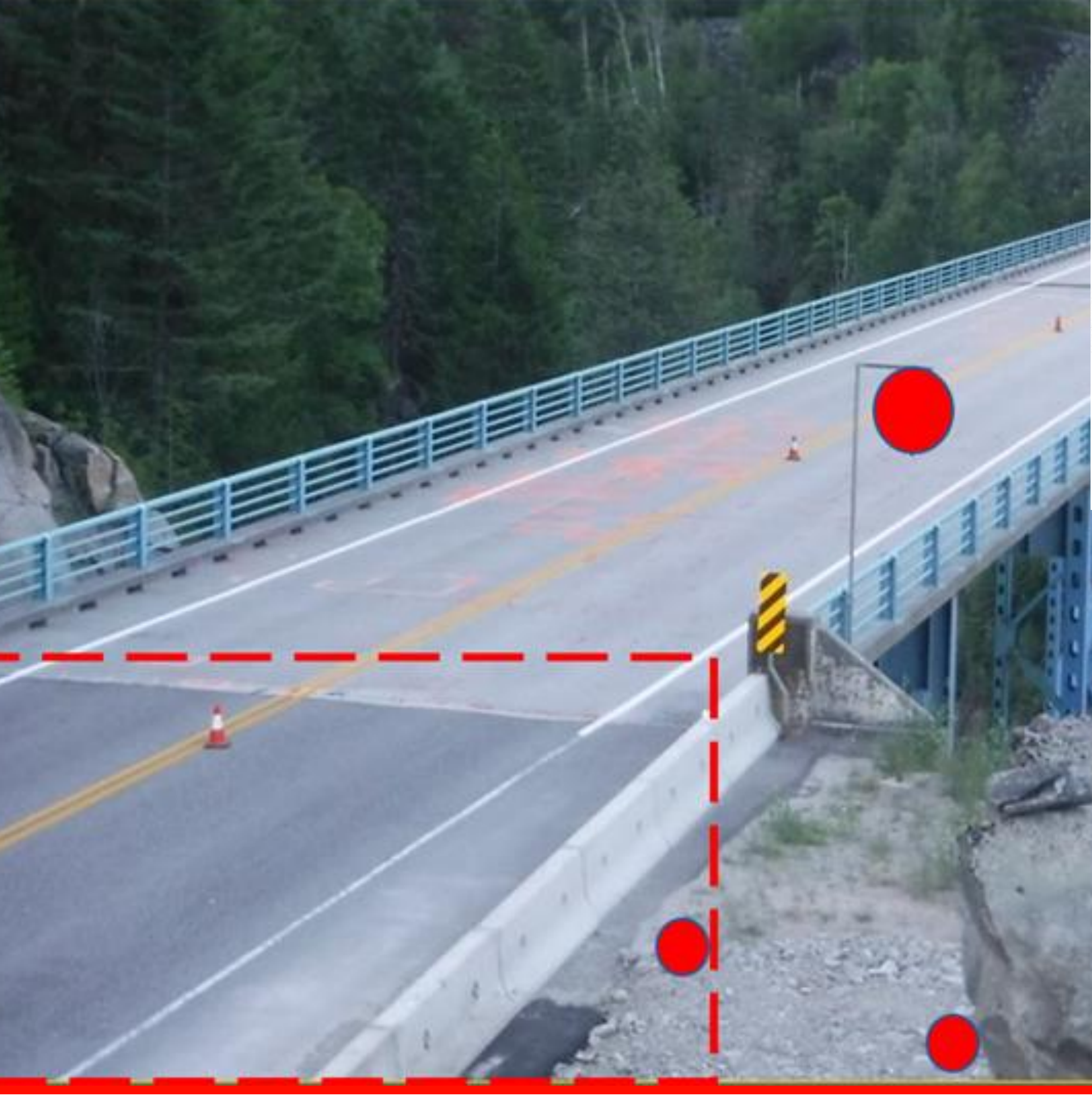

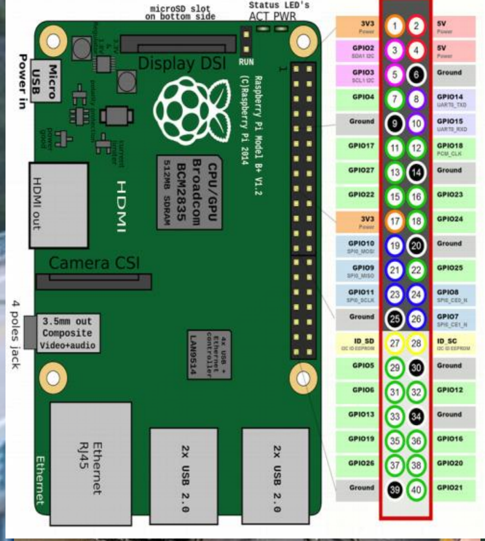


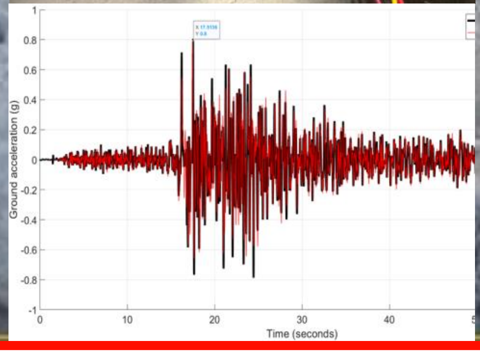


# Seismic Monitoring for Asset Management and Prioritization of Transportation Infrastructure

## A Pilot Study

Research Final Report from Vanderbilt University, the University of Alabama, and DS2A | Janey Camp, Silvana Croope, Eric Berman, Dao Thang, Keegan Fong, Olga Bredikhina, Tyler Nussbaumer | December 31, 2022

Sponsored by Tennessee Department of Transportation Long Range Planning

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16. Abstract

During and immediately after a seismic event, information on the condition of the transportation network and individual assets can be limited without deploying personnel for inspection. Damages to bridge and/or overpass approaches could render bridges useless for evacuation and/or response activities. Therefore, employing low-cost sensing to monitor ground motion in the vicinity of bridges could be valuable to inform decision making for response and asset management. Low cost, direct sensing and analytics has potential to be utilized at bridge approaches and nearby slopes to help identify and prioritize where significant ground movement has occurred that may require field response. This research project was a first attempt to pilot test the feasibility of developing and testing a low-cost direct sensing node to identify ground movement and lay the foundation for field testing and ultimately improved response and resilience of transportation infrastructure in seismic zones.


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# Executive Summary

During and immediately after a seismic event, information on the condition of the transportation network and individual assets can be limited without deploying personnel for inspection. Bridges, and more specifically the approaches, are susceptible to damage from ground motion and liquefaction. While bridges in western Tennessee have been designed and/or retrofitted to withstand some seismic activity due to concerns for the New Madrid Fault, it is more challenging to make approaches resistant to impacts of liquefaction and seismic waves. Damages to bridge and/or overpass approaches could render bridges useless for evacuation and/or response activities. Therefore, employing low-cost sensing to monitor ground motion in the vicinity of bridges throughout the region could be valuable to inform decision making for response and asset management. Direct sensing and analytics may be utilized at bridges and in the surrounding areas (i.e., approaches and nearby slopes) with connections to existing communication networks to help identify and prioritize where significant ground movement has occurred that may require field response.

Low-cost sensing can help offset the cost of labor and time for crews to physically visit and inspect bridges and approaches, especially along evacuation routes in the aftermath of an event. Such sensing could also provide insight to prioritize locations of other assets for health monitoring damage estimation following an event to improve public safety and return those assets to operational status.

This project was intended to serve as a proof of concept and pilot test of the potential to develop a low-cost sensor node that could be deployed in the field to monitor and provide information on seismic activity in the areas leading to bridges and overpasses. Low-cost sensor components were identified and assembled into nodes that were tested in a laboratory setting. From this testing, it was found that the sensors that cost a fraction of the cost of seismic instrumentation typically used were able to detect and measure soil movements when subjected to earthquake-like shaking. Lessons learned from development of the sensor nodes and testing contributed to a set of recommendations for field testing and potential future wide-spread deployment.

## *Key Findings*

Through this project, the following key findings were identified:

- Low-cost sensor nodes can effectively detect and measure soil movements representative of seismic activity.
- A sensor node that cost less than $300 was assembled and tested successfully in a laboratory setting which replicated earthquake-like movements.

## *Key Recommendations*

Due to the nature of the project being a proof-of-concept, the recommendations are primarily focused on potential for field testing and scale-up to field deployment.

- Field testing is recommended for the low-cost, direct sensing nodes at an active construction site with blasting and/or movement of heavy equipment to produce ground vibrations and potential soil movements similar to seismic activity.

- For field testing, new housing such as a encapsulated PVC pipe cylinder should be created to protect the sensors from soil and moisture.
- Connectivity to power and communication networks should be evaluated during field testing with considerations for potential service disruption as a factor due to the intent of the sensor nodes to be used as a response and resilience mechanism.
- Field deployment should include multiple sensor nodes at one location/site to provide redundancy and potential relative motion measurements at the site.
- Additional cost considerations for scale-up for broad field deployment with potential to purchase components in bulk should also be investigated for cost-benefit analysis.

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# Chapter 1 Introduction

Seismic activity can adversely impact transportation networks and efforts have been made in many regions to mitigate potential damage especially along evacuation routes. Bridges and more specifically the approaches are susceptible to damage from ground motion and liquefaction. In western Tennessee, bridges have been designed and/or retrofitted to withstand some seismic activity due to concerns for the potentially devastating New Madrid Seismic Zone. It is more challenging to make approaches, which may consist of various geologic materials, resistant to impacts of liquefaction and seismic waves.

Damage to bridge and/or overpass approaches could render bridges useless for evacuation and/or response activities and make it difficult or impossible to exercise the Essential Support Function No. 1 (ESF 1), enabling ESF 3, and supporting ESF 12 as defined by the United States Federal Emergency Management Agency (FEMA). Therefore, employing low-cost sensing systems to monitor ground motion in the vicinity of bridges throughout a region could be valuable to inform decisions for response and recovery efforts including field crew and logistics prioritization and asset management. Direct sensing and knowledge based on direct data capture and analytics could be utilized at bridges and in the surrounding areas (i.e., approaches and nearby slopes) with connections to existing communication networks to help identify and prioritize where significant ground movement has occurred. In turn, allowing for prioritization of field response due to the competing demands and the number of facilities requiring verification and potential repair. Direct, low-cost sensing can help offset the cost of labor and time for crews to physically visit and inspect bridges and approaches, especially along evacuation routes in the aftermath of an event. Additional benefits include ensuring access to- and exit from- elevated and connecting ramps to other transportation assets is stable, offering a more inclusive system that helps enhance and better accommodate current community calls for social equity investments. Review of frequency and severity of seismic waves can also provide insight to asset prioritize locations of other assets for health monitoring for damage estimation (also called asset condition-based management) following an event to improve public safety and return those assets to operational status. The data creation through the direct sensing systems in this context enables the advancement of digital transportation solutions.

## 1.1 Objectives

This research project was intended to develop and test a proof-of-concept for use of low-cost direct sensing to identify potential localized damages to bridge approaches due to liquefaction during a seismic event. The ultimate objective is to better prepare TDOT and other transportation agencies to more efficiently monitor infrastructure and prioritize field team resources for inspections and response during and/or after seismic events.

## 1.2 Project Goals

The overall goals of the project were to develop and test a low-cost, direct sensing node that could be used for field data collection, identify recommendations for field deployment, and develop a means to manage/assess the data coming from the sensors.

Ultimately, this project aims to bridge the gaps in research and instrumentation (i.e., the seismic network) through developing and testing the field deployment of low-cost, direct sensors to identify areas where liquefaction may be significant following an earthquake event. Using direct sensing in this way can help prioritize what evacuation routes may be out of service as well as identifying where field personnel may be needed to restore damaged infrastructure assets as part of response and recovery activities.

Use of low-cost, direct sensing may allow for more sensors to be deployed across a region with known seismic hazards, such as West Tennessee, resulting in a more-refined system network that produces data and information as an alternative approach and feasible trade-off to higher-cost, seismographs and other instrumentation, giving more field assets condition information enabling the use of existing dollars for more monitoring places.

Direct low-cost sensing can be seen as means to add to or augment existing data networks and systems, provide additional data points for model validation, and as a screening-level approach to identify areas of greatest concern and potential damage which cannot be done with a few dispersed sensors. Seismic systems have been slowly evolving with applications from geological sciences to engineering sciences through augmenting and shifting the paradigm from tectonic plate observations to local, fixed asset performance monitoring and mitigation. Examples include improved engineering design and construction practices that apply horizontal, vertical and vibration forces to structures constructed on top of tectonic plates in such a way that they are able to accept/absorb movement and/or vibrations and resist failure. Furthermore, seismic sensing systems are evolving toward asset health monitoring technologies that have been identified as valuable to departments of transportation and other agencies. Such systems are also now evolving to fit the more intense data consumption for decision support that is becoming an industry standard with the adoption of smart cities and smart infrastructure. This “smart technological approach” takes advantage of the proliferation of digital systems and sources of information, such as crowd-sourced data, cellphones, social media, and in particular the “internet of things (IoT)” and the “industrial internet of things (IIoT).” Such systems create a space for the direct, low-cost seismic systems to enhance a transportation agency’s ability to better manage transportation assets and associated infrastructure networks.

# Chapter 2 Background

The acquisition of (high quality) data to enhance specific and the overall transportation system performance as well as condition monitoring is of continued interest to system users and the mangers (i.e., all levels of government or governance). The design, deployment and operationalization of such systems can both enhance the capabilities of existing systems and create new opportunities to learn more about the built infrastructure and its interactions with the environment including earthquakes or seismic hazards. This section briefly describes an overview of earthquakes, the reason why this is of importance to Tennessee, the types of impacts and damage to infrastructure, and research expanding the development and use of different seismic monitoring systems that provide a foundational case for consideration of earthquake monitoring systems in transportation applications.

## *2.1 Earthquake Basics*

Areas in both West and East Tennessee are at risk for earthquake damages due to both the New Madrid Seismic Zone [1,2], and the East Tennessee Seismic Zone (ETSZ), also known as the Southern Appalachian Seismic Zone (Figure 2-1) [3]. The threat to infrastructure systems including transportation networks and assets is considered much greater in West Tennessee due to the New Madrid Fault.

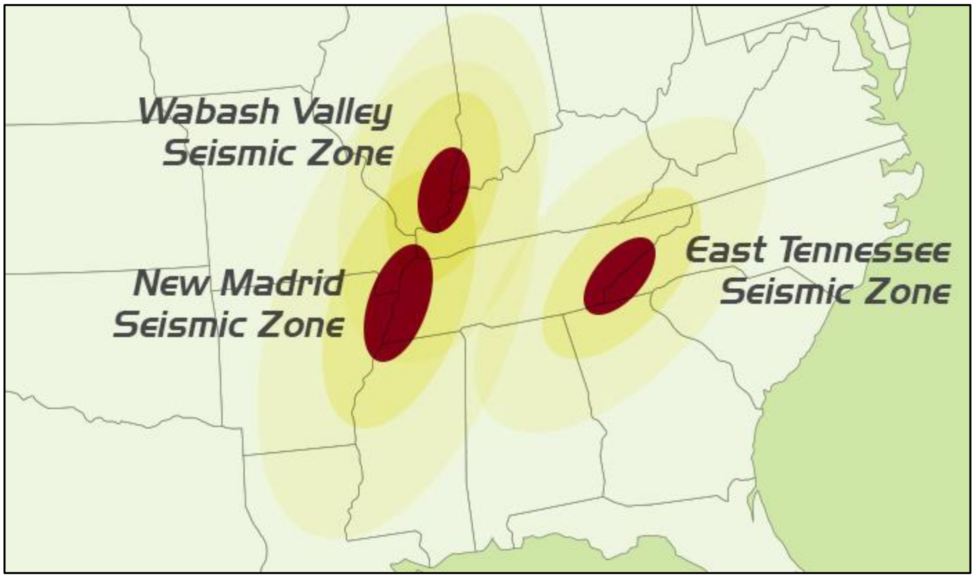



**Figure 2-1: Tennessee Seismic Zones (Source: CUSEC)**

Earthquakes occur as tectonic plates on the earth's crust slide past each other releasing energy in the form of ground shaking and wave propagation from the area of slippage. The edges where the tectonic plates slide past each other are called fault lines. Earthquakes happen worldwide each day [4]. Some are significant and others are barely noticed by people in the vicinity. The ones that are mild to strong that can cause damage to buildings and infrastructure are the types of events of interest to the state DOT.

Damages from earthquakes occur due to the waves that propagate through the surface of the earth from the epicenter being transmitted through the soils and ultimately into buildings and infrastructure. The magnitude and frequency of the waves as well as the direction of the waves can result in different levels of damage.

As tectonic plates move past each other very slowly, some areas get caught and do not move as easily. This causes friction between the plates and eventually the forces to move exceed the resisting forces in some areas resulting in slippage. Sometimes small slips can occur as plates are moving resulting in less severe earthquakes. Small slippages can be indicators of friction being overcome along a fault line and may serve as foreshocks or indicators of a larger earthquake on the horizon. For years, scientists have used seismographs to measure vibrations of the ground. Seismographs are used to identify both small earthquakes or ground shaking that might indicate a larger slippage or that an earthquake is about to happen. However, scientists (geologists and others) cannot really predict when an earthquake is going to happen nor how strong it might be.

In Tennessee, the Advanced National Seismic System (ANSS) consists of a network of seismographs nationwide to help detect earthquakes and seismic movements [5]. This is considered the "backbone" seismic network. Nevertheless, there are only three stations in Tennessee (Figure 2-2). There are other stations throughout the region, but they are part of other smaller networks of sensors being monitored [6]. However, access to those systems is not widely accessible as they are part of proprietary, third-party systems and different levels of engagement to establish such access to data or service would need to be considered. This limitation of instrumentation and data does not confer the level of detail necessary to manage the vast and diverse infrastructure assets part of the state's transportation network. Furthermore, with limited resources (personnel, equipment, and funds), it is nearly impossible to deploy individuals to inspect all structures or use drones with cameras to assist in assessing physical infrastructure damage across hundreds of miles of roadways expeditiously following a seismic event.

One example where sensors have been used to evaluate conditions and meet a large demand for data/information is the EPA's use of air quality sensing systems in communities across the U.S. [7]. Additionally, the Arizona DOT and other transportation mangers use sensors on roadways to collect and transmit real-time traffic data to roadway users as part of a Vehicle-to-Infrastructure (V2I) communication system to enhance traffic flow and build a foundation for adoption of autonomous vehicles in a safe and highly-sensed environment [8].

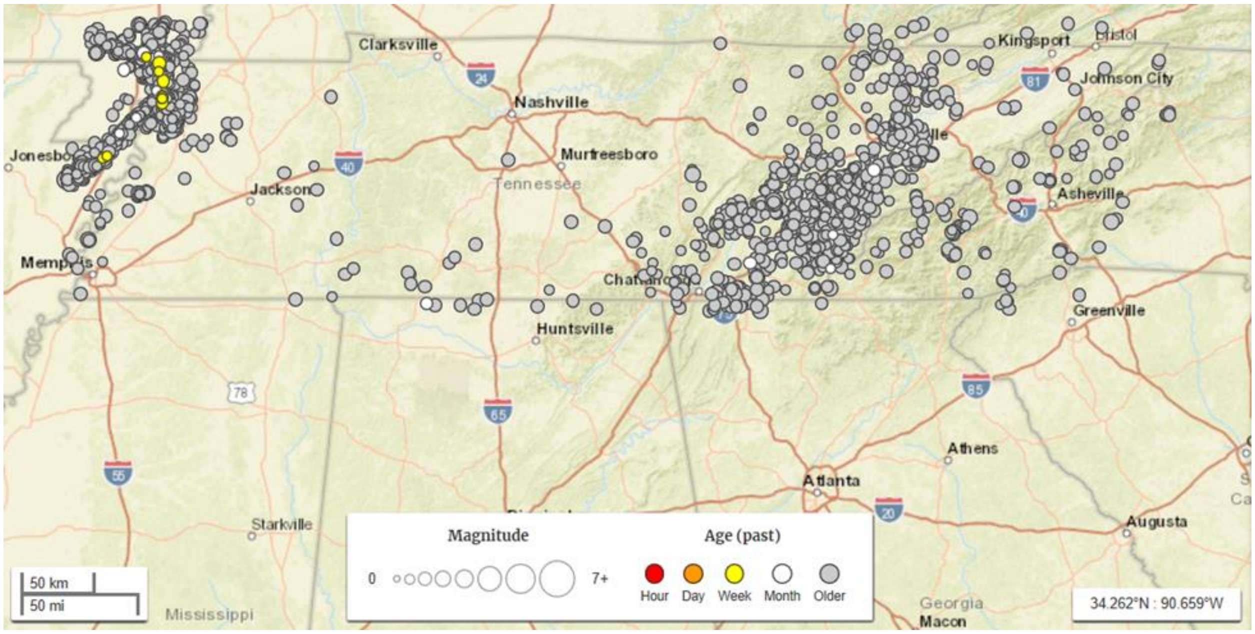



**Figure 2-2: Earthquakes in the Tennessee area from January 1996 to October 2019 (source: USGS Earthquake Catalog [9]) with ANSS stations indicated as red triangles [5].**

Geologic evidence of historic earthquakes learned by studying faults and geologic formations can help identify when and how significant historic earthquakes were and serve as data points in estimating the size and locations of future earthquakes. Models and scenarios have been developed to estimate future slippages and how the waves would propagate from estimated epicenters to help with planning, preparedness and response activities. The anticipation of such events also helps plan for recovery and provides insights into enhancing mitigation. Altogether, this provides the basis to help diagnose and have initial insights on both the infrastructure network resilience and the resilience engineering of specific assets, and that of all the services and systems involved in this overall challenge [10, 11].

## *2.2 Concerns for Tennessee*

The most seismically active area in the eastern US is the New Madrid Seismic Zone which runs along the Mississippi River on the western side of the state and spans across multiple states (Figure 2-1). According to the USGS, since 1996, over 5,500 earthquakes have occurred in the state of Tennessee alone (Figure 2-2). Approximately 95% of those earthquakes were at a magnitude of 2.5 or less. The most significant earthquakes that the state has experienced on record was when the New Madrid zone had a series of small earthquakes and three large ones that ranged in magnitude 7-8 in the winter of 1811-1812 [12]. The magnitude of these earthquakes have been approximated based upon comparison of visible damages in photographs to damages from other earthquakes over time. Accounts from that period state that church bells rang for hundreds of miles away and the earthquakes were significant enough to create Reelfoot Lake.

While scientists cannot predict when another major earthquake will happen along the New Madrid fault line, they are most certain another quake will happen.

The fault is very active (Figure 2-2) and the impacts could be severe due to the abundance of soils in the area that are not very stable structurally. The energy of some seismic waves tends to be absorbed by solid rock, while the slower waves may pass through the solid rock and become absorbed and amplified by soft sediments. Thus, we often observe much worse earthquake damage in areas with soft sediments where the waves are amplified than in areas of solid rock. In soft sediment like we have in western Tennessee, liquefaction (where soils become less stable and flow more like a liquid) is a large concern because it affects the stability of foundations of buildings, roadways, and other infrastructure. In one study where a New Madrid earthquake of 7.9 moment magnitude was modeled (and no apparent consideration for retrofitting of bridges in the region), it was found that only 2% of bridges could be expected to be fully functional with approximately 28% non-functional and 70% would be at 50% functionality [13].

Much effort and focus has been spent on New Madrid with exercises such as the Great Central US ShakeOut [14] and other activities to help emergency response personnel and leaders prepare for another large earthquake event in the region. The Tennessee State Department of Transportation (TDOT) and other agencies have worked to retrofit bridges and other infrastructure to withstand the vibrations and waves that may come from a large earthquake in West Tennessee. However, many bridge approaches are still at risk of impacts due to liquefaction, which can result in the disconnection of the approaches from bridges as soils migrate due to vibration, interrupting the physical roadway network. Multiple evacuation routes have been identified in the West Tennessee area (Figure 2-3) and while bridges may be retrofitted to withstand the ground shaking and waves from a New Madrid earthquake, the approaches to those bridges may not be equally prepared and suffer significant damages [15]. During an earthquake, roadways and bridges can collapse when their foundations and/or supports are compromised and become unstable. In a review of earthquake impacts and accounts of liquefaction occurring in major earthquakes in the Wairarapa Region, it was noted that bridge approaches settled away from the bridges as much as one meter, were damaged, and there was noted subsidence and cracking at the ends of the bridges [16]; therefore, disconnecting and interrupting the physical transportation network and disrupting traffic flow. This results in a decay of the broader transportation system, where gradual and/or total destruction of assets could render lead to overall reduced ability to meet demands (both in day-to-day operations and response and recovery efforts) resulting in overall reduced resilience for the system and state.

## *2.3 Determination of Earthquake Impacts and Damage*

Beyond anticipating damage using models and actively tracking seismic activities in an area, when an earthquake happens, it is critical to be able to quickly respond with resources and assess damages for the safety of the public and recovery efforts. In recent years, multiple approaches for remotely sensing damages and assessing impacts have been developed, but there are still limitations such as costs and the time/computing resources required to process the imagery or obtaining a good volume of data and information [17, 18]. However, they can be quite costly and do not necessarily quantify the local potential damage due to soil shifts and liquefaction caused by the earthquake wave propagation and changed soil structure due to engineered ground built to support bridges and roadways. Additionally, high-resolution satellite imagery tends to be used primarily in rapid assessment with a focus on buildings to estimate populations impacted and response needs [16].

Structural health monitoring (SMH) can be done on infrastructure such as bridges but is not easily done for the approaches and soil embankments that support the roads leading to/from bridges (and any ramps to/from bridges). Additionally, SMH does not allow reliable early detection of anomalies in bridges and such forms, and indirect damage detection often requires complex algorithms and can be costly [19]. Therefore, there is a need to develop a means to quantify the potential impacts to approaches locally and directly.

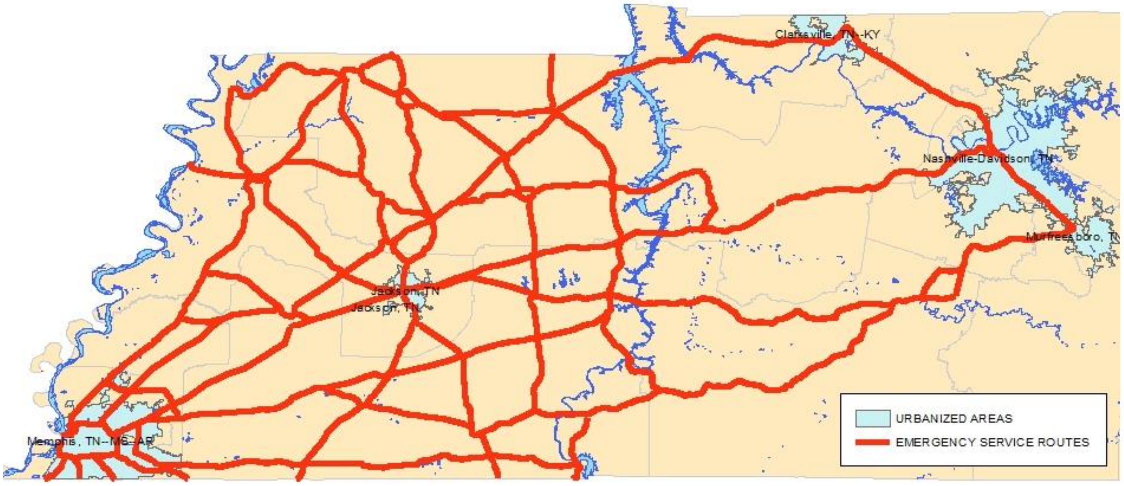



**Figure 2-3: West TN Emergency Service Routes**

## *2.4 Earthquake Sensing Systems*

To date, remote sensing or in-person visual examination is the most used approach to identify what infrastructure assets are still operational. Remotely sensed inspection using aerial imagery may not be at a resolution to accurately determine if a bridge approach has sustained some damages due to liquefaction. The cost for aerial imagery (drones or otherwise) increases as the resolution and granularity increases, which may be cost prohibitive for an area as large as Western TN and the potential impact zone. Additionally, deploying field teams to perform in-person damage assessments can also be costly and potentially put individuals at risk due to aftershocks, etc, and takes time and an idea of prioritization of which place to inspect first. In-situ, dynamic monitoring can also be costly depending on the instrumentation used. For any detection system, connectivity to communication systems is an important consideration as these networks may be disrupted in the aftermath of an earthquake also which could render some detection systems useless.

There have been some new efforts to densify existing robust, and expensive nodal sensor networks such as ANSS to gather more data by scientists and seismologists. Such monitoring networks can benefit from network densification as noted by Anthony et al. [20]. However, to date, limited efforts exist to utilize and field test direct sensing for seismic activity and potential impacts. The only other effort of this kind to date was done by Brady Ray Cox and his advisors at the University of Texas at Austin [21]. In his research, Cox created an in-situ instrument for field liquefaction measurements that was composed of a sealed, miniature pore water pressure transducer and a three-component (3D) Micro-Electrical Mechanical Systems (MEMS) accelerometer.

The goal of the project was to develop and implement a new in-situ liquefaction testing technique for use in geological studies. The costs of the sensors were not mentioned in the dissertation, but Cox [21] discussed that cost considerations should be considered when deploying multiple sensors. In a study by Anthony et al. [20], they found that small Raspberry Shakes (small seismographs built on Raspberry Pi computers ranging in cost from $100-$950 [22]) are "suitable for densifying backbone networks designed for studies of local and regional events".

To better understand the cost range of existing seismic and related health monitoring systems as well as the value proposed of the re-engineered systems, a broad-spectrum market research scan was developed to uncover potential "cost-approach" and practices used in such systems. Tables 2-1 through 2-3 show compiled information from different providers, which was used as foundational information to improve understanding of the current seismic system feasibility, and potential benefits for development. Table 2-1 shows a collection of existing market seismic package systems ranging from $175 to $4,000 depending on certain specifications, types of sensors and quantity of sensors. Table 2-2 shows detectors (sensors) ranging from $700 to $1,300. Table 2-3 provides a summary of additional software and equipment that could be utilized ranging from $400 to $6,000. All these systems are proprietary and vary according to the number of sensors and detailed information collection and data transmission requirements.

It is important to note that all of these systems can help address the needs for assessing the bridge health condition with respect to seismic activity and could potentially be part of the data used in and for FEMA's ShakeCast, or as part of monitoring and alert systems such as "BridgeWatch", a system currently used by TDOT.

This cost range shown in Tables 2-1 through 2-3 is focused on the equipment and software system, but the costs reported do not include maintenance, operations, data storage, analysis and any other decision-support or warning system resulting from the data created through the instrumentation.

Through the literature review and basic market search, it is clear there is a desire and importance to enhance the monitoring of bridges, the approaches to bridges, and any other transportation asset subject to the seismic risk of damage. The state of Tennessee has more than 21,000 bridges [24, 25]; therefore, there is potentially 42,000 approaches to bridges existing, and a substantial number of these fall in the New Madrid Seismic Zone, and other areas where seismic activities can happen. Therefore, the cost and the system that will consider such needs in an economically feasible way is needed.

The next section discusses the development of such a seismic system and provides a comparative cost assessment for such an approach.

This type of problem is anticipated and included in the recent Bipartisan Infrastructure Bill [26, 27] that makes resilience a funded mandate and requires a resilience plan and performance plan and action a requirement. This also includes the requirement to address repetitive damage, which can occur in faulty zones such as at the New Madrid Fault. Such an approach can enhance the social equity aspect of seismic safety monitoring systems.

**Table 2-1: All-in-one sensor systems (include accelerometers, dataloggers, and software systems within one device).**

| Sensor Model | Manufacturer | Sensor Description | Price |
|---|---|---|---|
| RS1D | RaspberryShake | • Combines a professional-grade vertical seismometer (called a geophone) digitizer, hyper-damper and computer.<br>• All-in-one highly portable solution for monitoring earthquakes and all types of ground motion activity.<br>• Outdoor package includes:<br>○ 1x Raspberry Shake circuit board (datalogger/ digitizer)<br>○ 1x Vertical Earth motion monitoring sensor with cables<br>○ 1x Raspberry Pi single-board computer<br>○ 1x 8 GB pre-programmed Micro SD Card<br>○ 1x Ethernet Cable, 3 meters long<br>○ 1x 5V 2.5 Amp power supply, 1 meter long (Plug types supported: A, C, G, I)<br>○ 1x IP67 Enclosure<br>○ 1x USB cable, 1 meter long<br>1x Aluminum mounting and levelling base | $174.99 – $894.99 |
| RS3D | RaspberryShake | • Advanced seismograph featuring three orthogonally positioned geophone velocity sensors, for millisecond accuracy and quality of data to record seismic activity of all magnitudes, both vertically and laterally.<br>• Outdoor package includes:<br>○ 1x Raspberry Shake 3D circuit board (datalogger/ digitizer)<br>○ 3x Earth motion monitoring sensors with cables<br>○ 1x Raspberry Pi single-board computer<br>○ 1x 8 GB pre-programmed Micro SD Card<br>○ 1x Ethernet Cable, 3 meters long<br>○ 1x 5V 2.5 Amp power supply, 1 meter long (Plug types supported: A, C, G, I)<br>○ 1x IP67 Enclosure<br>○ 1x USB cable, 1 meter long | $759.99 – $1,414.99 |

| | | | |
|---|---|---|---|
| | | 1x Aluminum mounting and levelling base | |
| RS4D | RaspberryShake | • Highly portable, turnkey device integrates the velocity and acceleration sensors, digitizer, hyper-damper, and computer into a single unit. Three accelerometer sensors built into the board detect ground motion both horizontally and vertically.<br>• Outdoor package includes:<br>o 1x Fully tested Raspberry Shake 4D circuit board (datalogger/ digitizer)<br>o 1x Vertical Earth motion monitoring sensor<br>o 1x Triaxial (east, north, and vertical) MEMS accelerometer<br>o 1x Raspberry Pi single-board computer<br>o 1x 8 GB pre-programmed Micro SD Card<br>o 1x Ethernet Cable, 3 meters long<br>o 1x 5V 2.5 Amp power supply, 1 meter long (Plug types supported: A, C, G, I)<br>o 1x IP67 Enclosure<br>o 1x USB cable, 1 meter long<br>1x Aluminum mounting and levelling base | $434.99 – $1,084.99 |
| SmartSolo IGU-16 | SmartSolo | • Single-channel seismic wave detection device<br>• Built-in 8GB non-volatile flash memory; could be expanded to 32 GB<br>• Includes mobile app for scanning and technical support<br>• Automatic sensor testing and GPS logging; auto-scan mode for faster deployment | $400.00 - $500.00 for the single channel |
| SmartSolo IGU-16HR-IES | SmartSolo | • Built-in 16 GB non-volatile flash memory; could be expanded to 32 GB<br>• Support for Bluetooth QC and Find Function<br>• Built-in DT-Solo High-Sensitivity Sensor<br>• 5Hz & 10 Hz options<br>• External sensor option<br>• Includes geophone, marsh strings, and hydrophone<br>• Sensor self-test and GPS positioning<br>• Up to 25 days of continuous recording | $400.00 - $500.00 for the single channel |

| | | | |
|---|---|---|---|
| SmartSolo IGU-16HR 3C | SmartSolo | • Compact all-in-one 3-channel sensor & datalogger with onboard GPS timing, and a self-contained power supply<br>• Can be used for both active and passive short-term experiments<br>• Storage capacity: 64 GB<br>• High resolution data with up to 0.25 MS sampling and 32-bit delta-sigma ADC<br>• Built-in GPS receiver and disciplined high precision clock<br>• Suitable for one station to million station operations<br>• Up to 30 days of continuous recording | $1,000.00-$4,000.00 |
| SmartSolo IGU-BD3C-5 | SmartSolo | • Internal battery supports up to 30 days of continuous recording<br>• Support for external power supply and Bluetooth QC<br>• Built-in GPS receiver and time-disciplined high precision clock<br>• High-resolution data with up to 0.25 MS sampling and 32-bit delta-sigma ADC<br>• Real-time seismic data monitoring and sensor status QC<br>• Internal 32 GB memory; can be expanded to 64 GB | $1,000.00-$4,000.00 |
| Vertical School Seismometer | Ward's Science | • Vertical school seismometer<br>• Delivers P and S-wave earthquake signals<br>• Includes software to analyze data<br>• Seismometer comes with Windows software which displays a full day's recordings on a single screen, automatically saves, and organizes the data for later analysis<br>The software supports identification of different types of ground waves in an earthquake, extraction of the earthquake signal, and determination of the distance and intensity of the quake | $842.49 |

**Table 2-2: Accelerators and Seismic Movement Detectors**

| Model | Manufacturer | Sensor Specifications | Price |
|---|---|---|---|
| VBC7000 | Azbil Corporation | • Sensing direction: horizontal and vertical<br>• 15 models are available with acceleration between 12-250 Gal<br>• Mounting: indoor, on firm wall or pillar surface | $1281.00 |
| Accelerometer SHM | Move Solutions | • High-precision three-axis wireless sensor, capable of synchronizing data samples with all the other Accelerometers SHM in the system<br>• Transmits accurate readings from the site via the Lora WAN wireless communication via a gateway<br>• Allows for the performance of modal and vibrational analysis on any type of structure<br>• Battery-powered device with operating autonomy of up to 8 years<br>• Includes temperature sensor | $960.00 |
| Model 393B05 | PCB Piezotronics | • Seismic, miniature (50 gm), ceramic flexural ICP accelerometer<br>• Applications include building vibration monitoring, earthquake detection, structural testing of bridges, geological formation studies, and others<br>• Sensitivity: (±10%)10 V/g<br>• Broadband Resolution: (1 to 10000 Hz)0.000004 g rms<br>• Measurement Range: 0.5 g pk<br>• Frequency Range: (±5%)0.7 to 450 Hz<br>• Electrical Connector: 10-32 Coaxial Jack | $659.00 |
| Model 393B12 | PCB Piezotronics | • Seismic, high sensitivity, ceramic flexural ICP accelerometer<br>• Sensitivity: (±5%)10.0 V/g<br>• Broadband Resolution: (1 to 10000 Hz )0.000001 g rms<br>• Measurement Range: 0.5 g pk<br>• Frequency Range: (±5%)0.1 to 200 Hz<br>• Electrical Connector: 2-Pin MIL-C-5015 | $780.00 |
| Model 393B31 | PCB Piezotronics | • Seismic, high sensitivity, ceramic flexural ICP accelerometer<br>• Sensitivity: (±10%)10000 mV/g<br>• Broadband Resolution: (1 to 10000 Hz) 0.000008 g rms | $1060.00 |

| | | | |
|---|---|---|---|
| | | • Measurement Range: 0.5 g pk<br>• Frequency Range: (±5 %)0.15 to 1000 Hz<br>• Electrical Connector: 2-Pin MIL-C-5015 | |

**Table 2-3: Software and Equipment**

| Sensor Model | Manufacturer | Sensor Specifications | Price |
|---|---|---|---|
| Multilogger Suite Software | Canary Systems | • Includes: MLWeb Web Client, MLWeb Hardware, Multilogger Datalogger Client, and MLField Mobile App<br>• MLWeb Web Client allows access to all your monitoring data from anywhere, in any standard web browser with unmatched flexibility and customization options for reports, views and actions<br>• MLWebHardware streamlines instrumentation setup and integration from anywhere, in any standard web browser with a simple user interface to make the process easier than ever<br>• MLField is a mobile application designed to bridge the gap between data collection in the field, and the hosted project database<br>• Multilogger is a Windows application designed to manage automatic data acquisition systems (ADAS) | $3,000.00 |
| MLDAQ | Canary Systems | Wireless acquisition station MLDAQ supports measurements from a wide range of available sensors, including vibrating wire, load cells, micro-electro-mechanical (MEMs) sensors, flowmeters, linear potentiometers, thermocouples, thermistors, SDI-12 sensors, 4-20 mA sensors, weather instruments such as wind sets, rain gages, temperature and humidity. | $6,000.00 |
| Gateway SHM for accelerometers | Move Solutions | • Control unit for data communication between sensors and cloud server<br>• Allows managing communication with dozens of devices and sensors at the same time<br>• Cellular 3G communication<br>• Wi-Fi hotspot<br>• One gateway can handle up to 25-30 accelerometers | $1,100.00 |
| Move Cloud Platform with | Move Solutions | • Online cloud platform for management and data analysis, for 0-10 sensors | $550.00 per year |

| | | | |
|---|---|---|---|
| Advanced Data Processing Algorithms | | | |
| Acquisition node IAU-19 | SmartSolo | Smart seismic acquisition node that is used to connect with external land and marsh geophone or hydrophone | $400.00-$500.00 |

For many of the off-the-shelf, all-in-one sensor systems (Table 2-1), the cost is a key consideration when considering broad distribution on potentially hundreds or thousands of bridge approaches. The RaspberryShake models hold promise both based upon cost and data collection with three orthogonally positioned geophone velocity sensors. The RS4D includes an accelerometer but can cost a minimum of over $400. This is similar in data and computing power to what the current project assembled but doesn't include soil moisture. The SmartSolo is another, more expensive option but includes GPS positioning (the level of accuracy needs to be explored) and potential for Bluetooth and external power supply connectivity. While the SmartSolo can store collect for up to 30 days with the high-end model, regular sampling intervals would be a better option for the current application considerations because earthquake prediction is still challenging, and one will not know when the data is needed to deploy and continuously collect data for a month at a time. The Vertical School Seismometer does not seem to be an adequate fit for the current application because it is developed for more indoor use in an educational setting. Based upon available data, none of the all-in-one sensor systems include the option to measure soil moisture which can be a factor in liquefaction.

When considering stand alone accelerometers and seismic movement detectors, many are not only expensive, but intended for indoor mounting or mounting to a structure, which is not the real intent of the current project. Hypothetically, one could mount one of these devices to a roadway sign or other non-permanent structure in the approach area and monitor its movements and potential vibrations. However, it may be difficult to discern if the movement is due to seismic activity or other means (significant wind, mowing vibrations, vehicular impact, etc.). As an example, the Accelerometer SHM holds promise for data collection and data transmission but must be mounted to a structure and costs approximately $980. The accelerometers from PCB Piezotronics hold some promise, but the costs are likely prohibitive. Little information was provided on the potential for outdoor applications and housing, and they seem to be intended for measurements of vibrations of structures. Applying some of these accelerometers and seismic movement detectors to an outdoor application in/around soils to measure liquefaction does not seem feasible or cost effective.

While there are several options on the market for sensing capabilities that align with our purpose, the feasibility of putting them into the field to measure liquefaction at bridge approaches would be limiting simply because of the hardware and housing needed or cost prohibitive. Therefore, the research team has developed a low-cost prototype to measure soil movement and potential liquefaction with consideration for potential field application in Tennessee, data collection, and costs. The sensor components and other information about the prototype and potential use are presented in the following chapters.

# Chapter 3 Sensor Development

TDOT uses BridgeWatch to monitor its bridges and participates in ShakeCast exercises with FEMA to improve preparations for a seismic event. However, the agency does not monitor the approaches to bridges and has experienced the of disruption under consideration following past earthquakes. A general approach to the monitoring system to detect the loss of integrity and connection of roadways to bridges suggests a "box edges" monitoring (See Figure 3-1). In this setup, multiple sensors would be placed in the approach area that work together as a small sensor "network" comprised of multiple individual sensor nodes.

The layout could include a minimum of one seismic system node deployed at each area of the roadway approach at each end of the bridge, or two at each bridge approach to cover both the left and right sides of the approaches for more redundancy. Optimization and prioritization are needed to determine the ideal number of seismic nodes to provide the level of information needed while considering economic feasibility. The proof-of-concept approach for creating a low-cost direct sensing system for seismic detection in the specific transportation application using off-the-shelf sensor components is described in the following sections.

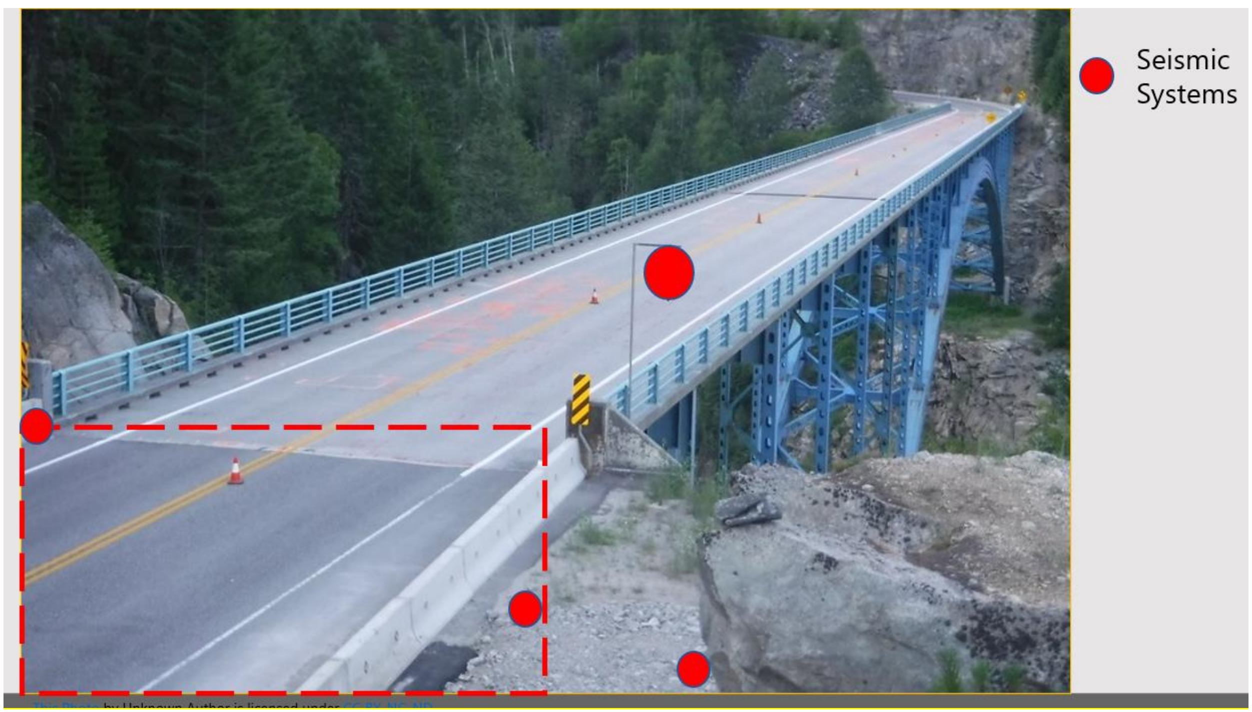



**Figure 3-1: Markup of potential direct sensing locations at bridge approach.**

## *3.1 Direct Seismic System*

Table 3-1 below provides the basic equipment list for the low-cost direct seismic system developed here.

**Table 3-1: Equipment list for low-cost sensor nodes**

| Sensor Components for TDOT Seismic Project | | | |
|---|---|---|---|
| | | | |
| **Costs for One Node** | **Amount** | **Tax** | **Total** |
| Rasberry Pis | $143.99 | $13.29 | $157.28 |
| JZK 4 x GY-521 MPU-6050 6DOF Module 3 axis Gyroscope 3 axis Accelerome | $7.35 | $0.68 | $8.03 |
| HDMI Cable | $5.94 | $0.55 | $6.49 |
| Moisture Sensor Kit | $8.98 | $0.83 | $9.81 |
| Vibration Sensor | $9.99 | $0.92 | $10.91 |
| Micro SD Card | $15.98 | $1.47 | $17.45 |
| Various Wires/Cables | $5.00 | $0.46 | $5.46 |
| Jumper Wires with Hooks | $9.99 | $0.92 | $10.91 |
| Housing and Electrical Tape | $7.50 | $0.69 | $8.19 |
| | | | |
| **TOTAL** | **$214.72** | **$19.82** | **$234.54** |

The cost of the prototype system is lower than the sensor systems presented in Chapter 2 for the basic components. For all systems presented as well as the current low-cost sensor node prototype, costs for the field housing setup, as well as connections to data and power must also be considered; however, these are site-specific, and comparisons are not easily made without real-world location and connectivity considerations. Assuming that the cost of maintenance and connections to power and communication networks are either negligible or consistent across systems and operational costs (i.e., the communications transmission for data) remain low, use of low-cost sensors to augment existing seismic measurements could prove promising for improving information about local bridge approach conditions remotely. The current prototype and some other sensor configurations have capabilities to utilize cellular modem, radio communications, Wi-Fi or hardwired communication systems to keep costs of data transfer minimal. Another consideration is data storage, which can be offset through licenses and various cloud-based or physical storage systems.

Additional costs may be involved in formatting and cleaning the data for analysis or for use by existing monitoring/warning systems. A rough comparison of the cost of some market systems with the direct sensing system proposed here is shown in Table 3-2 below,

**Table 3-2: Cost Analysis**

**Comparing Third-Party Systems Cost to DS-Quake System**

*DS-Quake is the name being used for the direct sensing low-cost seismic system proposed

| Provider System | Details | Cost | DS-Quake-Cost | 1:1 Comparison | How many DS-Quake System can be bought with Third-Party System Invetment Value? ** |
|---|---|---|---|---|---|
| SmartSolo | IMU-3C data logger | $400-$500 | **$235.00** | 400/235= 1.7 | 2 approaches to bridges instead of 1 |
| | IGU-16HR 3C 5Hz | $1,000-$4,000 | **$235.00** | 1000/235= 4.3 | 4 approaches to bridges instead of 1 |
| Canary Systems | MultiLogger® Suite | $3,000.00 | **$235.00** | 3000/235= 12.8 | 13 approaches to bridges instead of 1 |
| | MLDAQ acquisition station | Starts at $6,000 | **$235.00** | 6000/235= 25.5 | 25 approaches to bridges instead of 1 |

*** Assuming the systems were equally comparable, excluding cost of operations and maintenance.*

The economy of this system is quite promising. Creating a new, low-cost seismic detection system in a reliable, industrial, Internet of Things (IoT) approach which would enable a broad deployment and dense footprint depends on a successful working system. In the following, the details related to the development and testing of such a system is described.

## 3.2 Low-Cost Sensor Node Development

Several technical aspects were considered when developing a sensor system which met all the project objectives. In determining necessary components, the ability to collect highly accurate and reliable data was prioritized. Additionally, much effort was made to meet goals of low cost and modularity for the final product. With the intended purpose of the constructed sensor apparatus to be field testing, further considerations of size, portability, and durability were made.

### Microcontrollers

The constructed electronic system required an ability to collect inputted sensor data and store said information in a centralized, digital location. While a standard computer could fulfill the purpose of an electronic data hub, the intended data collection and storage would likely have minimal processing requirements; therefore, the usage of a computer was considered excessive and unnecessary. As an alternative, microcontrollers, or simple integrated circuits with high functionality and flexibility, were analyzed for their ability to meet all the project requirements.

Microcontrollers present several strengths which fit the requirements of the project, such as their sensing capabilities and data processing. Microcontrollers can be equipped with a variety of sensors that can measure various physical quantities, making it well suited for extracting highly precise and real-time data from external sources. Additionally, microcontrollers can be used to control various devices and systems based on the data it receives from its sensors. This can be incredibly useful when creating an integrated system of sensors and instrumentation. Microcontrollers also are generally smaller and less expensive than traditional computers, making it a more cost-effective and space-efficient choice.

### Raspberry Pi

Ultimately, a Raspberry Pi microcontroller was determined to be the best suited for this project. Specifically, the Raspberry Pi 3 microcontroller was ultimately selected for a variety of reasons. Its highly customizable nature allows users to add a variety of sensors and other hardware to it, making it well-suited for projects that require a high degree of customization. Additionally, the Raspberry Pi is relatively inexpensive compared to other microcontrollers, making it a cost-effective choice and increases the ability for the construction of multiple arrays. Compact and lightweight, the Raspberry Pi makes it easy to transport in a field setting, and its low power consumption provides usage in locations where access to power may be limited. A popular consumer device, the Raspberry Pi is also relatively easy to set up and use, even for people with limited technical experience. However, most importantly, the Raspberry Pi has a wide range of connectivity options, allowing it to easily interface with a variety of sensors and provide real-time data. For all these reasons, this model of microcontroller was determined to be the best suited to meet the needs of the intended sensor system.

### Sensor Modules

As previously mentioned, the Raspberry Pi 3 microcontroller allows for the connection of a variety of sensor modules through its General Purpose Input/Output, or GPIO ports.

These sensors can be connected through the usage of basic jump wires and connector pins, drawing power from the Raspberry Pi, and providing data from the external environment back to the microcontroller's central processing unit. An analysis was completed to determine what sensors were necessary to provide sufficient data on soil liquefaction, and ultimately four sensor modules were implemented. These were the MPU-6050 accelerometer, SW-420 NC vibration sensor, Raspberry Pi Camera Module 2, and the Kuman 5PCS Soil Moisture Sensor.

### *MPU-6050 Accelerometer*

Because soil liquefaction concerns the overall movement of the earth during seismic events, it was determined that understanding the forces applied on the soil would be vital to analyzing test conditions. To derive this information, the MPU-6050 sensor module was selected for this project (Figure 3-2).

The MPU 6050 is a microelectromechanical systems (MEMS) device that combines a 3-axis accelerometer and a 3-axis gyroscope into a single package. This makes it ideal for use in a project such as this, as it can provide accurate measurements of both linear and angular motion. Additionally, it is small, has low power requirements, and can be easily integrated with a Raspberry Pi, requiring only two pins for connection to the microcontroller. The accelerometer is capable of detecting changes in acceleration in the range of +/- 16g, while the gyroscope can detect rotational motion in the range of +/- 2000 degrees per second. This makes the MPU-6050 ideal for applications that require precise measurements of movement, and particularly well suited to record data in the intended testing scenarios of this project. In addition to its high-precision sensors, it also includes a built-in digital motion processor (DMP) that can be used to process the raw data and provide even more accurate measurements. The DMP can be used to perform tasks such as sensor fusion, which combines the data from the accelerometer and gyroscope to provide a more accurate estimate of the device's orientation. Overall, the MPU-6050 is a very powerful and versatile device that makes it appropriate for this application.

**Figure 3-2: JZK 4 x GY-521 MPU-6050 6DOF Module 3 axis Gyroscope 3 axis Accelerometer**

### *Raspberry Pi Camera Module 2*

Because the final product is intended to study real-world soil liquefaction at bridge abutments, it was helpful to also present visual data to improve comparative analysis. Therefore, it was necessary to find a way to collect photographic or videographic recordings of the soil when undergoing seismic activity. Conveniently, the Raspberry Pi Camera Module 2 is a product specifically developed for integration with the base microcontroller and can capture both high resolution photo and video recordings. As a result, this module was selected for usage on the project's sensor array; however, for application it would be unnecessary for the module to record during periods of no relevant seismic activity. Therefore, by utilizing the Raspberry Pi's aforementioned ability to integrate with other sensors, a more effective system was developed for this project by connecting the camera to the two sensor modules to be discussed.

### *SW-420 NC Vibration Sensor*

Ideally, the camera module is activated when specific triggers in the external environment are met, consequently leading to relevant sensors providing an input signal to the Raspberry Pi. With seismic activity the source of soil liquefaction, it stands to reason that vibration and movement can be used as a valid trigger. Therefore, the SW-420 NC vibration sensor module was one of two sensors that was integrated with the camera. The module is a simple device that can be used to detect vibrations in a variety of applications and is commonly used in security systems, toys, and other devices that require the ability to detect motion or vibrations. The sensor uses a built-in piezoelectric sensor to detect vibrations, and the output signal is sent to a digital pin on a microcontroller. This allows users to easily monitor vibrations and trigger events based on the sensor's readings. One of the key features of the SW-420 NC vibration sensor is its ability to provide reliable and accurate readings. The sensor is sensitive enough to detect even small vibrations, and it has a wide detection range. The output signal is also stable and consistent, making it easy to interpret and use in a variety of projects. For this project, the vibration sensor was set up to provide a signal to the Raspberry Pi when certain thresholds of vibration were met. Once this signal was detected, the Raspberry Pi would activate the camera, allowing for visual recording of the soil movement.

**Figure 3-3: WINGONEER 5Pcs SW-420 NC Type Vibration Sensor Module Vibration Switch for Arduino Smart Car**

*Kuman 5PC Moisture Sensor*

In addition to vibration of the soil, liquid saturation of the soil was another form of data which was determined to be potentially useful in analysis. Traditionally, the Kuman 5PC Moisture sensor (Figure 3-4) is a component used for measurement of soil water levels in garden settings. However, for the purpose of this experiment, it can be used to detect increased levels of water saturation in the ground. This data can be helpful to build a comprehensive understanding of the soil conditions during certain events and in the determination of whether seismic induced soil liquefaction occurred.

The sensor itself consists of two parts, one which is a two-pronged component which is inserted directly into the ground. The other component consists of a small LED, potentiometer, and signal connectors to the microcontroller. The potentiometer can be adjusted with a small screwdriver and sets the level of moisture for activation. When the pronged component measures moisture level exceeding the activation level, the LED lights up and produces an output signal for the microcontroller to read. In a similar manner to the vibration sensor, this output signal provided a trigger to activate the camera module.

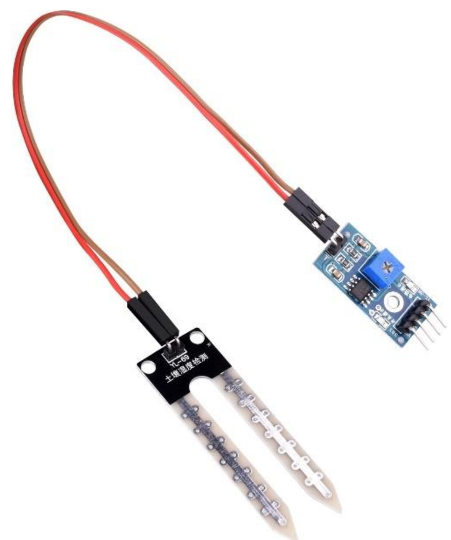


**Figure 3-4: Kuman 5PCS Soil Moisture Sensor**

## 3.3 Setup of the Integrated Sensor Node

As previously discussed, a Raspberry Pi 3 was used as the central hub of the sensor array. The microcontroller was set up from completely brand-new factory settings, along with a 64 GB microSD card for optimal storage capabilities. Once booted up and prepared for usage, the Raspberry Pi was interfaced with all four of the aforementioned sensors. Using a ribbon wire, the camera module was connected to a designated port on the microcontroller. The other sensors were connected to the Raspberry Pi using basic electrical wires and a breadboard. Utilizing the built in I2C signal, ground, and power ports, the sensors were easily interfaced with the microcontroller. Once connected, the Pi was programmed with specific goals in mind to most effectively gather data during testing. In order to activate the code and begin data recording, the Raspberry Pi had to be turned on and connected to an external monitor.

Instructions for construction of the sensor array and the code used on the Raspberry Pi can be found in the Appendix.

Given the strengths of each sensor component, along with their abilities to be integrated with other instruments, a fully linked system of sensors was developed. The SW-420 NC vibration sensor was coded to provide an output signal back to the Raspberry Pi whenever a specific level of movement was detected. The moisture sensor, likewise, was set up to provide an output signal when the soil moisture threshold was met. Whenever either of these signals were read by the microcontroller, the camera module was then activated. At activation, a photo was taken, followed immediately by a short video recording. The duration of the video recording was adjustable, and the file was stored on the Pi immediately after terminating recording. The accelerometer began recording gyroscopic and acceleration data in all three planes at the moment of activation of the code; the Raspberry Pi collected all six of those data points, on a consistent interval that could be adjusted. This completed sensor array was constructed such that it was easily replicable, and additional systems were constructed following the same model.

# Chapter 4 Proof of Concept – Laboratory Testing

## 4.1 Testing Equipment

The experimental facilities at the University of Alabama's (UA) Large Scale Structures Laboratory (LSSL) were utilized to conduct the experimental tests of the sensors. The state-of-the-art LSSL is designed and fully equipped for performing full-scale structural component testing under dynamic loading conditions including an advanced control system and a full suite of large-capacity MTS hydraulic actuators. A dynamic actuator of 110-kip capacity was used in this sensor study with instrument variables described in Table 4-1.

**Table 4-1: Summary of testing equipment parameters.**

| Load Capacity | Stroke | Characteristics | Over-head Dimensions | Interior Depth |
|---|---|---|---|---|
| 110 kip | ±10 inch | Dynamic | 26 in x 19.5 in | 14 inches |

## 4.2 Testing Setup

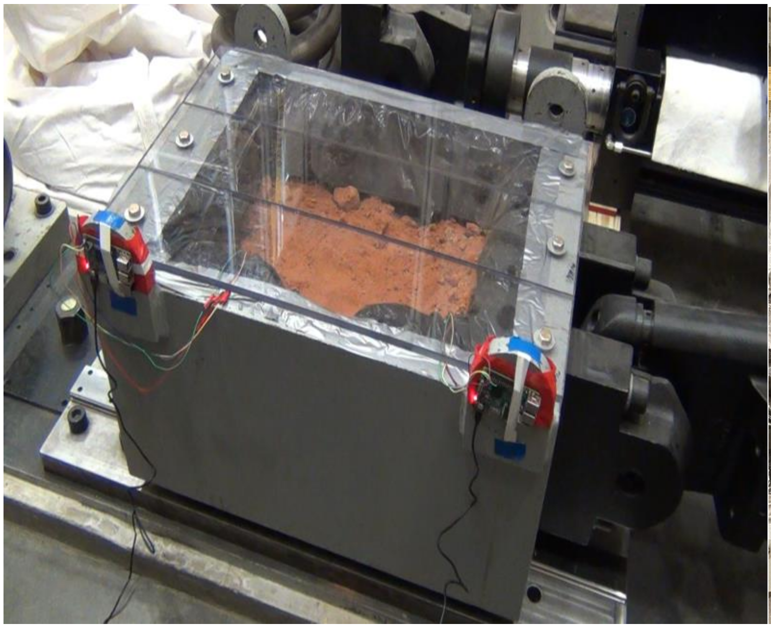
The dynamic actuator was attached to a box filled to a depth of about 10 inches with a red clayey sand, and the sensors were placed in the soil at varying depths. Sensor 1 was placed 5.75 inches from the bottom of the actuator, and Sensor 2 was placed 1.75 inches from the bottom of the box. Both sensors were fully immersed in the soil and able to move with the soil during the tests. The sensors were attached to two separate Raspberry Pi microcontroller boards, which were taped with electrical tape to the outside of the actuator. The microcontroller boards were connected to a power source as well as a functioning monitor, keyboard, and mouse that were placed next to the actuator and microcontroller boards for fast and easy access to the sensors/data. There was also a plastic liner placed between the actuator and the soil and clear plastic covering the top of the actuator so that no soil was lost during testing. A camcorder was set up on a desk next to the actuator for video. All sensor components and test setup are shown in Figure 4-1.

## 4.3 Testing Procedure

### *Scaling earthquake data*

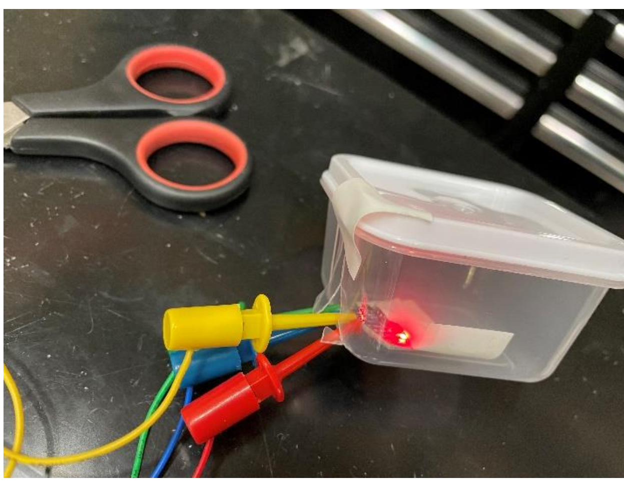
Ground records used in this study was collected at Fire Station No. 2494 in Paris, TN collected by USGS during the Bellmont, IL Earthquake of 18 April 2008, magnitude 5.2 (Figure 4-2). The ground records were downloaded from USGS website including displacement, velocity, and acceleration in *x, y,* and *z* directions. The ground motions were scaled to different peak ground accelerations 0.1g, 0.2g, 0.4g, 0.6g and 0.8g before feeding into actuators. Since the actuator was used under displacement control, the ground displacement in *y* direction (largest peak ground acceleration component) was used during the tests. To make sure the input ground displacement can simulate the ground acceleration at desired levels, the second derivative versus time of scaled input ground displacement was calculated and compared with scaled data of ground acceleration. Figure 4-3 shows the scaled ground displacement results the same ground acceleration data scaled at peak acceleration of 0.8g.

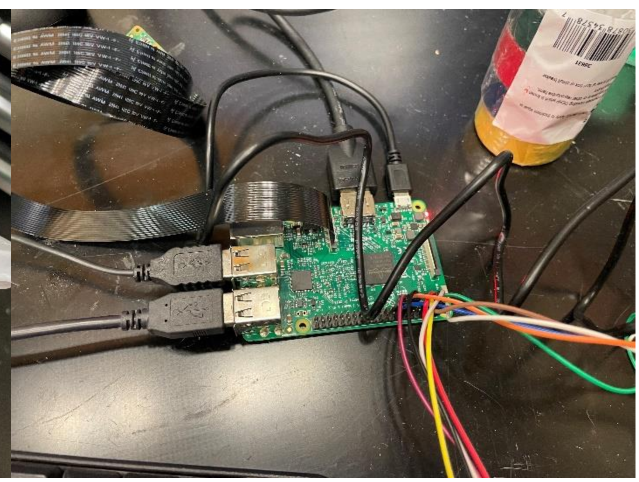
The comparison shows that scaled ground acceleration calculated from scaled displacement is the same as ground acceleration scaled from the earthquake ground records. This means that scaled ground displacements can be used to simulate the scaled ground acceleration.



a) Clay sand box

b) Sensors before soil cover





c) Plastic box for protection

d) Raspberry Pi microcontroller boards

**Figure 4-1: Laboratory Testing Setup**

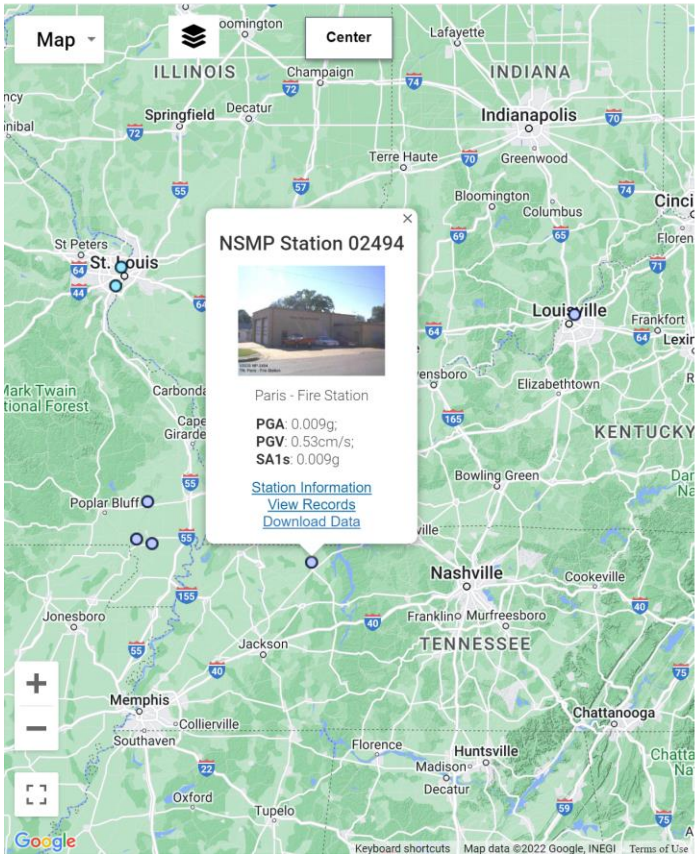



**Figure 4-2: Location of earthquake record used for study**

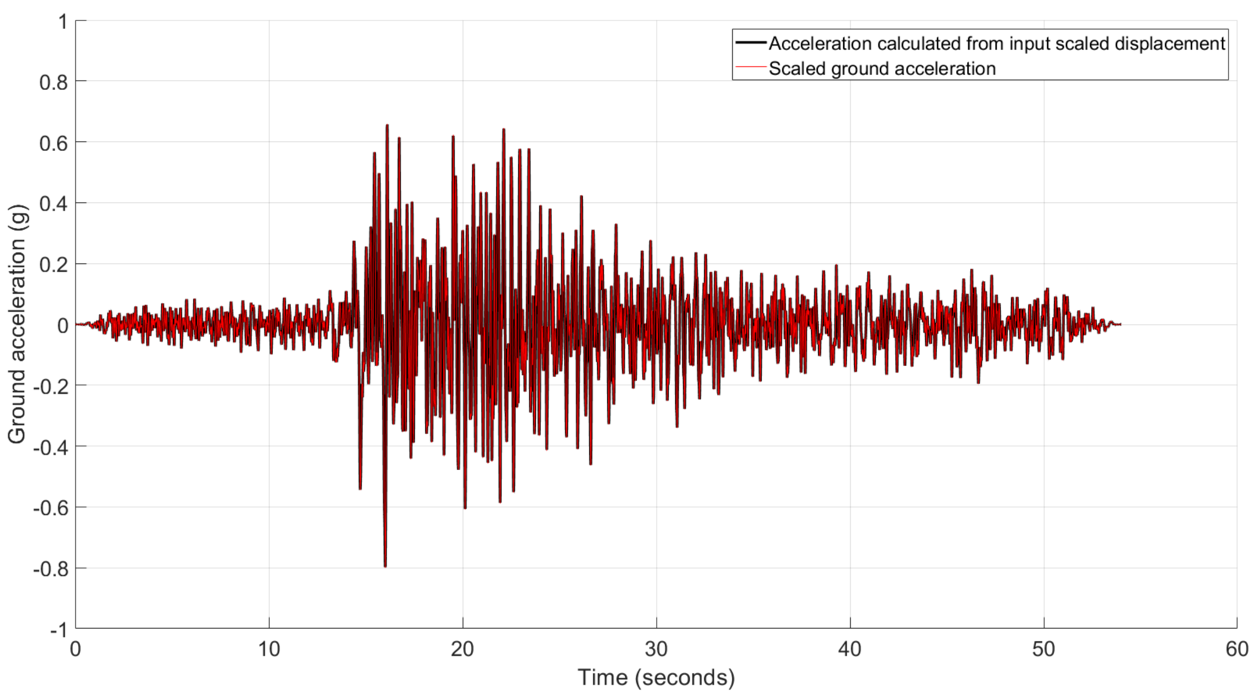



**Figure 4-3: Comparison of scaled acceleration from scaled displacement versus scaled acceleration**

## Checking actuator performance

To make sure that the actuator successfully simulated the ground motion, the actuator feedbacks were recorded during the tests and compared with the input displacements. Figure 4-4 shows the comparison between command and feedback during the test for ground acceleration of 0.8g. The comparison shows that the actuator successfully simulated the ground motion during the tests as the displacement command and displacement feedback overlap each other for the entire records.

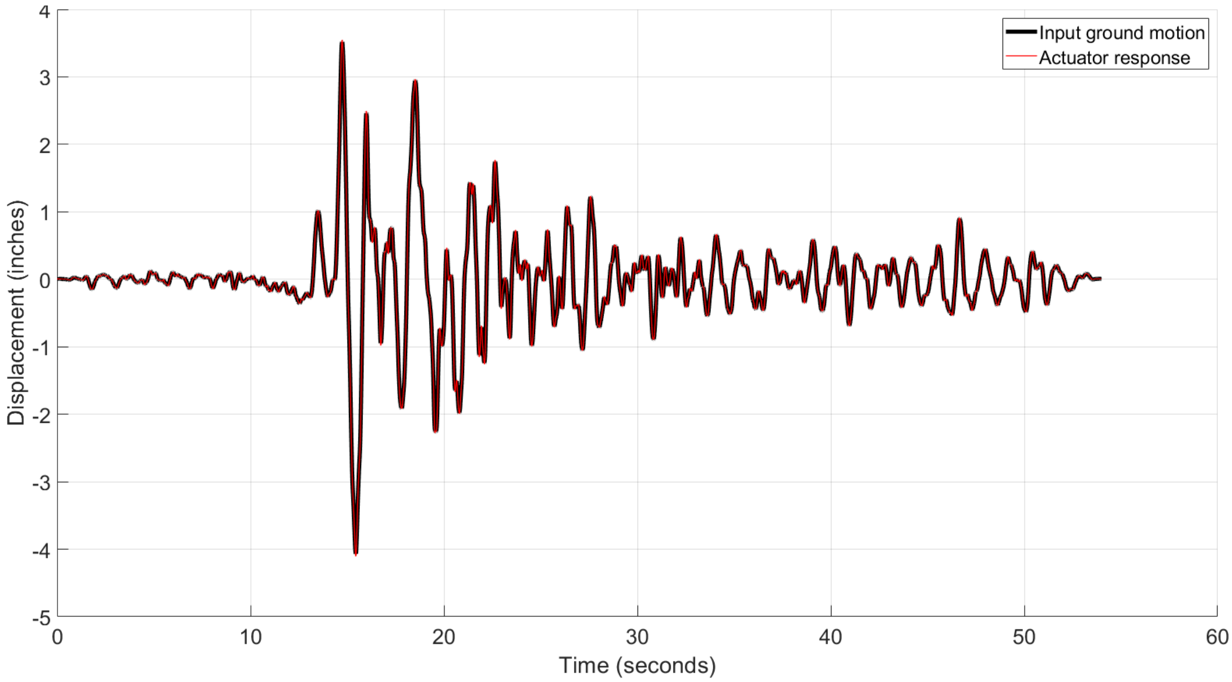



**Figure 4-4: Actuator command versus actuator feedback**

## Checking sensor accuracy

To check the sensor accuracy, a series of sinewaves of magnitude 0.5 inches with different frequencies was used as input command during the tests. The input sinewave started with 0.5Hz with increment of 0.5Hz for every 5 seconds of the test until the frequency reach 4Hz making total of 8 frequencies were included during the tests. The displacement input can be written by equation:

$$x(t) = 0.5\sin(2\pi ft)\,(in.)$$

where x(t) represents the displacement at a given time (t) and f is the frequency, and t is the time. The acceleration can be calculated as:

$$a(t) = -0.5(2\pi f)^2\sin(2\pi ft)\,(in./s^2)$$

Acceleration at a given time [a(t)] is calculated as a function of frequency (f) and time (t). These are common harmonic displacement and acceleration formulas. Ultimately the displacement and acceleration are dependent on time and frequency and follow a sine wave pattern because the motion is repetitive and can damper out.

Table 4-1 shows the calculated acceleration magnitudes for different input frequencies of the displacement sinewave with magnitude of 0.5 in, $a_{max} = 0.5(2\pi f)^2\ (in./s^2)$.

The two sensor nodes described earlier were tested and data collected from the frequency test of the two sensors are plotted in Figure 4-5. It has been observed in Figure 4-5 that both sensors were able to capture well the acceleration in the frequency range. When the frequency reach to 3.0Hz or higher, due to the vibration of the sensor attachments, there were some differences between calculated magnitudes and real data. In addition to frequency test, the sensors were also tested with the earthquake ground motion records scaled at 0.8g acceleration. Figure 4-6 shows the comparison of the data captured by each sensor and ground accelerations simulated by the actuator. The data in Figure 4-6 also show that the sensor data fits well with the simulated ground acceleration.

After the performance of actuators and the accuracy of the sensor had been checked, the sensors were embedded in soil box to measure the soil acceleration under the earthquake motion simulation of the soil box. The earthquake record was scaled at peak ground acceleration of 0.1g, 0.2g, 0.4g, 0.6g, and 0.8g before each test. The data collected from each test was plotted in Figures 4-7 to 4-16 for different representations. The data plot in Figures 4-7 to 4-16 is not necessary to be the same as scaled ground acceleration due to the movement of soil in the box. Also, since the sensors were installed at different locations in the soil, the data of the two sensors should be different due to shear deformation in soil. At the beginning, the *y* directions of the sensors are pointed with actuator axis. However, during the test, the movement of the soil shift the sensor directions, and sensor's *y* axes are no longer parallel to the actuator loading direction, but sensor's *y* axes were still the major loading direction. The *x* axis of the sensors was initially parallel to the ground while *z* axis was pointed in vertical direction. The data in Figures 4-7 to 4-16 show that accelerations in *x* and *z* are significant, but much smaller than acceleration picked up in *y* direction.

It should be noticed that noise in sensor data was filtered before the data was plotted. Sensor 1 was filtered with 20Hz noised and Sensor 2 was filtered with 16Hz noised using moving average filtered. Further study of how the noise affects sensor measurement should be conducted before deploying sensors to sites.

**Table** Error! Use the Home tab to apply 0 to the text that you want to appear here.**4-2: Maximum accelerations at different frequencies for 0.5 in sinewave**

| Frequencies $f$ | 0.5Hz | 1.0Hz | 1.5Hz | 2.0Hz | 2.5Hz | 3.0Hz | 3.5Hz | 4.0Hz |
|---|---|---|---|---|---|---|---|---|
| $a_{max}$ | 0.0128g | 0.0511g | 0.1150g | 0.2044g | 0.3194g | 0.04600g | 0.06261g | 0.8177g |

## 4.4 Summary of Laboratory Test Results

While the sensor noise needs to be removed for the sensor to work more effectively, it is still capable of sensing ground motion through capturing the acceleration. In the field, it could be used to pick up seismic activity and could give a close idea of the magnitude of such activity if it is properly scaled.

The frequency tests and 0.8g earthquake simulation with the sensor attached to the wall shows that the sensor can detect earthquake-like movements very well with little error.

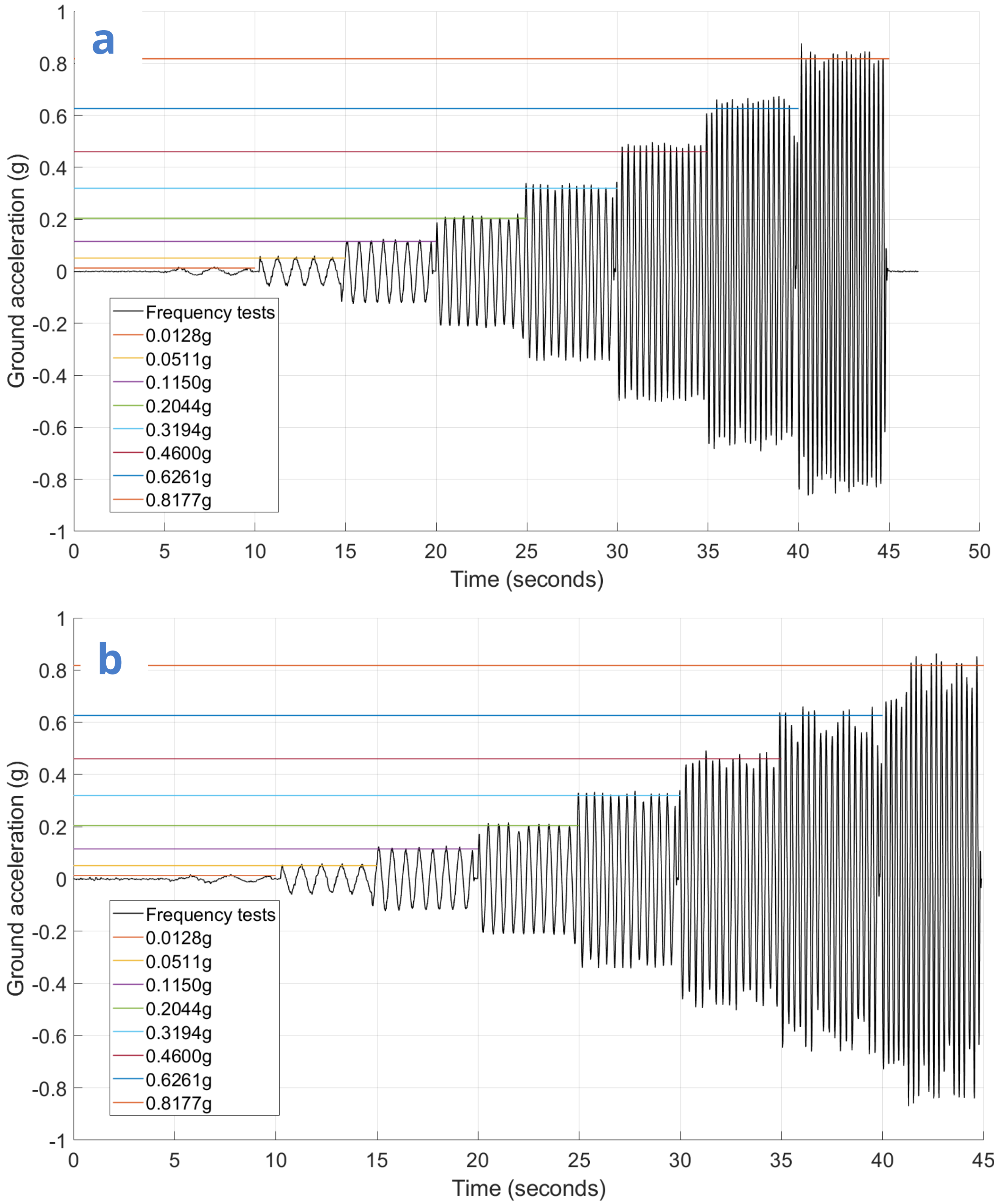



**Figure 4-5: Sensor frequency test data: (a) Sensor 1 data and (b) Sensor 2 data.**

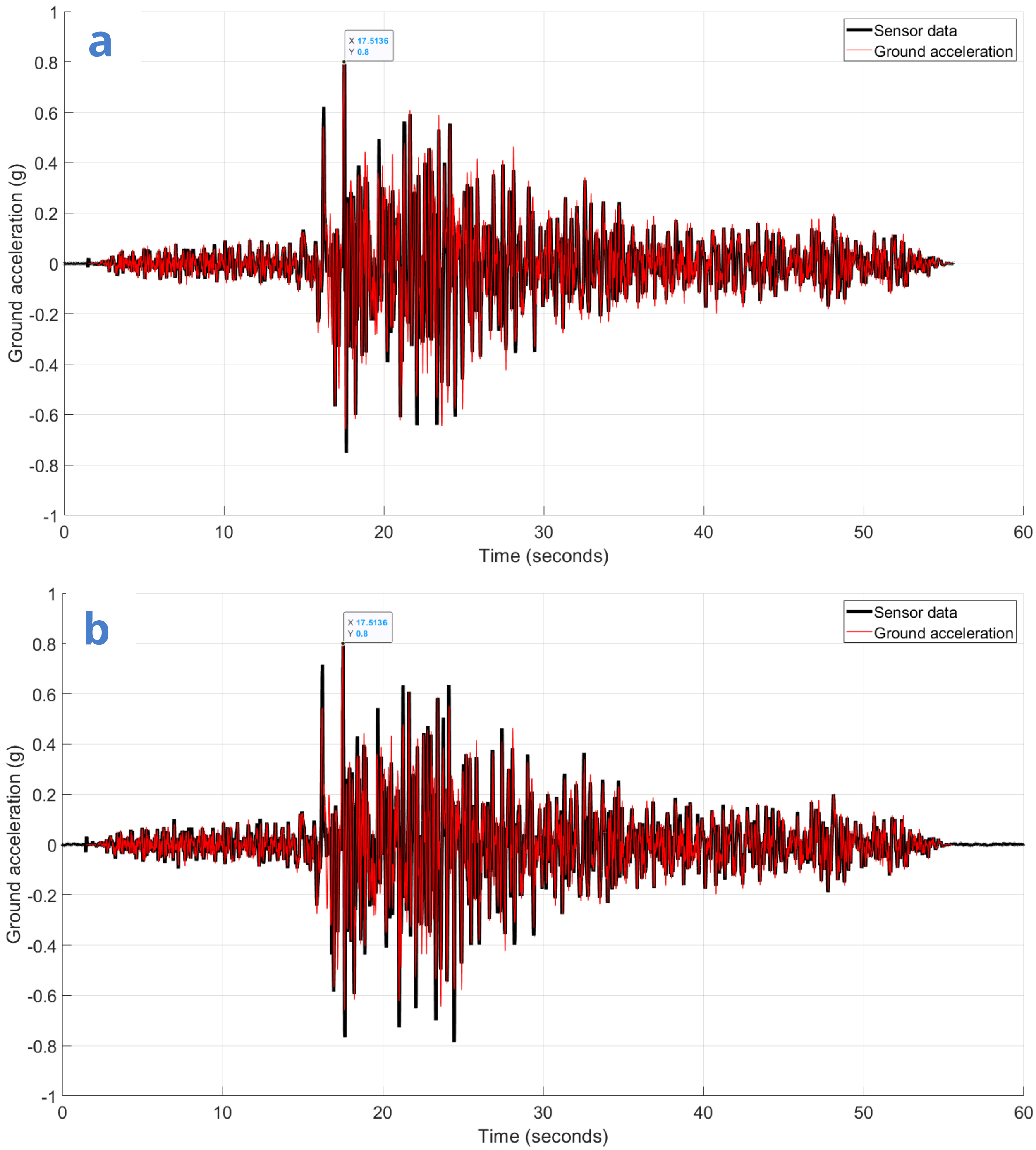



**Figure 4-6: Sensor versus earthquake ground acceleration input: (a) Sensor 1 data and (b) Sensor 2 data.**

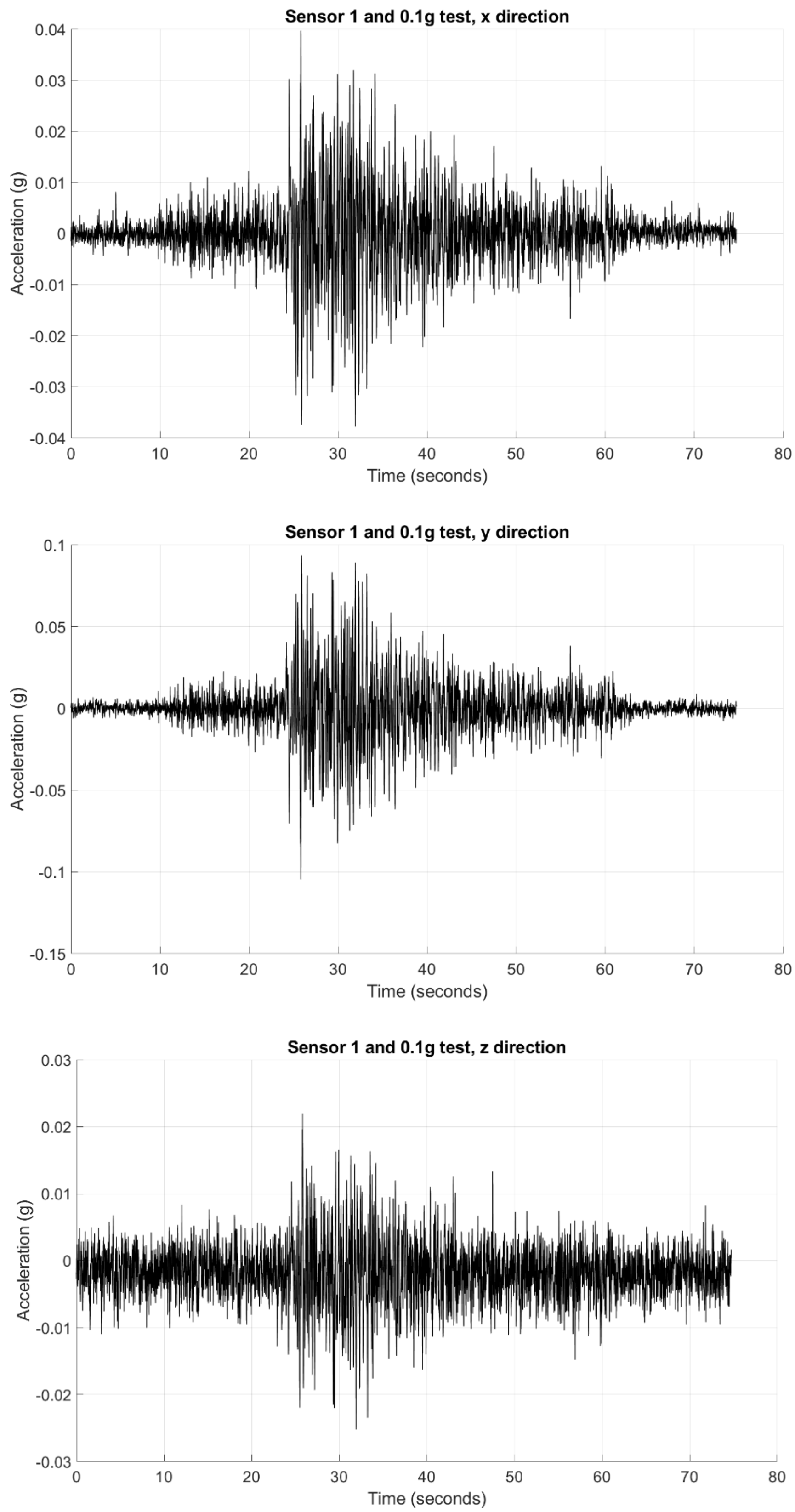



**Figure 4-7: Scaled earthquake test with Sensor 1 embedded in soil, 0.1g scale.**

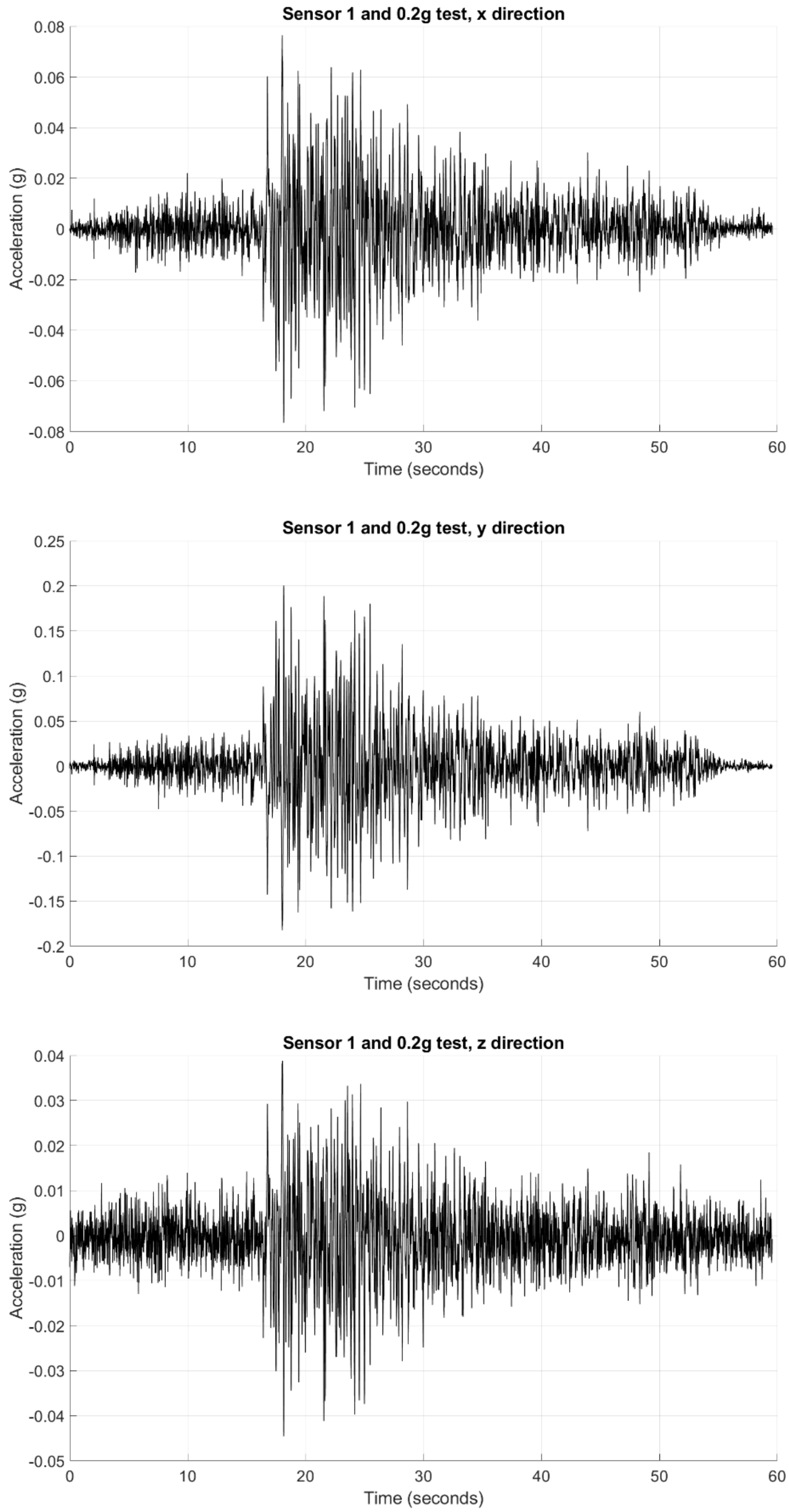



**Figure 4-8: Scaled earthquake test with Sensor 1 embedded in soil, 0.2 g scale.**

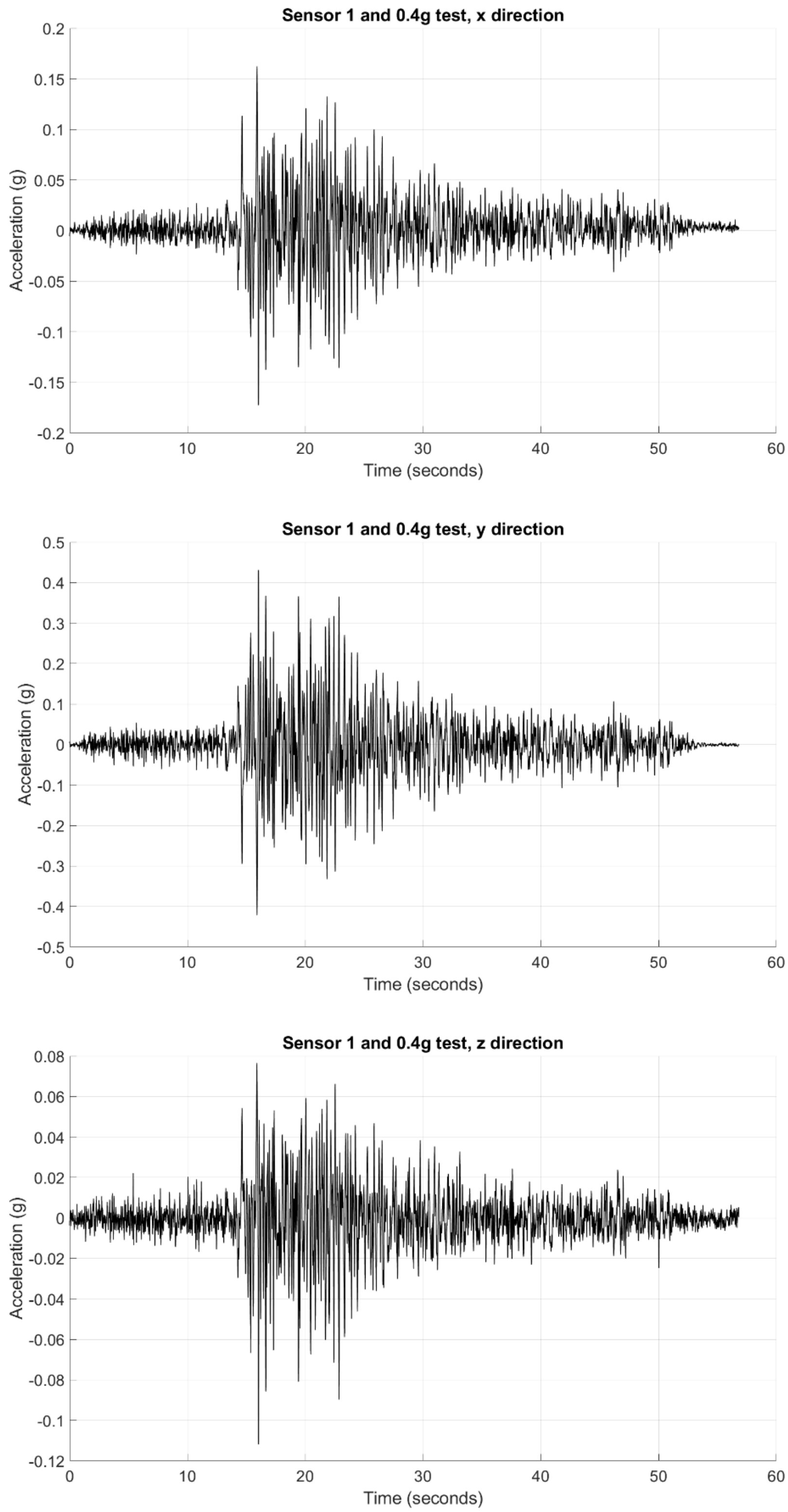



**Figure 4-9: Scaled earthquake test with Sensor 1 embedded in soil, 0.4g scale.**

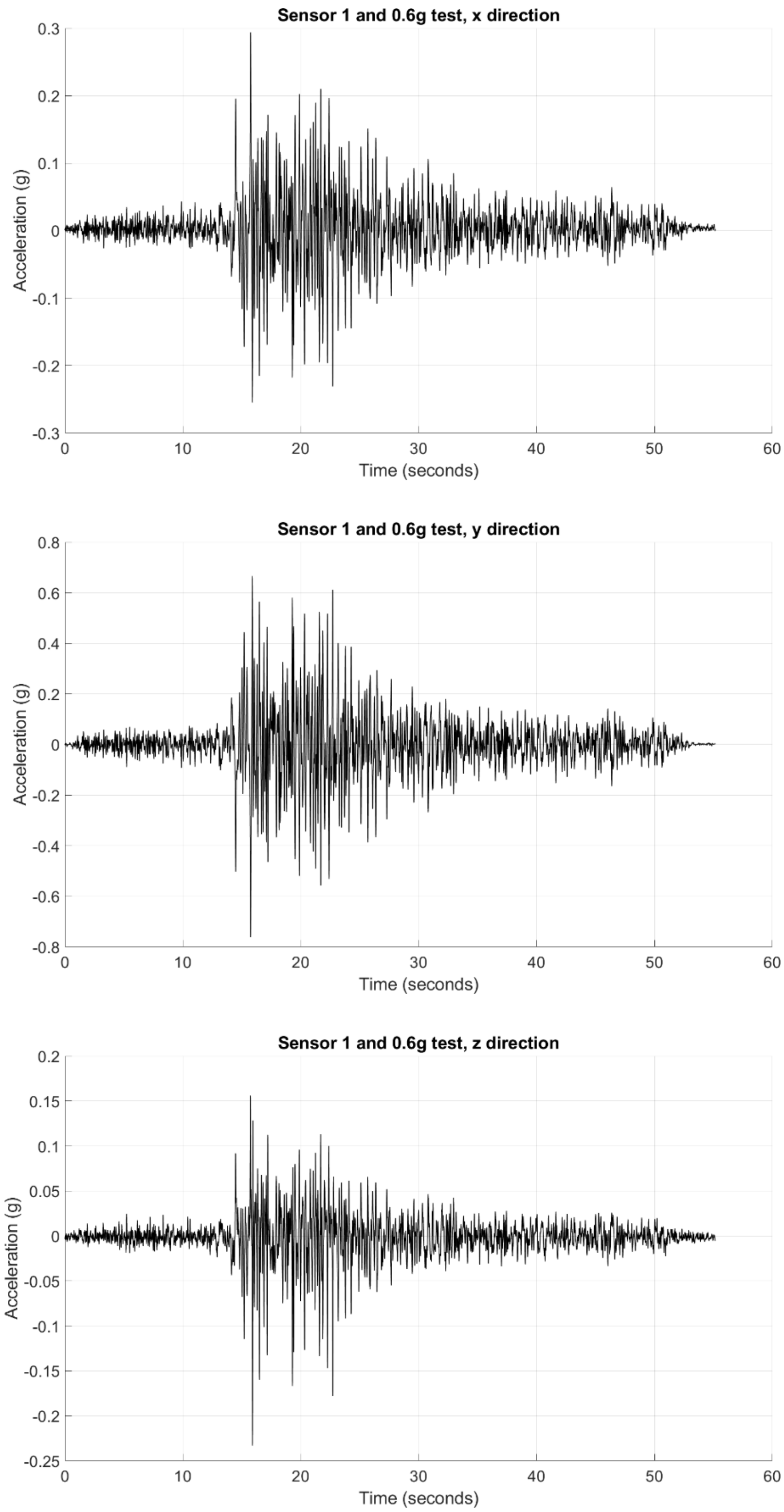



**Figure 4-10: Scaled earthquake test with Sensor 1 embedded in soil, 0.6g scale.**

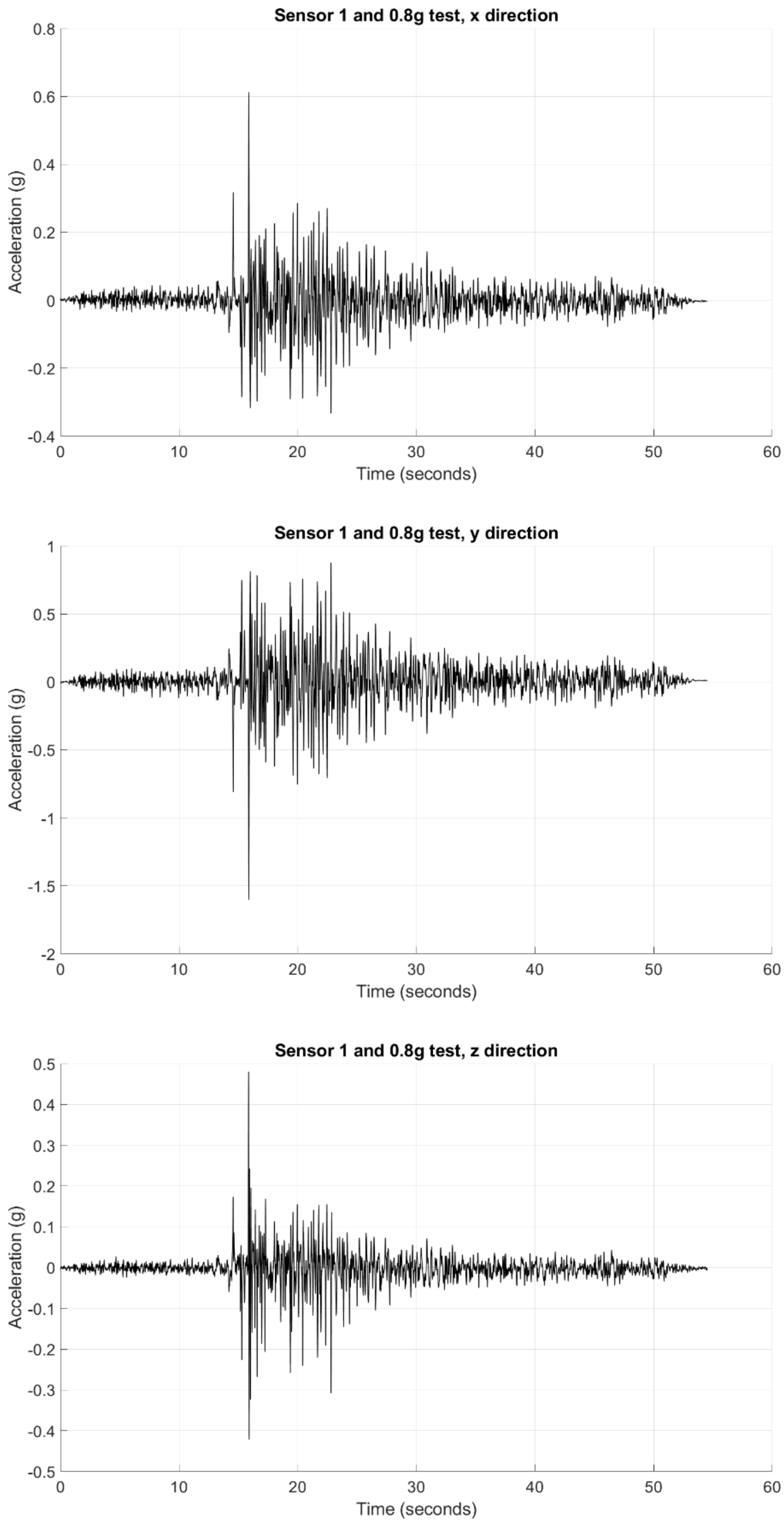



**Figure 4-11: Scaled earthquake test with Sensor 1 embedded in soil, 0.8g scale.**

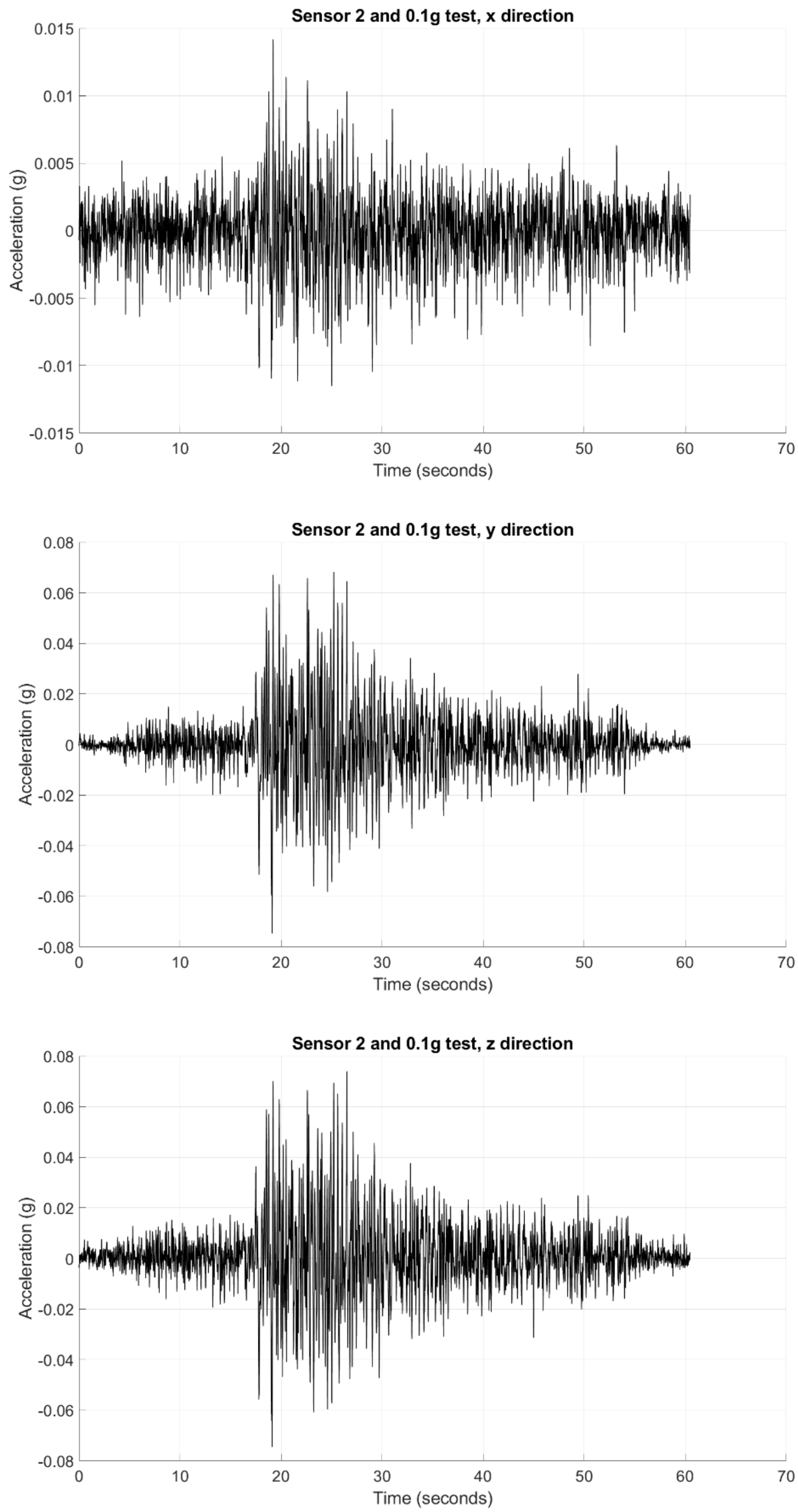



**Figure 4-12: Scaled earthquake test with Sensor 2 embedded in soil, 0.1g scale.**

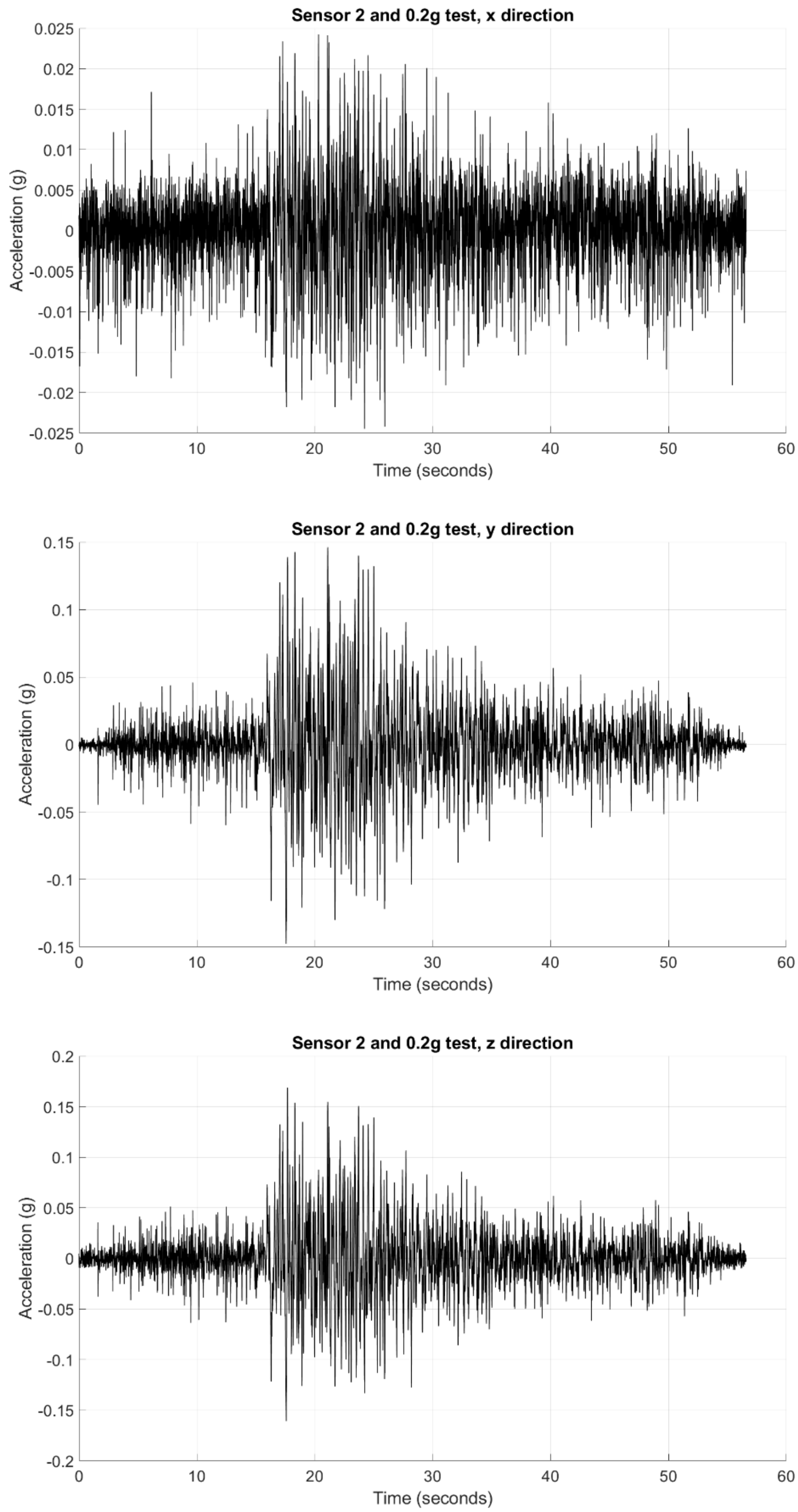



**Figure 4-13: Scaled earthquake test with Sensor 2 embedded in soil, 0.2g scale.**

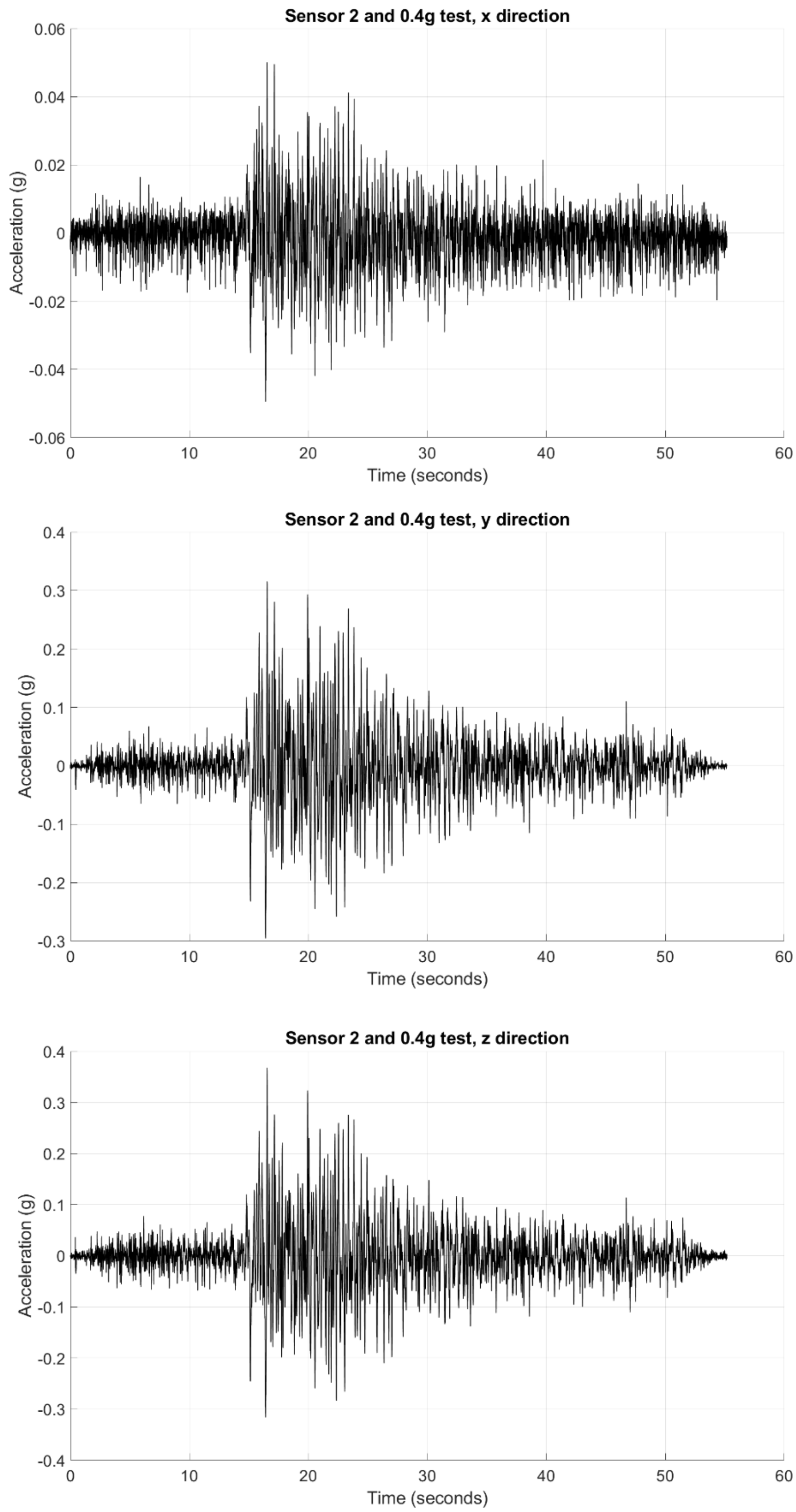



**Figure 4-14: Scaled earthquake test with Sensor 2 embedded in soil, 0.4g scale.**

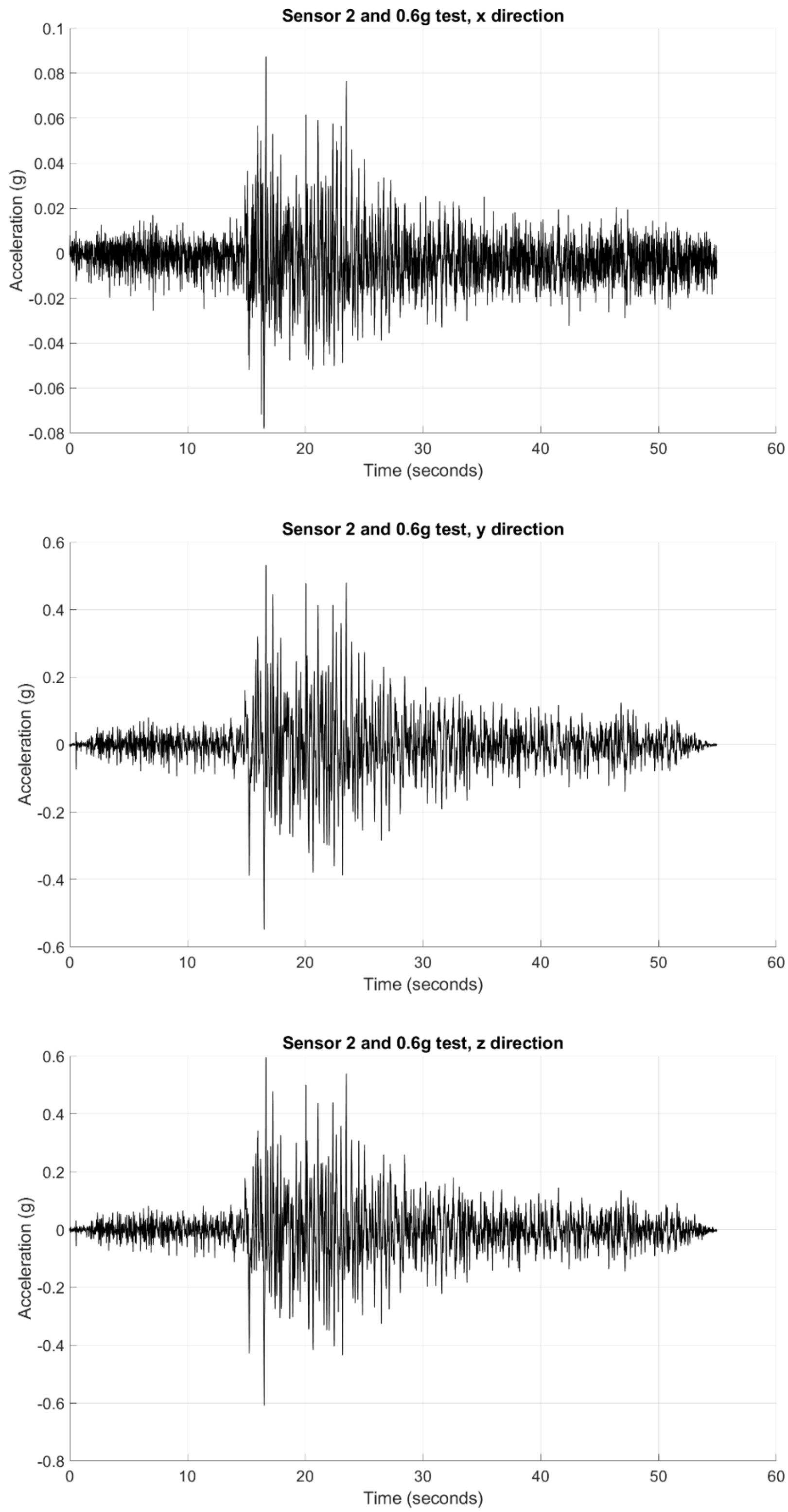



**Figure 4-15: Scaled earthquake test with Sensor 2 embedded in soil, 0.6g scale.**

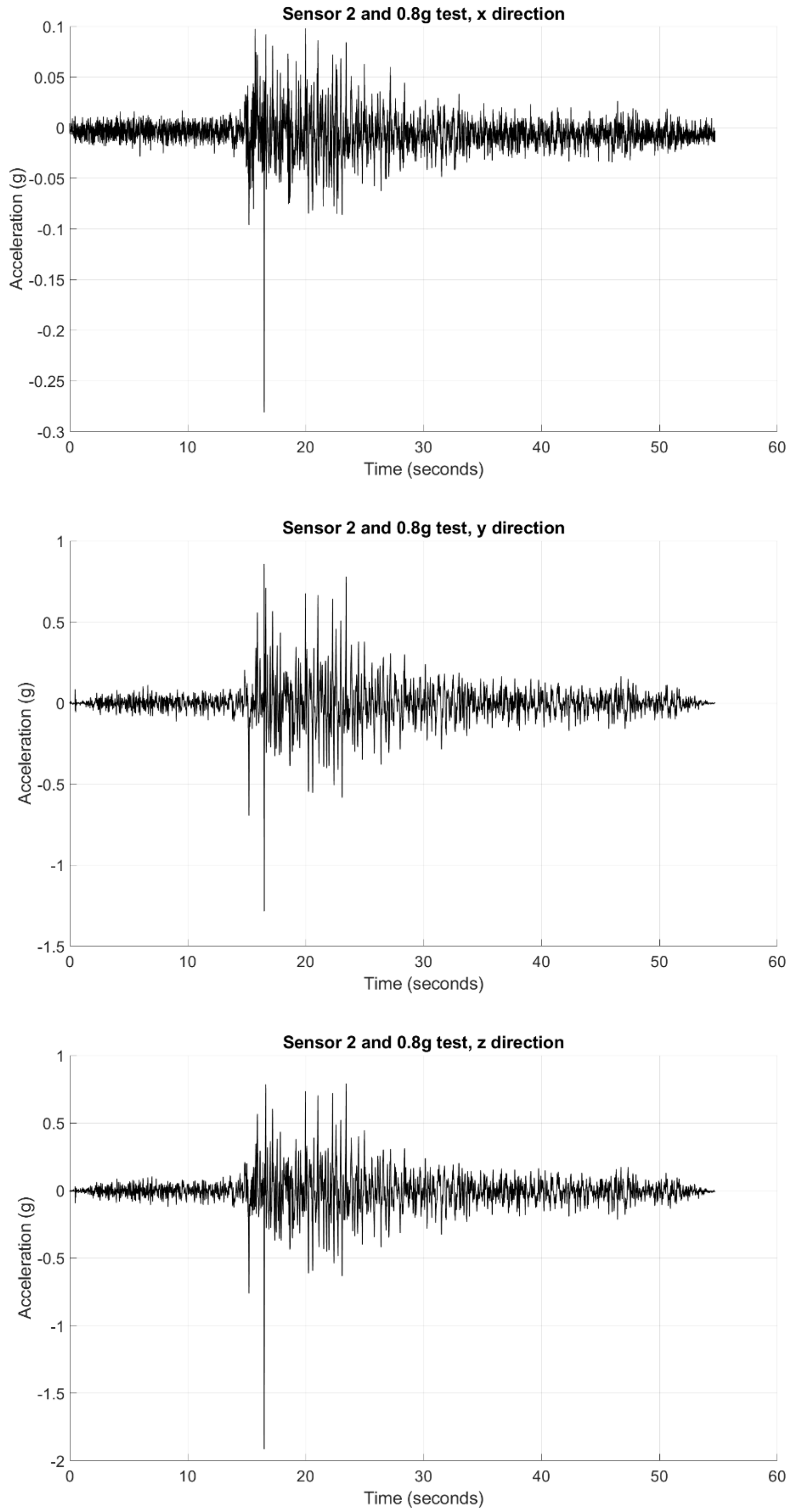



**Figure 4-16: Scaled earthquake test with Sensor 2 embedded in soil, 0.8g scale.**

# Chapter 5 Recommendations for Field Testing

Based upon the lessons learned in the laboratory testing and examination of best practices for other direct sensing, low-cost node usages, the following recommendations are made regarding the future development and field testing of the sensor node.

Since creating earthquake-like conditions in the field would be nearly impossible, it is recommended that field testing take place near construction sites with blasting and/or use of moving heavy equipment to create some ground vibrations that could be detected by the sensors.

## 5.1 Equipment Housing for Field Testing and Deployment

During testing, small off-the-shelf plastic boxes were used to contain and protect the sensor modules because the sensors were embedded in the soil. While adequate for protecting the sensors for a short duration laboratory testing and no exposure to weather and or vandalism or other potential disruptions, it is highly recommended in the case of long-term field testing that durable and fitted housing of the equipment should be implemented. Custom-made housing specifically designed for the dimensions of each sensor node would reduce chances of soil impacting the sensors, shifting of the sensor position, or losing connection from the microcontroller. 3D printing these components would likely provide a cost efficient, sufficiently study, and form-fitting solution to contain and protect the sensors with rubber gaskets or similar used to create a seal.

The project team investigated off-the-shelf housing for sensors, but most options were not weather-proof or sized appropriately. By using small housing for the sensor node, the sensor is more likely to replicate the surrounding movements and conditions. Using a large housing box may not move as freely in the soil and may dampen the localized movements that are detected by the sensors creating an inaccurate reading at the site.

One consideration is to use a small section of PVC pipe embedded in the soil with one fully sealed end and the other allowing a small opening for the wires (see Figure 5-1), which could then be connected to a post with power and communication connections. Electrical tape or other weather-proof tape could be used to seal the wires in the pipe. Another consideration is to design and use a 3D printer to create appropriately sized custom housing using rubber gaskets or other means to ensure it is weatherproof.


**Figure 5-1: PVC pipe example for housing of sensors. (Source: Autodesk Instructables)**

The Raspberry Pi and connections for power and communications could be housed in a separate, weather-tight housing container, many of which are readily available for low cost, similar to a utility box. This could be mounted on a signpost or utility pole for easy access to collect a microUSB chip, etc. if needed should communication lines be interrupted in a disaster.

It is recommended that each location for field deployment have several sensor nodes that could connect with wires run underground to one Raspberry Pi as a mini network. Having two or more nodes at one field site would provide redundancy in the data being collected as well as an ability to look at movement relative to one another. Including a global positioning system (GPS) location sensor may be beneficial for each mini network for identification and tracking. Most inexpensive GPS sensors are not capable of providing sub-meter accuracy in location; therefore, the GPS would not be useful for measuring a shift in the soils at the site.

Furthermore, the sensors need to be buried below the ground surface at a depth more than a few inches and soil compacted and marked for retrieval if needed. During laboratory testing, the sensor boxes were not deeply buried in the soil due to the depth of the testing box and the boxes would move to the surface during the shaking. To prevent unearthing of the sensor nodes, it is recommended that they be buried more than 1 ft deep. During field testing, efforts should be made to identify the appropriate depth for the sensors to be placed.

## 5.2 Camera Module

The longest distance of wire that was used to attach the integrated camera module to the Raspberry Pi spanned 1 meter. As described in the testing setup, this distance was sufficient to place the camera above the testing apparatus to capture video and photographs of the soil movement. However, in field testing, it is recommended that a longer ribbon wire is used to connect the camera. This would provide more flexibility, as field testing may require a wider camera angle or analysis of soil farther away from the sensor node than 1 meter.

## *5.3 Connectivity for Data Retrieval*

Although limited by location of testing and availability of internet, connecting the Raspberry Pi to the internet or a Wi-Fi signal would allow for digital transfer of information and reduce the need for physical data collection. If possible, this addition would greatly increase the capabilities of the sensor nodes and provide more extensive real-time monitoring of soil conditions.

A consideration for this for field deployment is power and communication system resilience. Should power outages occur and or disruption to the internet/communication systems, data would not be readily available. One means to overcome this is to use radio channels or similar that are less impacted by outages. Additional investigation is necessary to identify the local options available and appropriate connections to ensure data can be transmitted appropriately during times of disruption. This should be tested in field applications before broad deployment.

# Chapter 6 Conclusions

This project intended to serve as a proof-of-concept for creating and testing a low-cost, direct sensing approach to detect ground motion at bridge and overpass approaches in a seismic zone to early detect and prioritize field response for asset management. The team successfully assembled a sensor node that cost less than $300 using readily available sensors and a Raspberry Pi. Two sensor nodes were assembled and tested in a laboratory setting under a range of earthquake-like shaking. The sensor nodes successfully detected the motion of the soil in the testing box and were able to closely detect and replicate the acceleration and movement of the testing apparatus.

Lessons learned during laboratory testing have led to recommendations for field testing and future deployment such as improved sensor housing and connectivity to the internet or other communication systems. Additional laboratory testing would be recommended to further verify and validate the potential ranges of motion detection and vibrations prior to field testing. Field testing is highly recommended to be conducted at an active construction site with blasting or involvement of moving heavy equipment to create ground vibrations that may be representative of seismic activity.

This study has proven that it is possible to detect and measure soil movements using low-cost, direct sensing that could be deployed broadly in a cost-effective manner to augment existing seismic monitoring. Use of low-cost direct sensing has the potential to provide localized information on the amount of potential liquefaction and shifting of soils at bridge or overpass approaches to help transportation agencies identify which evacuation routes may be most or least effective and prioritize response efforts toward improved recovery from an event and overall resilience.

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# Appendices

## Appendix A:  Raspberry PI Setup

**Instructions for preparing the Raspberry Pi:**

1. Insert MicroSD card to external computer
2. Install Raspberry Pi Imager at https://www.raspberrypi.com/software/
3. Click on “Choose OS” and select “Raspberry Pi OS (32 bit)”
4. Click on “Choose Storage” and select the SD card
5. Click on “Write” and wait on completion
6. Once done, eject SD card from computer and insert into Raspberry Pi microSD slot

**Instructions for sensor setup (refer to the following diagram for port number instructions):**

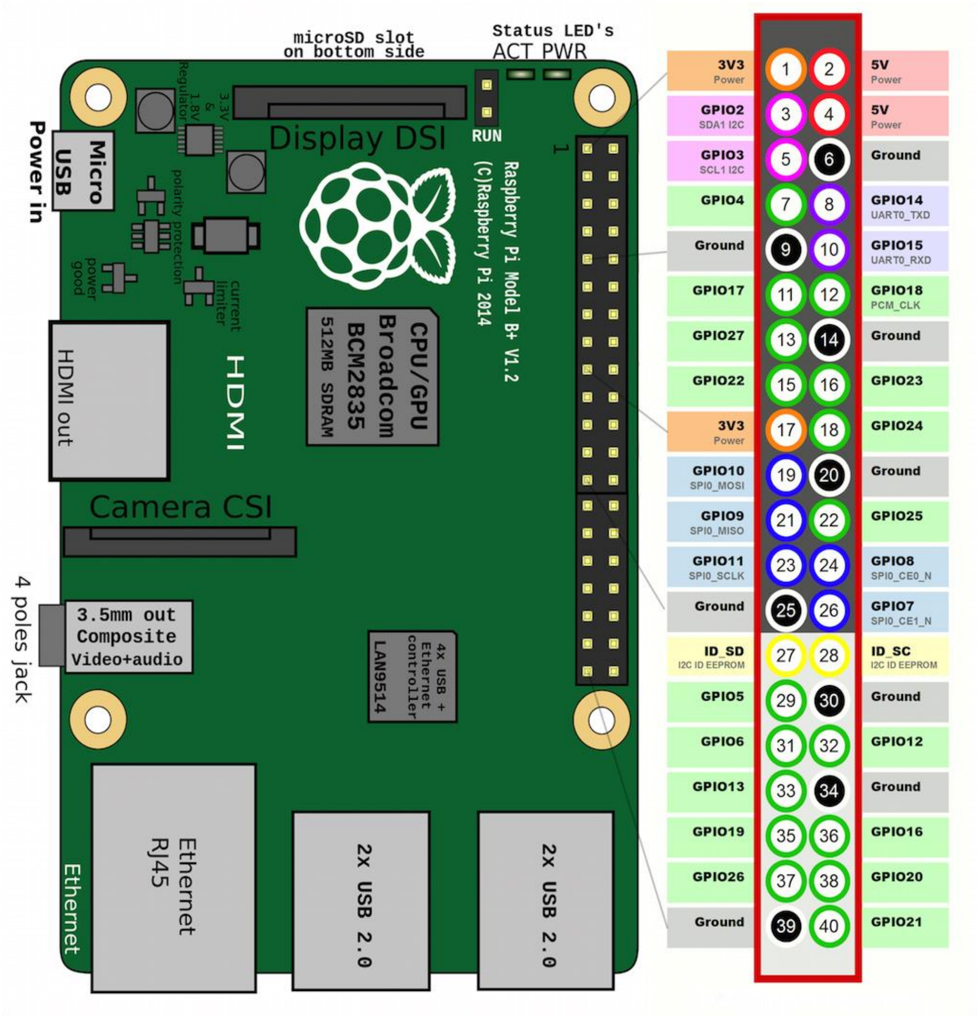


Figure A-1: Diagram of the Raspberry Pi microcontroller, with ports labeled by their associated number.

**To connect the vibration sensor:**

1. Connect the sensor's port labeled "VCC" to the Pi's port #2
2. Connect the sensor's port labeled "GND" to the Pi's port #6
3. Connect the sensor's port labeled "DO" to the Pi's port #11

**To connect the moisture sensor:**

1. Connect the sensor's port labeled "VCC" to the Pi's port #1
2. Connect the sensor's port labeled "GND" to the Pi's port #9
3. Connect the sensor's port labeled "DO" to the Pi's port #13
4. Connect each of the two open ports on the end of the moisture sensor to a port on the two-pronged insertable component.

**To connect the accelerometer:**

1. Connect the sensor's port labeled "VCC" to the Pi's port #4
2. Connect the sensor's port labeled "GND" to the Pi's port #14
3. Connect the sensor's port labeled "SCL" to the Pi's port #5
4. Connect the sensor's port labeled "SDA" to the Pi's port #3

**To connect the camera:**

1. Insert the ribbon wire of the camera module into the Camera CSI port on the Raspberry Pi.
2. Remove the plastic covering on the lens of the camera.

**Instructions for initially turning the Raspberry Pi on:**

1. Connect HDMI cable to monitor and the HDMI port on the Raspberry Pi
2. Connect keyboard and mouse to USB ports
3. Insert power cable into micro USB slot
4. Following bootup, select proper time zone and language settings
5. Create username and password for the Pi
6. Connect to Wi-Fi (optional)

**Instructions for preparing the Raspberry Pi Software:**

1. Open the command prompt terminal in the top left corner of the screen
2. Run the following commands:

   *sudo apt-get install -y i2c-tools*

   *sudo apt-get install python-smbus*
3. Run the following command:

   *sudo raspi-config*
4. Select “Interfacing Options” and enable I2C
5. Repeat step 3 and select “Interfacing Options” to enabe “Legacy Camera”
6. Restart the Raspberry Pi using the menu in the top left of the screen.

**To program the Raspberry Pi:**

1. Either manually type the code using the Thonny IDE program, or move pre-programmed code files onto the Raspberry Pi using a flash drive.
2. Right click on the desktop and create a file called “Acceleration Data”

**To activate code and begin testing:**

1. Open the code file for the accelerometer, and press the green arrow in the program to begin collection of data
2. Open the command prompt terminal and type the following command

   $ python (name of other coded program files).py
3. Unplug the monitor, mouse, keyboard from the Raspberry Pi and begin testing