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Development and Validation of Cost-Effective Real-Time Seismic Monitoring System

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ABSTRACT

Earthquakes result from the sudden release of energy along fault lines within the Earth's crust, generating seismic waves that can travel over considerable distances. Although Malaysia experiences relatively low seismic activity, the country remains vulnerable to earthquakes originating from neighboring regions, highlighting the importance of effective earthquake monitoring and early warning systems to enhance public safety and minimize potential damage. This study presents the design and implementation of a cost-effective, real-time earthquake detection system based on an SM24 geophone and a Raspberry Pi platform. The SM24 geophone, a highly sensitive transducer with a sensitivity of 28 V/(m/s), serves as the primary sensing device by converting ground vibrations into electrical signals for seismic monitoring. The Raspberry Pi performs real-time data acquisition, signal processing, and seismic event analysis, while Virtual Network Computing (VNC) functionality enables remote system access, monitoring, and maintenance. During system development, challenges related to sensor calibration, data acquisition, signal processing, and detection algorithm optimization were systematically addressed to improve measurement accuracy and operational reliability. The proposed system was extensively validated through controlled laboratory experiments using shaker-table simulations and benchmark seismic waveform data. Experimental results demonstrate that the system can accurately detect seismic events across different vibration levels while maintaining reliable real-time performance. Owing to its low cost, scalability, and ease of deployment, the proposed solution is particularly suitable for continuous seismic monitoring in resource-constrained and remote environments. Overall, the proposed system provides an efficient, accurate, and affordable approach to earthquake detection and offers significant potential for supporting early warning systems, disaster preparedness, and seismic risk mitigation in earthquake-prone regions.

Keywords: Earthquake, Geophone, Monitoring System, Raspberry Pi.

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1. Introduction

The Earth's subsurface is a dynamic environment where the rapid release of energy along fault lines results in powerful tremors known as earthquakes [1]. These events generate seismic waves that radiate from the epicenter, causing ground vibrations and potentially catastrophic damage to infrastructure [2]. Seismic events fluctuate in magnitude, ranging from negligible tremors to calamitous incidents and can cause significant damage to infrastructure, trigger landslides, and even spawn tsunamis [3]. Given the potential for catastrophic damage and loss of life, establishing a robust monitoring network is a critical step toward effective disaster mitigation and public safety.

Various methods have been explored to optimize earthquake detection systems, including hydrophones [4], accelerometers [5], seismometers [6], geophones [7], and optical sensors like Fiber Bragg Grating (FBG) [8], Distributed Acoustic Sensing (DAS) [9] and distributed optical fiber [10]. Despite their utility, existing detection technologies face significant operational constraints. Hydrophones, for instance, are power-intensive and susceptible to mechanical failure from glass deformation and seabed noise interference [11]. Accelerometer-based systems often struggle with high internal noise and impedance, while DAS requires significantly higher data volumes than traditional seismic experiments. Furthermore, optical sensors such as FBGs present durability concerns due to the brittle nature of the fiber, which makes them prone to breaking during deployment. [12] [13].

Geophone-based earthquake detection systems have been studied [14]. Still, the technique used an Arduino, which is discontinued and does not support popular languages like Python. Despite these challenges, each detection method can be solved using various tools [15] and technologies [16], depending on the situation with its Internet of Things (IoT) application capabilities [17], [18]. For example, the methodology employed for environmental monitoring, as demonstrated by [19] in their study on weather monitoring using an IoT-enabled ESP32 platform, is particularly relevant to seismic detection. The methodologies established for IoT-based weather monitoring specifically the integration of real-time data acquisition and wireless transmission provide a functional blueprint for seismic applications. By adapting the ESP32-based architecture originally designed for environmental sensing, this study develops a low-cost framework that can incorporate high-sensitivity geophones or accelerometers into a distributed seismic network.

This study proposes a novel system that uses a geophone with a Raspberry Pi to detect earthquakes in real time. Geophones were selected for this study because they offer a superior balance of sensitivity and affordability compared to other seismic sensors. These operational advantages facilitate early earthquake warnings and rapid response strategies. The proposed system utilizes these strengths to provide a practical, efficient solution for seismic monitoring. By analyzing the seismic response, the differential between measured voltage and a baseline reference, the system characterizes subsurface activity. Structurally, these analog instruments use a spring-mounted coil wrapped around a mass, suspended within a stationary magnetic field. Seismic vibrations induce coil displacement, generating an electromagnetic flux directly proportional to the tremor's magnitude. Consequently, this architecture offers a compact, high-sensitivity geophone-based detection system integrated with a Raspberry Pi platform.

2. Methodology

Geophones are essential instruments in seismic exploration, as they record ground vibrations by converting mechanical motion into an electrical voltage. Utilizing the principle of electromagnetic induction, these devices transform seismic energy into electrical signals. The core architecture consists of permanent magnets coupled to the ground surface to track local tremors. When seismic waves occur, they induce movement in a wire coil situated within the geophone. This movement, in turn, leads to flux due to changes in the magnetic position, generating an induced electromotive force that can be visualized as a sinusoidal signal. This movement, in turn, leads to flux due to changes in the magnetic position, generating an induced electromotive force that can be visualized as a sinusoidal signal.

Geophones are frequently employed in mining operations and earthquake detection due to their cost-effectiveness, considerable bandwidth, and durability. The hardware architecture for this study integrates an SM-24 geophone with a Raspberry Pi 3 Model B+ (4GB RAM) and an Adafruit ADS1115 analog-to-digital converter (ADC). The Raspberry Pi and ADC were tasked with processing and analyzing the electrical signals generated by the geophone, thereby providing valuable data for our seismic investigations.

The selection of the Raspberry Pi 3 Model B+ (4GB) was driven by its enhanced computational capacity relative to alternative micro processing units [16]. The Raspberry Pi 3 controls the input, processing, and output stages as the central processing unit of the electronic network. Additionally, the Raspbian operating system, which comes pre-installed with Python software, allows for remote monitoring and updating, further enhancing the system's functionality.

Analog-to-digital converters (ADCs) serve as the essential bridge for translating continuous analog inputs into a discrete digital format. It is extensively utilized in industrial process regulation and data processing. The ADC’s sampling rate determines the frequency at which the analog signal is converted into a digital signal at specific intervals. The ADS1115 offers 16-bit precision at 860 samples per second, outperforming I2C. This chip can function as four input channels or two differential channels. It also features programmable gain amplifiers, with up to x16 amplification, to enhance smaller single or differential signals to the full range. In this architecture, the ADS1115 digitizes the raw analog outputs from the geophone, enabling the Raspberry Pi to process and interpret the seismic data. It is user-friendly and capable of measuring an extensive signal range.

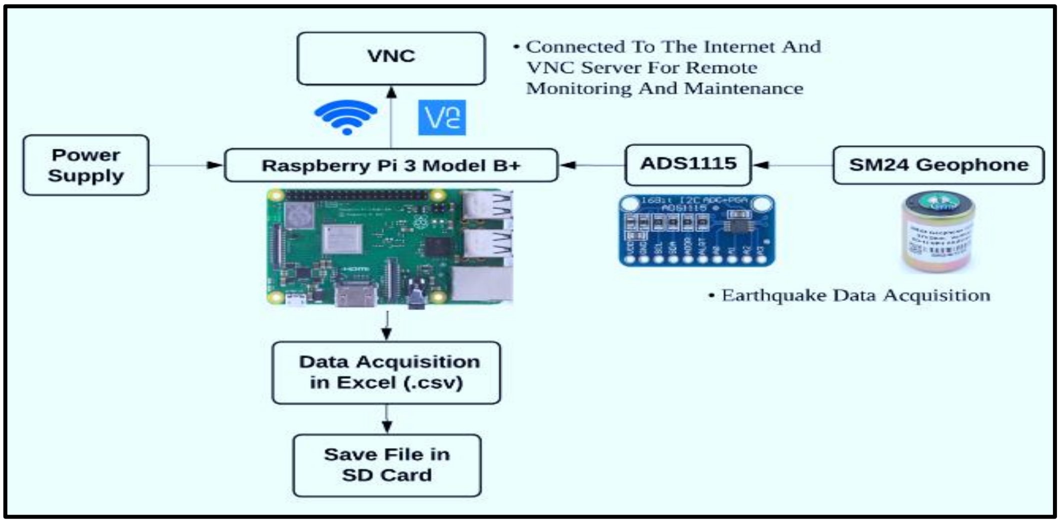

Figure 1. Construction of electrical circuits using a Geophone and a Raspberry Pi

Figure 1 illustrates the hardware configuration for earthquake detection, integrating an SM24 Geophone, a Raspberry Pi, and an ADS1115 ADC. The geophone-acquired seismic data is recorded and archived in an Excel-compatible format. To enable distributed management, the system utilizes Virtual Network Computing (VNC) as a cross-platform interface for remote control and monitoring. A secure connection with a remote computer was established by setting up a VNC server on the Raspberry Pi. This connection facilitated access and interaction with the earthquake detection system's graphical interface and real-time applications. Additionally, the VNC integration allows for software updates, system maintenance, and remote troubleshooting. This capability eliminates the need for physical access to the Raspberry Pi deployment site, ensuring the earthquake detection system remains functional and efficiently managed.

As shown in Figure 2, a 1 kΩ resistor connected to the geophone serves as a calibration resistor, normalizing the response curve. Additionally, two other 1kΩ resistors, R2 and R3, are connected to the ADS1115 board to limit the electric current. These resistors safeguard the circuit control system when the geophone output voltage exceeds the ADC's maximum input voltage. Even if the output voltage is significantly higher than the typical geophone output of a few millivolts, the current will be restricted to 5 mA.

The Raspberry Pi is encased in a custom 3D-printed case for maximum protection and seamless integration. This case is specifically designed for this project, offering a secure, protective environment for the Raspberry Pi. It aims to shield the device from external factors that could affect its performance or longevity. Beyond physical protection, the 3D-printed case presents a neat, organized space for the geophone's electrical circuit.

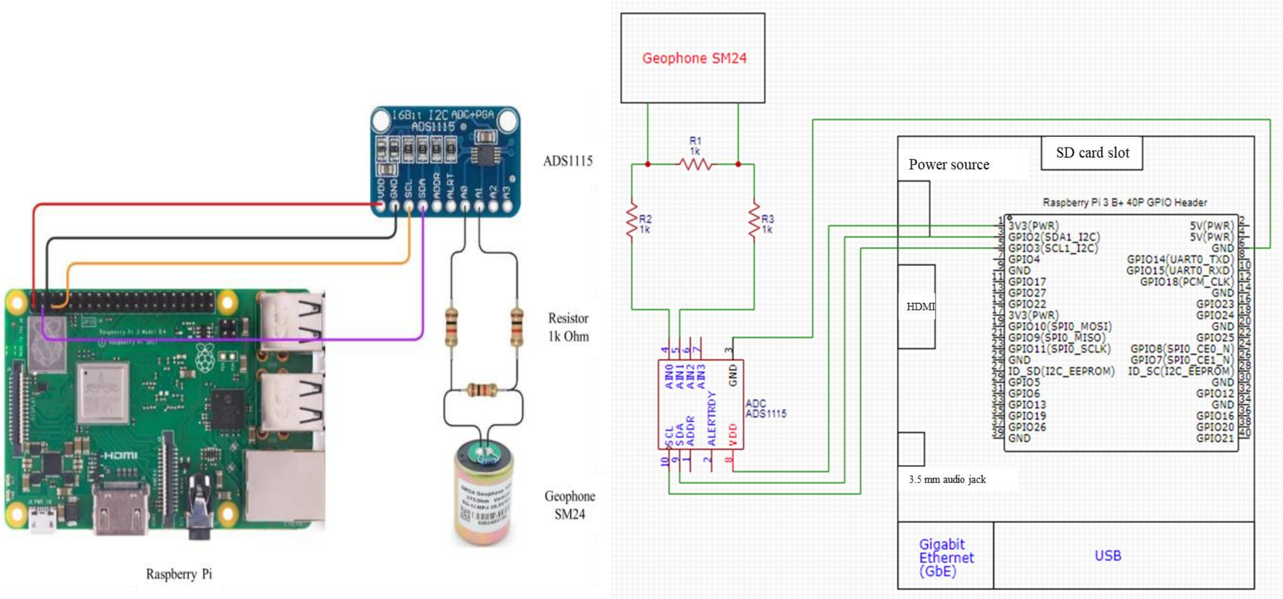

Figure 2. Schematic Diagram of the Geophone Earthquake Detection System

Figure 3 presents a flowchart of the hardware system. Initially, all necessary libraries and board features are imported into the program. The geophone sensor then captures ground vibration data, which is amplified by the ADC (ADS1115). The analog geophone data is subsequently converted to digital data for interpretation by the Raspberry Pi. The Raspberry Pi executes data collection and processing. A Python script generates a plot of the geophone's voltage or magnitude data on the Raspberry Pi. This process continues until it is manually stopped or reaches a predetermined time limit. Finally, all collected data is saved in an Excel file (.csv) format for further comparison and analysis with reference seismic data.

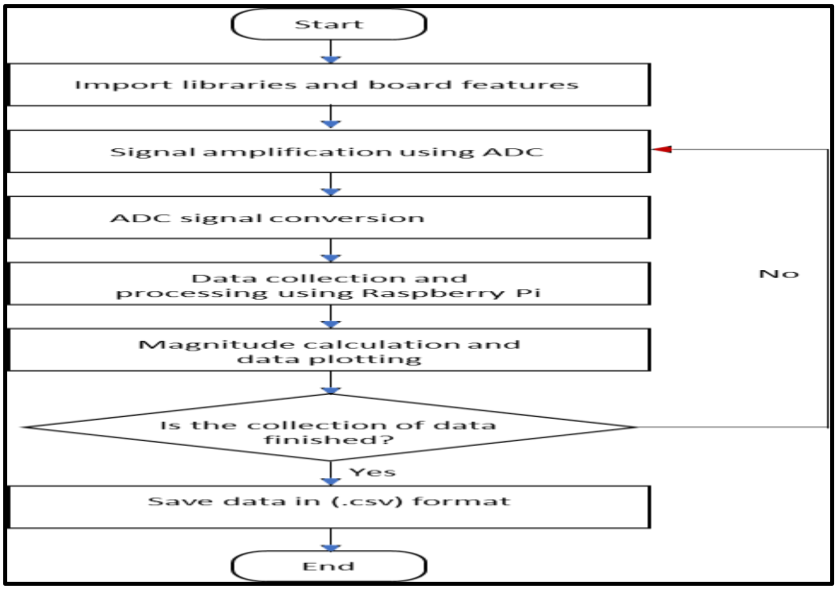

Figure 3. Flowchart of the Hardware System.

3. Results and discussions

Figure 4 illustrates the 3D model and printing of the system casing by using an Ender Pro 3D printer. Polyethylene Terephthalate Glycol-Modified (PETG) was selected for the enclosure due to its superior mechanical properties compared to Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS). PETG provides high structural integrity and durability, significantly minimizing the risk of stress-induced cracking or mechanical failure. Its robust chemical resistance ensures the system remains protected against environmental exposure. Additionally, PETG's thermal stability allows it to maintain its shape without softening or deforming under high temperatures, which is essential for long-term outdoor deployment. From a fabrication standpoint, PETG's versatile extrusion temperature range simplifies the printing process by reducing common defects such as warping and cracking.

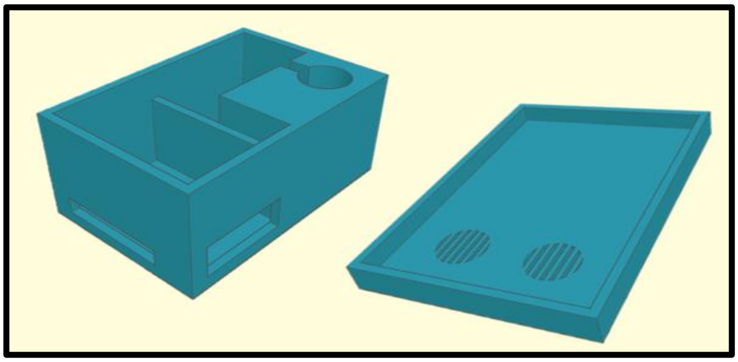

Figure 4. Modelling of System Case

In this study, Raspberry Pi is the core component of the seismic geophone system, providing computational power and compatibility for capturing, processing, and performing various functions on seismic data. As shown in Figure 5, the components are placed in a 3D-printed custom case to ensure a secure, organized setup, enhancing the reliability and appearance of the geophone system.

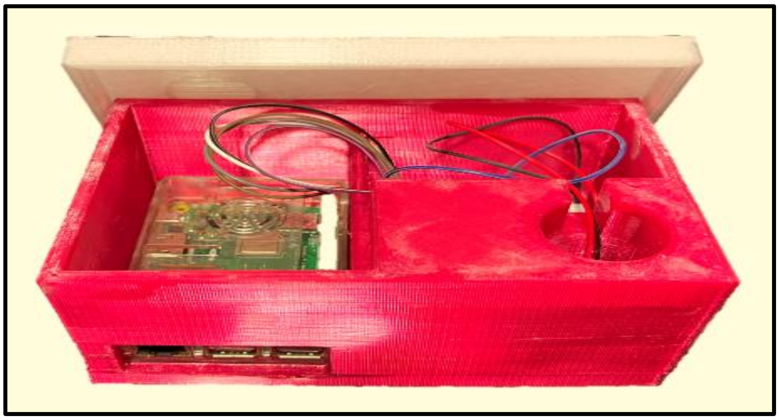

Figure 5. Geophone Electrical Circuit Setup; Custom-designed 3D-printed Case for the Geophone System

The system is configured, and Virtual Network Computing (VNC) connectivity is initiated, enabling remote access and control of the geophone system. This feature provides flexibility and convenience, enabling system performance monitoring, data management, and real-time adjustments via a secure, user-friendly virtual interface. This feature enhances the accessibility and usability of the geophone system. Python libraries such as NumPy and Adafruit (ADS1x15) are installed on the Raspberry Pi to optimize its functionality. These libraries support data processing, analysis, and communication, ensuring seamless operation of the Raspberry Pi and its interfacing with external devices or sensors.

The geophone system’s code is developed in Python, leveraging its robust libraries to create a live plotting feature that displays real-time seismic data captured by the geophone system. As shown in Figure 6, this visual feedback provides valuable real-time insights into seismic events, including their magnitude, frequency, and duration. The live plotting capability significantly enhances monitoring and analysis, enabling timely, informed decisions based on real-time data. This feature enhances understanding of seismic activity and improves the system’s usability and responsiveness, making it an invaluable tool for earthquake detection and research.

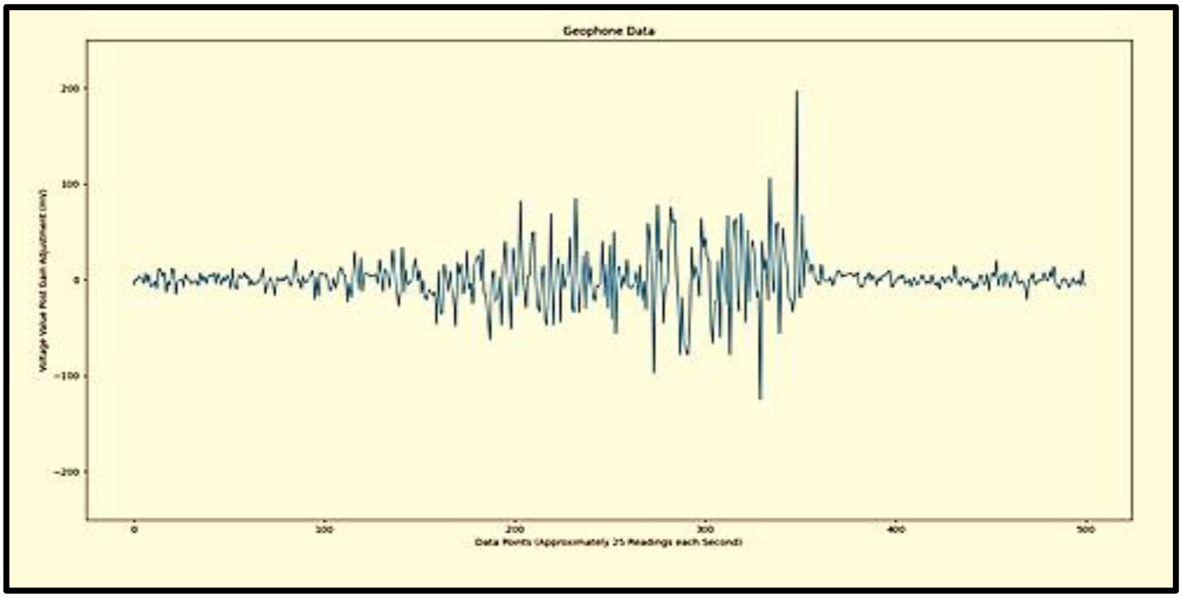

Figure 6. Live Plotting of Seismic Data

In addition, a separate code was developed to retrieve geophone data and store it in a .csv file. This data storage mechanism enables comprehensive recording of seismic events, including timestamps, amplitudes, and other relevant parameters captured by the geophone system. The .csv file contains all recorded seismic data and appropriate parameters. The simplicity and compatibility of the .csv file format make it ideal for easy import into various data analysis tools or visualization software for further detailed examination:

A shaking table test, one of the most widely used techniques for assessing the seismic performance of various materials, was conducted to verify the geophone system's performance. This test also simulated controlled ground vibration to test the geophone system's detection. Figure 7 shows the geophone system on the shaking table, and the reference seismic wave data input into the shaking table, respectively. The resulting data from the shaking table simulator was compared with the data produced by the geophone system on the Raspberry Pi. The reference and seismic data captured by the system and stored in the .csv file were plotted in a graph for comparison, as shown in Figure 8.

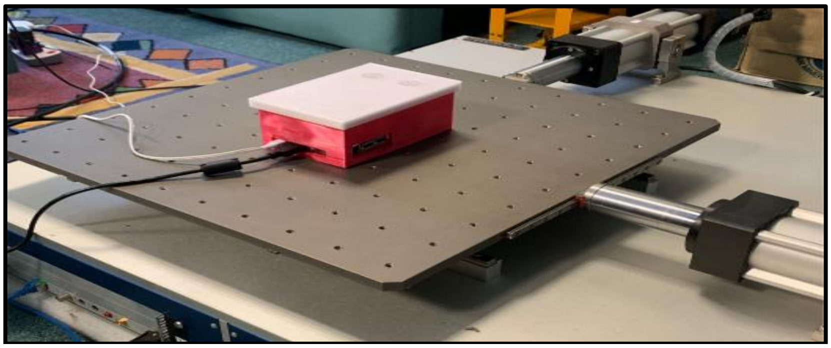

Figure 6. Shaker table testing

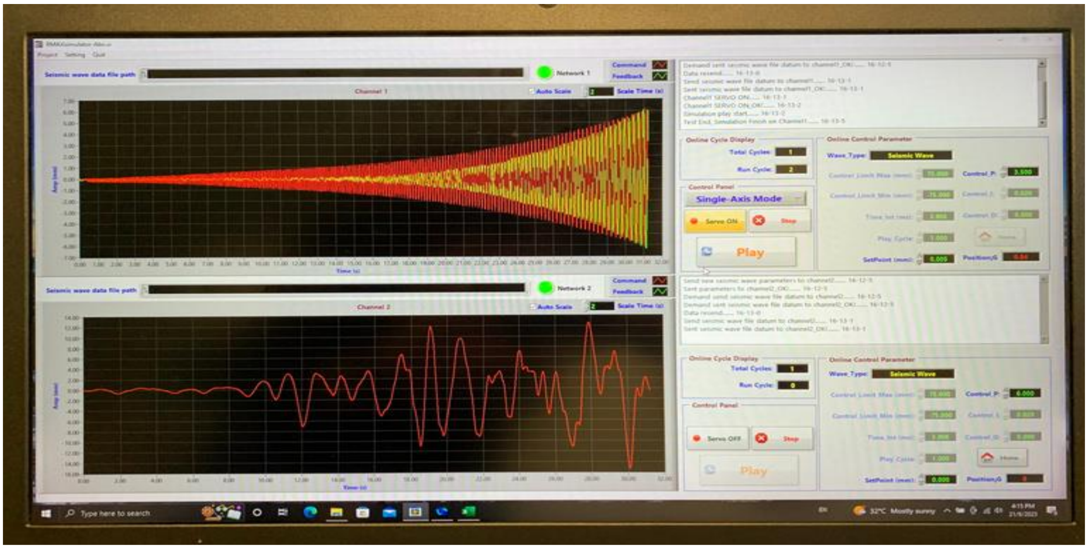

Figure 7. Shaker Table Testing configuration

The y-axis of the graphs in Figure 9 and Figure 10 represents the amplitude of the seismic activity, while the x-axis represents the data points collected within a 30-second simulation period. The graphs show a linear increase in both positive and negative directions over time, indicating that the data from the geophone system closely mirror those from the simulator. However, the proposed system has certain limitations. Within 30 seconds, the geophone system captured only around 3000 data points, compared to the simulator’s 8000. As a result, some of the simulated seismic vibration data may not have been recorded by the geophone system.

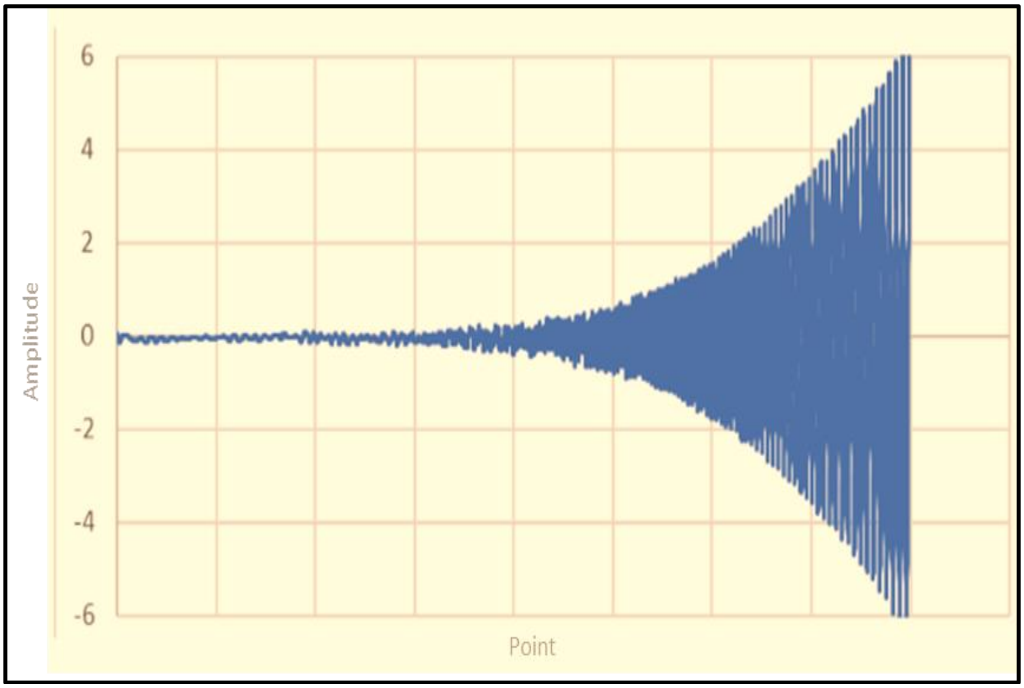

Figure 8. Shaker Table Simulator Results

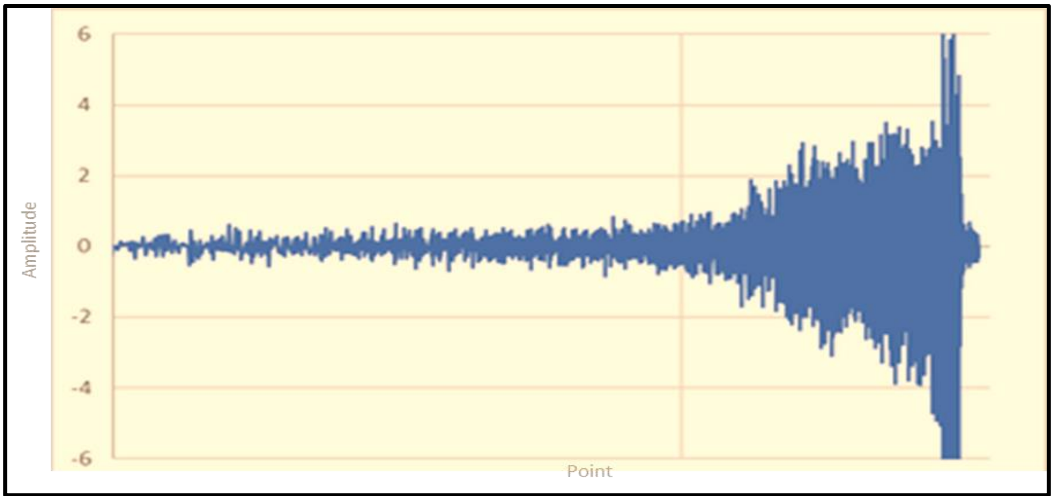

Figure 9. Geophone System Results

Comparing the results shown in Figure 10 indicates that the geophone system is functioning as expected. The system’s high sensitivity of 28V/ms-1 allows it to effectively detect ground vibrations associated with earthquakes. This is further corroborated by the fact that the geophone system's output closely matches the reference data from the shaker table simulator. Figure 5 shows an example of Temporal Analysis for the TA. According to Figure 5, the TA is clearly activated during pedal release. A detailed analysis of this finding is performed using statistical analysis to determine the association between each parameter.

5. Conclusion

Developing an earthquake monitoring system requires meticulous attention to many factors, with hardware and software components playing crucial roles in its effectiveness. The primary objective of this project was to develop a more precise and cost-effective method for detecting earth vibrations using a Geophone device. The results of this study indicate that the Geophone device has the potential to detect earth vibrations more accurately than current methods using seismometers or hydrophones. A functional, budget-friendly, low-power, compact, and portable geophone-based earthquake detection system has been successfully developed. The integration of the Raspberry Pi and geophone provides a dependable and high-performance alternative for real-time seismic monitoring. By harnessing the computational power and flexibility of the Raspberry Pi and the Geophone's sensitivity, a robust system for detecting seismic activity has been realized. This capability is essential for providing the rapid, precise data needed to trigger early warnings and coordinate effective emergency relief efforts.

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Ethics declarations
This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication
Not applicable.

Competing interests
All authors declare no competing interests.

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