorized to facilitate comparative analysis, allowing for the identification of trends, gaps, and potential areas for improvement in the context of low-cost EEWS. The analysis will specifically focus on the P-ALERT system, examining its design, implementation, and performance, and comparing it with other MEMS-based EEWS. The findings will be synthesized to provide a comprehensive understanding of the current state of the field, identifying key challenges and opportunities, and potentially proposing recommendations for future research and development. This literature review will serve as a solid foundation for understanding the effectiveness and limitations of low-cost EEWS, particularly those based on MEMS technology, and how the P-ALERT system performs in comparison to other systems [9].

4. RESULT AND DISCUSSION

4.1. Potential and Limitations of P-ALERT as a Low-Cost Earthquake Early Warning Systems Solution

P-ALERT holds significant potential due to its lower cost compared to traditional seismic instruments, enabling the deployment of denser sensor networks. Such density allows P-ALERT to provide early warnings in areas close to the earthquake source—referred to as the "blind zone" of larger regional EEWS like those operated by Taiwan's Central Weather Bureau (CWB). The dense network also contributes to the generation of real-time shakemaps, which are crucial for damage assessment and emergency response efforts. P-ALERT has proven effective in delivering early warnings during damaging earthquakes in Taiwan, such as the 2016 Meinong earthquake and the 2018 Hualien earthquake. However, P-ALERT also faces several limitations. One major constraint is the limited dynamic range and data quality of MEMS sensors compared to high-grade seismic instruments. This can affect the accuracy of magnitude and location estimations, which in turn may impact the reliability of early warnings. Furthermore, despite the system's dense network, earthquake location and magnitude estimations can still be affected by errors in source localization and seismic wave propagation. Another limitation is the system's dependence on existing infrastructure, such as reliable power supplies and stable internet connections, which can pose challenges in certain regions. Nonetheless, P-ALERT continues to be improved, with newer versions addressing several issues identified in earlier deployments [7].

False alarms represent an additional concern. Since P-ALERT relies on threshold-based algorithms to detect earthquakes, there is a risk that the system might issue warnings even when the shaking is not hazardous. This could lead to alert fatigue and a decline in public trust in the system. Moreover, network security is a growing concern, especially in community-based networks, where the potential for cyberattacks could disrupt system operations.

4.2. Recommendations for the Improvement and Development of Low-Cost Earthquake Early Warning Systems

The development of low-cost Earthquake Early Warning System presents significant opportunities to enhance earthquake preparedness, especially in regions with limited resources. One of the key areas for improvement lies in the system architecture. Decentralized or edge-level processing, where data is processed at the sensor node level rather than at a central hub, can greatly reduce system latency, enhance redundancy, and lower implementation costs. This approach has been highlighted as a promising paradigm for real-time Internet of Things (IoT) applications, addressing critical challenges related to response time, bandwidth usage, and security. The integration of Software-Defined Wide Area Network (SD-WAN) solutions can further improve connectivity and network reliability, especially in community-based sensor networks, where sensors may be deployed in diverse and potentially unstable networking environments.

Another important advancement area lies in sensor technology and algorithm optimization. The integration of multisensor capabilities—allowing for the use of multiple types of MEMS-based sensors—can support denser and more resilient sensor networks. This approach also encourages community engagement by enabling individuals to contribute their own ground motion sensors to the network. Implementing ground-motion or wavefield-based EEW algorithms, which have shown promise in overcoming the limitations of source-based algorithms, can enable faster and more reliable alerts, particularly for regions located near the earthquake epicenter. The use of ground motion parameters such as Cumulative Absolute Absement (CAA) has also demonstrated potential for producing more stable magnitude estimations [10].

Addressing challenges associated with community-based EEW systems is also essential. Network security remains a critical concern, and robust measures are required to prevent spoofing and malicious attacks. This includes securing communication channels between sensors and processing units, as well as implementing authentication mechanisms to ensure data integrity. Finally, sensor density is a vital factor in the performance of regional EEW systems. Increasing the number of sensors can reduce detection time and improve the accuracy of alerts, ultimately enhancing public safety and emergency response capabilities [11].

4.3. Comparative Analysis of Low-Cost Earthquake Early Warning Systems

A comparative analysis of selected low-cost Earthquake Early Warning Systems (EEWS) is presented in Table 1. Each system represents different approaches to cost-efficiency, sensor type, and alert dissemination strategies.

P-ALERT, developed in Taiwan, uses MEMS accelerometers deployed in both regional and on-site configurations. It has demonstrated high responsiveness and effective real-time shakemap generation during significant seismic events such as the 2016 Meinong and 2025 Dapu earthquakes [12], [13].

In contrast, MyShake is a smartphone-based EEWS relying on crowdsourced data. Developed by the Berkeley Seismology Lab, it has proven capable of detecting M≥5 earthquakes in real time, though its performance is dependent on active user participation and mobile network coverage [3], [15].

Google EEWS, integrated directly into Android OS, represents a passive but globally scalable solution. While it ensures broad access without user installation, it lacks the capacity for shakemap generation or intensity mapping [15].

ASTUTI (Costa Rica) adopts an MEMS + IoT-based approach for rural areas with limited infrastructure. It is designed to be highly affordable and easily maintained, while still offering reliable regional alerts [6].

China's GL-P2B and SIT-S system leverages a hybrid model of MEMS and broadband seismometers, resulting in a dense network capable of detecting even small earthquakes (M>3.0) and generating shakemaps with high spatial resolution [8].

These findings illustrate the trade-offs between physical sensor networks and smartphone-based systems, with decisions on deployment depending on the target region's infrastructure, population density, and hazard profile. Countries like Indonesia, with both urban clusters and rural islands, may benefit from hybrid systems combining multiple approaches.

Table 1. Key Features of Selected Low-Cost Earthquake Early Warning Systems

System / Country	Sensor Type	Deployment Mode	Lead Time	Real-Time Shakemap	Key Feature / Highlight
P-ALERT / Taiwan	MEMS Accelerometer	On-site & Regional	4–8 s	Yes	Efficient on-site & regional alerts; detailed shakemaps within 2 minutes ([13])
MyShake / USA	Smartphone Accelerometer	Crowdsourced (App-based)	5–20 s	No	Real-time M≥5 wave detection; depends on user density ([3], [15])
Google EEWS / Global	Smartphone Accelerometer	OS-integrated (Android)	~10 s	No	Global coverage; passive alerts embedded in Android OS ([15])

4.4. Challenges and Future Directions

Despite the promising potential of MEMS-based Earthquake Early Warning Systems (EEWS) such as P-ALERT, several technical and implementation challenges remain. One of the primary limitations lies in the accuracy and reliability of MEMS accelerometers, especially under strong-motion scenarios where high-grade broadband sensors outperform low-cost units in dynamic range and sensitivity [16]. This discrepancy can lead to either false positives or underestimation of seismic intensity.

In addition, network connectivity and latency are critical issues, particularly in rural or disaster-prone areas with unstable power supply and limited communication infrastructure. Systems such as P-ALERT, which rely on rapid data relay, are vulnerable to these disruptions, potentially reducing lead time and warning effectiveness [13].

Another major concern is standardization and interoperability. With growing interest in community-based EEWS using diverse MEMS platforms, ensuring consistent data formats, calibration standards, and response protocols across different regions remains a challenge [8].

Future research directions:

- Integration of machine learning algorithms to reduce false alarms and improve real-time magnitude estimation [17].
- Development of multi-hazard early warning frameworks, combining EEWS with tsunami and landslide alert systems [18].
- Exploration of hybrid sensor networks, combining MEMS and broadband instruments.
- Cost-effectiveness assessments in varying socioeconomic contexts [6].

4.5. Potential of P-ALERT-Like EEWS in Indonesia

Indonesia, situated along the Pacific Ring of Fire, experiences frequent tectonic activity with a high risk of destructive earthquakes. Despite the presence of a national seismic network operated by BMKG, many regions—particularly remote or urban centers—remain vulnerable due to limited local lead time [14].

Drawing from Taiwan's P-ALERT success, Indonesia could replicate a similar model in high-risk zones such as:

- Yogyakarta (Opak fault)
- Padang (Sumatra subduction zone)
- Palu (strike-slip system)

According to Hong et al. [11], MEMS-based technology is increasingly feasible in the Asian context. Allen et al. [3] also stress the scalability of mobile- or IoT-based EEWS in budget-limited regions.

Collaborative deployment through BMKG–Government partnerships could enable SeisComP3-based community EEWS integration, inspired by Costa Rica's ASTUTI network.

5. CONCLUSION

This literature-based study concludes that MEMS-based Earthquake Early Warning Systems (EEWS), such as the P-ALERT system, offer a compelling solution to seismic risk mitigation—particularly for developing countries with budgetary and infrastructure constraints. Compared to traditional EEWS, MEMS-based systems significantly reduce cost barriers while enabling high-density sensor networks capable of real-time shakemap generation and on-site warning delivery.

The analysis highlights that among existing low-cost EEWS, P-ALERT demonstrates superior performance in terms of deployment scalability, dual-mode alert capability, and field-proven effectiveness during major earthquakes. When compared to systems like MyShake, Google EEWS, and ASTUTI, P-ALERT's combination of affordability and physical sensor reliability makes it highly suitable for both urban and rural seismic risk contexts.

In the Indonesian context, the adoption of a P-ALERT-like system presents a strategic opportunity to expand early warning coverage across vulnerable regions—especially those beyond the reach of centralized seismic networks. With its low cost, ease of installation, and capacity for community-based deployment, MEMS EEWS can fill critical gaps in national disaster preparedness efforts.

Furthermore, this review underscores the urgent need to address technical challenges such as sensor calibration, data quality, network latency, and cyber resilience. Future studies should explore integration with IoT and mobile platforms, hybrid sensor models, and algorithmic optimization—particularly using machine learning—to enhance alert precision and lead time.

Ultimately, the findings of this review provide a strong academic foundation for national policy, public investment, and cross-sector collaboration aimed at building inclusive, data-driven, and resilient earthquake early warning infrastructure in Indonesia and other seismically active regions.

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