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IoT-Based Seismic Sensor Network Design for Early Warning System in Kalimantan : Literature Review

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A B S T R A C T

Kalimantan is not commonly associated with significant seismic activity due to its relative distance from major tectonic plate boundaries; however, it remains vulnerable to earthquakes that pose risks to human safety and the integrity of infrastructure. A recent seismic incident in the region has raised alarms about the adequacy of current preparedness and mitigation measures. This review seeks to establish a robust early warning system (EWS) for earthquakes by incorporating seismograph technology and IoT-based sensor networks tailored for Kalimantan. Despite its traditional classification as a low-seismic area, the region is susceptible to risks stemming from nearby active faults and tectonic dynamics. By analyzing recent research, this paper highlights the distinct geographical and environmental factors that must be considered when implementing a seismic sensor network in Kalimantan. It also examines the critical elements of seismographic devices for earthquake detection and discusses the role of IoT in enhancing real-time monitoring and early warning capabilities. The proposed IoT-based EWS utilizes affordable, distributed sensors to improve response times and detection precision, thereby providing timely notifications to vulnerable areas. This strategy presents a scalable and economically viable model for regions at risk of earthquakes, emphasizing the significance of both sophisticated instrumentation and accessible IoT technology for communities.

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1. INTRODUCTION

Kalimantan, while not typically recognized for significant seismic activity due to its distance from major tectonic plate boundaries, still faces considerable risks from earthquakes that threaten both human safety and infrastructure integrity. A recent seismic event in the area has highlighted the need for improved preparedness and mitigation strategies. Specifically, Kalimantan is situated on the Sunda plate, bordered by the Philippine Sea plate and the Indo-Australian plate [1], [2], [3], [4]. Geologically, the island's core consists of Paleozoic and Mesozoic formations characterized by complex folds and fractures, which are irregularly overlaid by Cenozoic sediments. The timing and causes of active deformation in both the onshore and offshore regions of the island remain ambiguous, particularly in the context of the transition from compressive to gravitational tectonics, raising questions about the island's tectonic activity [5], [6].

Unlike cyclones and tsunamis, which can be forecasted hours in advance, earthquakes present a unique challenge as they can only be detected seconds before their impact. The brief interval between the detection of an earthquake and its resultant effects complicates the establishment of an effective earthquake early warning system (EEWS) [7]. An Early Warning System (EWS) is a multifaceted framework that integrates hazard monitoring, forecasting, predictive analysis, disaster risk assessment, and the promotion of communication and preparedness efforts. This system aims to enable individuals, communities, governmental entities, businesses, and other stakeholders to take timely actions to reduce disaster risks before hazardous events occur [8]. The earthquake early warning system (EEWS) is crucial for detecting ground shaking during seismic events and notifying the public and authorities to implement necessary safety measures, thereby minimizing potential harm to lives and property [9].

The Internet of Things (IoT) constitutes a comprehensive framework that interconnects a variety of objects, thereby allowing for their management, data analysis, and access to the information generated by these entities. The primary aim of IoT is to integrate devices, actuators, and sensors to execute a multitude of functions, including customized environmental monitoring [10]. A basic and universal architecture of IoT is structured into three layers: (i) the local environment, which consists of intelligent objects or sensors that engage in communication with one another and collect data from their surroundings; (ii) a transport layer that enables communication between the end-nodes of the first layer and the higher layers and infrastructures; and (iii) a layer focused on storage, data mining, and processing, usually hosted in the cloud, which may encompass systems and interfaces for user access and data visualization. In the context of disaster management and Early Warning systems, the Internet of Things (IoT) enhances extensive environmental monitoring through various data sources, facilitates low-latency communication, and supports real-time data processing. These functionalities are crucial for generating accurate and timely alerts during disasters or when predicting potential threats.

This review aims to amalgamate contemporary seismograph technology with an Internet of Things (IoT)-based seismic sensor network to create a more dependable and scalable earthquake early warning system (EEWS). Effective EEWSs require a network of widely distributed ground motion sensors to detect seismic events and issue real-time alerts. By utilizing various sensors and sensing devices, these systems can proficiently monitor ground vibrations and movements, generating alarms to inform individuals in affected areas before seismic waves arrive. Even a short warning period of several seconds or minutes can be vital for saving lives. The primary method for detecting earthquakes relies on the identification of P-waves. During seismic activity, both compressional P-waves and shear S-waves are released from the epicenter. Since P-waves travel faster and are less destructive, their early detection enables timely warnings to be communicated before the more harmful S-waves reach a specific location. A straightforward IoT-based system proposed by Alphonsa et al. [11], employs accelerometers connected to microcontrollers to collect and analyze ground vibration data, which is then transmitted via Zigbee to a computer receiver that alerts users. Furthermore, GSM modules can be used to send warnings to a base transceiver station, which subsequently informs mobile phone users. Although many countries have implemented earthquake monitoring systems, ongoing initiatives are dedicated to improving sensor networks, ensuring reliable and low-latency communication, and minimizing data processing delays, which frequently contribute to the overall latency in earthquake alert systems [12].

Seismographs play a crucial role in the detection of seismic waves; however, traditional configurations often encounter obstacles such as substantial maintenance expenses and restricted coverage. Furthermore, Earthquake Early Warning Systems (EEWS) require a network of widely distributed ground motion sensors to effectively identify earthquakes and issue real-time alerts. Consequently, the establishment and operation of EEWS can be financially burdensome. The integration of Internet of Things (IoT) technology allows for the deployment of numerous low-cost sensors over extensive areas, thereby enhancing both the precision of data collection and the immediacy of detection. Although the warning time may be limited, EEWS can serve as a significant resource for enhancing safety in areas susceptible to severe ground shaking [13]. The duration of the warning may be sufficient for pre-programmed systems to execute emergency protocols, such as shutting down machinery to mitigate potential losses and closing gas distribution valves [14]. In regions where conventional EEWS have already been implemented, low-cost Micro-Electro-Mechanical Systems (MEMS)-based networks can function as supplementary systems. Numerous examples exist where a low-cost EEWS acts as a backup for primary high-end systems, including locations such as Taiwan, the US West Coast, and various parts of mainland China [15], [16]. Additionally, a brief public alert can empower individuals to undertake basic safety measures, such as the drop-cover-hold technique, and mentally prepare for an imminent earthquake [17], [18], [19].

2. RESEARCH METHOD

2.1. Research Questions

This review poses five research questions to guarantee that all critical elements concerning the integration of seismic instrumentation and IoT technology in Kalimantan are addressed :

- What are the environmental and geographical considerations for deploying a seismic sensor network in Kalimantan?
- What are the key components and functions of seismograph instrumentation used in early warning systems?

- How is IoT technology being integrated with seismic sensor networks for real-time monitoring and early warning systems?
- How do IoT-based early warning systems improve response times and accuracy in detecting seismic activities?
- How can seismograph data be processed and analyzed using IoT platforms for efficient early warning in earthquake-prone areas?

2.2. Search for Relevant Article

The identification of pertinent articles within the existing literature was performed through a keyword search in the Google Scholar and Web of Science databases, initiated due to the limited availability of relevant studies prior to 2017. Consequently, only those articles published after this date were included in the analysis. To effectively address the review questions, the primary search terms employed were "earthquake early warning" and "IoT-based." Additionally, alternative terms such as “seismograph,” “earthquake instrumentation,” “network design,” and “seismic sensor” were incorporated into the search strategy. Publications not written in English, along with grey literature, including governmental and corporate reports as well as non-scholarly research, were systematically excluded from the review. After applying the established inclusion-exclusion criteria and conducting the necessary filtering, a total of 20 articles were selected for this review.

2.3. Extract Relevany Data and Analyse The Literature

The next stage of the methodology, after identifying relevant articles, entails the extraction of significant information followed by its analysis to respond to the research questions. A key approach for analyzing qualitative data involves comparing the data through naming and classification processes [20], [21]. This approach establishes a framework for the data using Microsoft Word, which aids in developing a thorough understanding of the issue, the field, and the data itself. Continuous comparative analysis of the articles is conducted to identify the different methodologies utilized concerning EEWS and IoT-based systems, thereby creating a classification framework [22], [23].

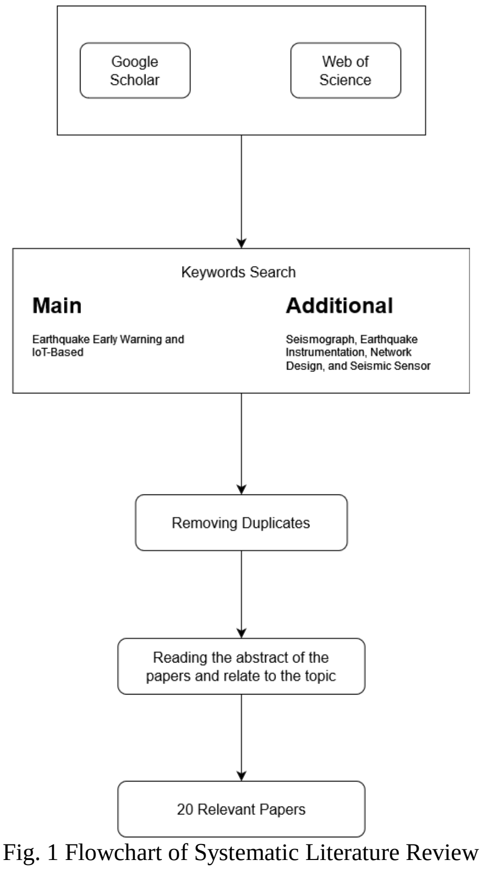

Fig. 1 Flowchart of Systematic Literature Review

3. RESULT AND DISCUSSION

3.1. Three Core of Discussion

- Earthquake

  Several studies focus on tectonic activity in Kalimantan. For example, the paper titled *"Major Strike-Slip Faults Identified Using Satellite Data in Central Borneo, SE Asia" (2018)* [5] investigates whether Kalimantan has active geological faults. The study uses Google Earth satellite data and USGS earthquake instruments, emphasizing geomorphological features like river flow shifts and sediment deformation to identify the main fault systems in Kalimantan, such as NW-SE dextral and NE-SW sinistral faults. The study highlights the importance of remote sensing in geological studies.

  Another study, *"Shuttle Radar Topography-Based Analysis Reveals The Active Borneo Island Fault in Borneo, SE Asia" (2024)* [24], uses shuttle radar topography and geodetic data to map fault lines and geological structures, revealing tectonic activity caused by the interaction between the Australian and Sunda plates.

  For detection of small earthquakes using new technology, the study titled *"Small Local Earthquake Detection Using Low-Cost MEMS Accelerometers: Examples in Northern and Central Italy" (2021)* [25] investigates the effectiveness of low-cost MEMS accelerometers in detecting small earthquakes. The study demonstrates that MEMS sensors, deployed across Italy, successfully detected nine small earthquakes with magnitude less than 3.0, providing valuable insights for integrating these sensors into seismic monitoring networks.

- Early Warning System

  Several studies explore the development and implementation of earthquake early warning systems. The paper *"A Real-Time Early Warning Seismic Event Detection Algorithm Using Smart Geo-Spatial Bi-Axial Inclinometer Nodes for Industry 4.0 Applications" (2019)* [26] presents the SWEDA algorithm, which successfully detects seismic waves in 1.7 milliseconds, analyzes 1.6 million data samples from sensors, employing signal processing techniques for accurate detection. The algorithm detects seismic waves with minimal latency, offering early warnings within microseconds after an earthquake's initiation.

  Another paper, *"A Distributed Multi-Sensor Machine Learning Approach to Earthquake Early Warning" (2020)* [27], develops the DMSEEW system, which integrates GPS and seismometer data. The system uses ensemble stacking methods for classification and utilizes distributed computing for efficiency. This system shows more accuracy in detecting medium and large earthquakes than traditional methods.

  The study of community-based earthquake warning systems *"The Earthquake Network Project: A Platform for Earthquake Early Warning, Rapid Impact Assessment, and Search and Rescue" (2020)* [28] illustrates the effectiveness of using smartphone accelerometers for detecting seismic events globally. The project involves 500,000 users and has successfully issued over 3,000 alerts in regions without traditional seismometer networks.

  On paper "*Earthquake Early Warning: Recent Advances and Perspectives" (2020)* [29] reviews existing EWS globally, analyzing their effectiveness in risk mitigation. The study Synthesizes findings from various systems, focusing on algorithms for rapid detection and ground motion prediction. The findings is highlights significant improvements in EWS, emphasizing the need for better risk communication strategies.

- Internet of Things (IoT)

  Several papers focus on how IoT can enhance earthquake early warning systems. The study *"Employing Machine Learning and IoT for Earthquake Early Warning System in Smart Cities" (2023)* [30] integrates IoT devices with machine learning models for real-time earthquake detection. The study highlights how IoT networks can trigger disaster mitigation measures, such as automatically shutting down power grids during an earthquake.

  Another paper, *"Design Concept of an IoT-Based Earthquake Early Warning Platform" (2021)* [31], demonstrates the capability of IoT-based sensors embedded in consumer electronics to detect ground motion and predict earthquake intensity in real-time with employing a neural network for intensity prediction, optimizing detection speed and accuracy, highlighting the system's potential for widespread deployment.

The paper that study prototype design for IoT-based early warning systems *"BLESeis: Low-Cost IoT Sensor for Smart Earthquake Detection and Notification" (2020)* [32] discusses the development of a low-cost IoT-based seismic network. The system, using MEMS accelerometers and Raspberry Pi units, showed fast response times in detecting earthquakes and issuing early warnings, making it a viable option for both urban and rural areas.

3.2. Additional Topics

- Earthquake Early Warning Systems and Risk Management

  "Earthquake Early Warning Systems as an Asset Risk Management Tool" (2021) [33] focuses on using historical data from significant earthquakes, such as the 2008 Sichuan Earthquake, the study underscores EEWS's role in alerting populations and enabling rapid protective actions. EEWS is presented as essential in mitigating economic impacts by giving advance warnings, thus allowing individuals and automated systems to take preventive actions, which can save lives and reduce damage.
- Community and Crowdsourced Early Warning Systems

  "The MyShake Platform: A Global Vision for Earthquake Early Warning" (2020) [34] leverages smartphone accelerometers to detect earthquakes, creating a global seismic network with over 300,000 users. This study examines the app's capability to distinguish earthquake-like movements from everyday activities and issue alerts within seconds. MyShake represents an innovative, low-cost solution to EWS by leveraging widely available smartphone technology, enhancing earthquake response in regions with limited traditional seismic monitoring systems.
- Security and Reliability in IoT-based Early Warning Systems

  "A Security Transmission and Early Warning Mechanism for Intelligent Sensing Information in Internet of Things" (2022) [35] addresses security risks within IoT networks, especially focusing on unauthorized access and data tampering. It introduces a three-stage security mechanism that includes data encryption, secure transmission, and an early warning algorithm to detect anomalies. By enhancing data security, this approach aims to protect the integrity of sensing information, ensuring that IoT-based early warning systems can reliably function without vulnerability to cyber threats.

  "Recent Advances in Internet of Things Solutions for Early Warning Systems: A Review" (2022) [36] reviews on the literature concerning the incorporation of Internet of Things (IoT) technologies into early warning systems (EWS) for a range of natural disasters, such as earthquakes, floods, and landslides. It categorizes IoT-based EWS into layers—perception, communication, and application—to illustrate how each layer functions, from data collection using sensors to real-time response generation. The study highlights the promise of IoT-integrated EWS in mitigating disaster risks through scalable monitoring solutions, though it also calls for improvements in sensitivity, power management, and minimizing false alarms.

3.3. Guide from Research Questions

- What are the environmental and geographical considerations for deploying a seismic sensor network in Kalimantan?

  Environmental and geographical factors are crucial in deploying seismic sensor networks, especially in Kalimantan, where fault lines and tectonic activity influence the layout of sensors. According to *"Major Strike-Slip Faults Identified Using Satellite Data in Central Borneo, SE Asia" (2018)* [5], Kalimantan has active shear faults, including NW-SE and NE-SW directional faults, which create challenges in the consistent positioning of sensors due to variable geological formations such as river flow shifts, hill slopes, and sediment deformations. Additionally, the study *"Shuttle Radar Topography-Based Analysis Reveals The Active Borneo Island Fault in Borneo, SE Asia" (2024)* [24] confirms tectonic activity influenced by plate interactions that affect the topographic formations, such as the Oroclinal

Bend in Sarawak. These considerations highlight the need for sensor networks to accommodate various elevations and soil conditions to ensure accurate data collection.

- What are the key components and functions of seismograph instrumentation used in early warning systems?
  Seismograph instrumentation in early warning systems typically includes accelerometers, gyroscopes, GPS modules, and signal processing units, each contributing to real-time earthquake detection and data analysis. In the study *"Implementation Early Design of Prototype EEWS Development in Indonesia" (2019)* [37], seismographs deployed across Indonesian regions utilize accelerometers and intensity meters integrated with eBEAR modules for ground motion analysis. This configuration enables real-time alerts and efficient dissemination of warnings through mobile and web applications. Furthermore, the *"The Multi-Parameter Wireless Sensing Systems (MPwise): Its Description and Application to Earthquake Risk Mitigation" (2017)* [38] study details a multi-sensor approach, incorporating GNSS, accelerometers, and cameras, forming a wireless network capable of early earthquake detection. These components work together to enhance data accuracy and ensure timely alerts for public safety.
- How is IoT technology being integrated with seismic sensor networks for real-time monitoring and early warning systems?
  IoT technology enhances seismic monitoring by enabling distributed data collection and processing, as illustrated in the paper *"Employing Machine Learning and IoT for Earthquake Early Warning System in Smart Cities" (2023)* [30]. This study integrates IoT networks with machine learning algorithms, where IoT devices collect and send seismic data to central servers. These servers then process the data in real-time to detect potential earthquakes. Similarly, *"Design Concept of an IoT-Based Earthquake Early Warning Platform" (2021)* [31] uses MEMS sensors embedded in IoT devices, establishing a sensor network that communicates seismic activity information to central processing units. The connectivity enabled by IoT allows for rapid data transfer and seamless monitoring across vast geographical areas, making it especially useful in regions prone to seismic hazards.
- How do IoT-based early warning systems improve response times and accuracy in detecting seismic activities?
  IoT-based early warning systems significantly enhance response times and accuracy by enabling continuous, real-time monitoring and automated data analysis. For instance, the *"BLESeis: Low-Cost IoT Sensor for Smart Earthquake Detection and Notification" (2020)* [32] paper demonstrates that IoT sensors, equipped with MEMS accelerometers and connected to Raspberry Pi units, can detect P-wave arrivals and rapidly estimate earthquake intensity. These IoT systems can issue early warnings within seconds, which is crucial in reducing the time lag typically associated with traditional seismographic methods. Moreover, the *"The Earthquake Network Project: A Platform for Earthquake Early Warning, Rapid Impact Assessment, and Search and Rescue" (2020)* [28] study shows that IoT systems utilizing smartphone accelerometers provide nearly instant alerts to communities in areas without established seismic infrastructure. This rapid response capability is integral to minimizing damage and safeguarding lives in earthquake-prone regions.
- How can seismograph data be processed and analyzed using IoT platforms for efficient early warning in earthquake-prone areas?
  IoT platforms provide a scalable solution for processing and analyzing seismograph data through machine learning and real-time data transmission. According to the study *"A Distributed Multi-Sensor Machine Learning Approach to Earthquake Early Warning" (2020)* [27], seismograph data from IoT devices are processed using the DMSEEW method, which combines GPS and seismometer data through distributed computing. This method enhances detection accuracy and computational efficiency. Additionally, *"Employing Machine Learning and IoT for Earthquake Early Warning System in Smart Cities" (2023)* [30] illustrates that IoT platforms can use machine learning algorithms (e.g., Random Forest,

SVM) to interpret seismic data, enabling systems to automatically classify events and determine the need for an alert. Such integration of IoT with machine learning allows for a more efficient and robust early warning system, especially valuable in densely populated or highly vulnerable areas.

4. CONCLUSION

The reviews presented in the document collectively enhance the understanding of earthquake dynamics, the evolution of early warning systems, and the incorporation of Internet of Things (IoT) technologies in seismic monitoring. The amalgamation of IoT with seismograph networks marks a notable progression for earthquake early warning systems (EEWS), especially in areas such as Kalimantan, where seismic threats may not be adequately addressed due to economic or infrastructural constraints. This methodology facilitates swift data processing and real-time surveillance, which are crucial for delivering prompt alerts. By utilizing a network of affordable sensors and IoT devices, the accuracy and scalability of data are significantly improved, enabling a wider distribution of monitoring locations. Through the detection of seismic occurrences via diverse data types, including ground motion and intensity readings, this IoT-enhanced system offers a viable solution for bolstering preparedness in regions susceptible to earthquakes. Each category emphasizes vital advancements within their respective domains, highlighting the significance of interdisciplinary strategies in improving earthquake preparedness and response initiatives.

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