

## The Use of Wireless Sensors in Geotechnical Field Applications

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### Abstract

This paper describes the potential of wireless sensing networks to improve geotechnical field monitoring and the use of wireless sensors in two on-going geotechnical research projects. Both studies are Network for Earthquake Engineering Simulation Research (NEESR) projects funded by the National Science Foundation (NSF). The first project focuses on the phenomenon of time-dependent changes in the state and properties of recently deposited, disturbed, and/or densified saturated sand deposits. Wireless sensors are being integrated with pore pressure transducers and accelerometers to record the response of the deposits undergoing explosive compaction, vibrocompaction, and vibroseis shaking. In the second project, wireless sensors are being used to monitor the performance and health of buried pipelines crossing a fault plane undergoing differential movement. The focus is on concrete pipelines that are often used in water distribution networks. There is great potential for use of wireless sensors and wireless sensor networks in geotechnical fieldwork because of their relatively low cost and easy adaptation for use on construction sites and in urban areas because their placement is not restricted by cables.

### Introduction

Instruments, such as pore pressure transducers, geophones, accelerometers, settlement monitors, and inclinometers, are commonly used in geotechnical fieldwork. Traditionally, these instruments have been used with cable-based data acquisition (DAQ) systems that restrict their placement in urban areas and construction sites. Wireless sensing systems are compatible with many

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geotechnical instruments and represent an improvement over tethered DAQ by eliminating concerns about maintaining of a wired connection between instruments and a global DAQ. Additionally, wireless sensors are endowed with both memory capacity and embedded data processing resources. For example, wireless sensor networks can maintain recorded data at the node so that the data can be locally processed or held until transmission is possible.

Due to their durability, economical pricing, and the previously mentioned advantages, wireless sensors have potential for greatly expanded use in geotechnical engineering. With a little more research and experience, the health monitoring of buried infrastructure could be as mature an area as structural health monitoring is now. Potential applications where wireless sensors could advance the current state of geotechnical engineering practice include monitoring strain in buried pipelines and tunnels, recording vibrations near construction or blasting sites, measuring foundation settlement, and providing early warning of slope instability.

In this paper, a wireless sensor prototype under design at the University of Michigan is discussed first. Next an overview of wireless sensors being used in geotechnical experiments is presented, followed by a discussion of the sensor's utility in geotechnical performance and health monitoring.

### **Wireless Data Acquisition**

The wireless sensor system developed at the University of Michigan (Lynch et al., 2005) is featured in this section. As was briefly mentioned in the introduction, wireless sensors and wireless sensing networks offer several advantages over traditional tethered systems. First, their placement is not restricted by cables, and the lack of cables reduces the chance of cable damage and data corruption. This is particularly important in construction projects. Also, the wireless sensing network allows a greater number of sensors to be used at the same cost as tethered monitoring systems. For example, the authors' laboratory owns a field-portable, cable-based DAQ with 16 channels and the Network for Earthquake Engineering Simulation (NEES) vibroseis has a 72 channel cable-based DAQ. However, the number of sensors with wireless DAQ is limited only in cases of high sampling rates for long duration. In such cases, data transmission must occur before the wireless sensing unit's random access memory (RAM) becomes full and begins to overwrite existing data with new data. Because high frequency, long duration events are atypical in geotechnical applications, the number of sensors (synonymous to number of channels) is not a limitation.

The wireless sensing system that was developed at the University of Michigan is pictured in Figure 1 and is primarily built from commercial components. The system was originally developed for structural health monitoring and is capable of performing analog-to-digital conversion, data aggregation, data processing, and wireless transmission of raw and/or processed data to a receiving computer. With a sampling rate as high as 10 kHz, the wireless DAQ is compatible with most geotechnical applications. The analog-to-digital converter (ADC) has a resolution

of 16-bits, matching the capabilities of most tethered DAQ. It is controlled by the unit's 8-bit Atmel Atmega128 microcontroller, which has 128 kB of read only memory (ROM) where different algorithms can be embedded for execution. Because the microcontroller has limited RAM, 128 kB of off-chip RAM is included in the design of the unit's computational core allowing 64,000 data points to be stored on the wireless sensor at one time.

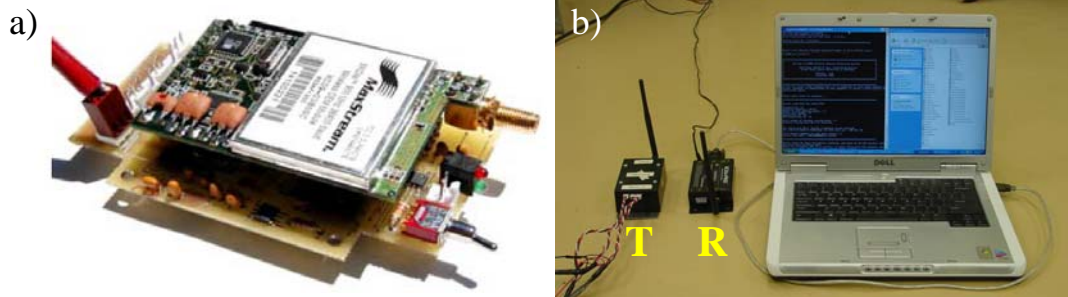


Figure 1. a) Wireless sensing unit prototype (battery and external housing not shown). b) Complete wireless sensing system with the assembled transmitter marked with “T” and receiver with “R”.

In cases where instruments are located below grade, cables connect the buried instrument to the wireless sensor located at grade. A 900 MHz Maxstream 9Xcite wireless transceiver transmits the data to a receiving laptop computer. The transceiver is integrated with the wireless sensing unit's architecture and is capable of communicating up to 300 m line-of-site with an over-the-air data rate of 38.4 Kbps. Only one laptop, connected to the wireless sensing receiver, is needed to receive and store the data from the sensors.

### Experimental Use

To date, wireless sensing has been used more in geotechnical laboratory testing than field applications, most extensively in the geotechnical centrifuges (e.g., the Center for Geotechnical Modeling at the University of California, Davis (Wilson et al., 2007)). Being selected as a NEES equipment site, UC-Davis upgraded the data acquisition capability of its centrifuge equipment. Through the use of wireless sensors, they now have the ability to record data from a greater number of sensors, up to 448, at a significant cost savings per channel compared to cable-based DAQ.

While the centrifuge work demonstrates wireless sensors' applicability in laboratory testing, the technology is not yet widely used in geotechnical field applications. However, one on-going application is the NEESR study on time-dependent changes in the state and properties in recently deposited, disturbed, and/or densified saturated sand deposits, referred to as “sand aging.” There is evidence of sand aging in site improvement projects, laboratory tests, and field tests (Mitchell and Solymar, 1984; Dowding and Hryciw, 1986; Charlie et al., 1992). One way that aging manifests is in increases in strength, for up to several

months, while surface settlement and excess pore pressure dissipation are generally complete after hours to days, depending on the site. Strength gain is generally characterized by increases in standard cone penetration test (SPT) blow count and/or cone penetration test (CPT) tip resistance and shear wave velocity.

In this project, sand aging will be monitored at a sand and gravel quarry in Griffin, IN. Three methods will be used to break down the soil structure: explosive compaction, vibrocompaction, and the NEES vibroseis, shown in Figure 2. While explosive compaction introduces blast gas into the pore water and vibrocompaction introduces heavily aerated water during jetting of the vibroflot, the NEES vibroseis only introduces seismic waves into the soil deposit. The different methods will allow the influence of the respective changes in pore fluid on the aging phenomenon to be studied. The difference disturbance methods being used to break down the soil structure also impart vastly different energies to the soil as a function of time. Wireless instrumentation arrays will capture acceleration and pore pressure data and will allow a comparison of aging effects to be made as a function of disturbance energy.

Different instrumentation was selected specifically for blasting and the vibration-based disturbance methods. Blasting creates the most demanding instrumentation requirements because of high frequency and high amplitude motions; however, blasting is also the least expensive due to the high equipment costs of the other methods. This will allow additional tests to be performed if there is instrumentation failure. Because aging has not been observed at every site (Hryciw and Dowding, 1988; Jefferies et al., 1988), blasting will be first method performed, to determine whether aging occurs at the Griffin, IN site.



Figure 2. NEES vibroseis at the University of Texas Austin equipment site.

Piezoelectric shock accelerometers will be used to measure the ground motions during explosive compactions because they can withstand the large amplitude motions generated from the blast, while accurately measuring motions. Dytran 3200-series shock accelerometers are the only instruments in the aging study

that will be used with a tethered DAQ. The wireless DAQ being used in the aging study is compatible with voltage output, while the piezoelectric accelerometers output a regulated current. This is mentioned to contrast the applicability of a wireless DAQ versus a tethered DAQ. Figure 3 shows the tethered DAQ system that will be used in the aging study. It is easy to imagine the added difficulty of both setting up and maintaining this system in the field due to the cables, as compared to the wireless DAQ shown in Figure 1b.

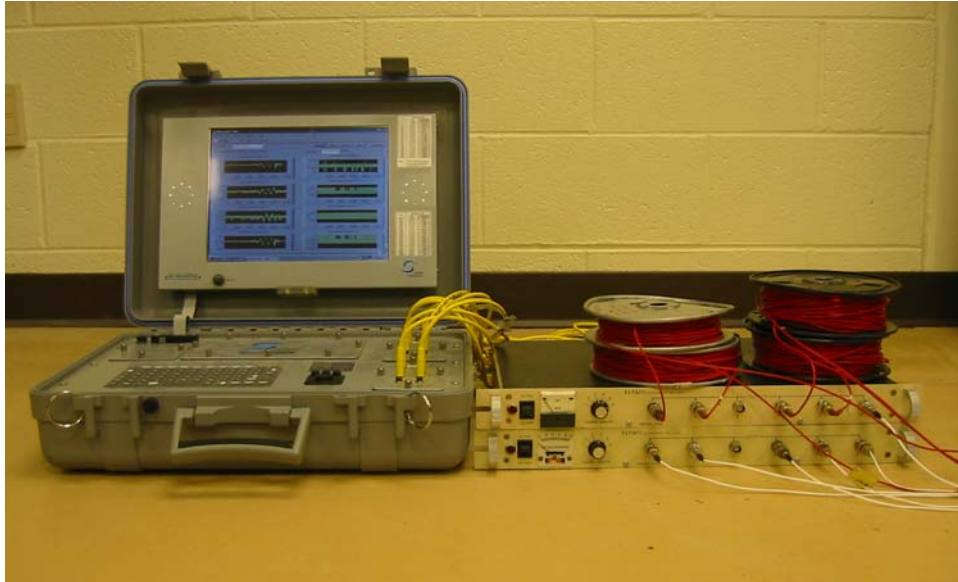


Figure 3. Tethered DAQ connected to piezoelectric accelerometers (not pictured).

In the vibration-based disturbance methods (i.e., vibrocompaction and vibroseis), microelectromechanical systems (MEMS) accelerometers will be used. MEMS accelerometers are durable, accurate, inexpensive, and are compatible with the wireless DAQ. Cox (2006) successfully demonstrated the use of MEMS accelerometers to measure the ground motions from the NEES vibroseis. Using this experience and the methods described by Fellin (2000) and Green (2001), the authors designed an instrumentation plan for both vibration-based methods by calculating an upper bound of the maximum acceleration expected during vibrocompaction when the vibroflot impacts the soil. Clearly the maximum acceleration will attenuate with distance from the compaction point (due to geometrical spreading and material damping), but at an unknown rate. Accordingly, the authors chose triaxial Crossbow capacitive MEMS accelerometers of 2, 5, 10, and 25g range.

Finally, pore pressure will be recorded in order to verify complete breakdown of the soil skeleton (i.e., liquefaction). Additionally, the pore pressure transducers will allow the authors to measure the dissipation of excess pore pressure with time and to ensure that changes in penetration resistance are not simply due to temporary decreased vertical effective stress. Rollins et al. (2005) used the

Sensotec P-050 piezoresistive transducers in similar experiments and found them to be durable enough to survive the blast pulse, while sensitive enough to accurately record pore pressure dissipation (e.g., these transducers are capable of surviving an approximate 41.4 MPa (6,000 psi) shock pressure wave while having a resolution of 0.7 kPa (0.1 psi)). These transducers are, therefore, responsive enough to measure the pore pressure build up and dissipation expected in the aging project. While vibrocompaction and vibroseis will not produce as high of a peak pore pressure as blasting, the Sensotec P-050 transducers are sensitive enough to accurately measure lower amplitude pore pressure response. Because the bandwidth of the transducers is 0-300 Hz, the peak pressure from the blast shock wave may not be accurately recorded; however, the instruments will accurately measure the residual pore pressure generation and dissipation, which is of greater interest.

Figure 4 shows the proposed instrument layout for the explosive compaction test. While the vibrocompaction and vibroseis tests will require slight adaptations of this layout, it is representative of the overall approach that will be used. Each instrumentation node will contain an accelerometer and a pressure transducer, with up to four instruments connected to each wireless transmitter depending on instrument spacing. The instrumentation for each method used to breakdown the soil structure will be tested prior to full-scale field tests in a 12' diameter, above ground, impermeable, flexible-walled containment apparatus filled with saturated sand. Blasting caps will be used to simulate the same blast-to-instrument scaled distance, but with smaller than the actual 3.0 lb equivalent TNT charges. Vibrocompaction will be simulated with a vibrator used in pouring concrete and a mobile shaker will be used to simulate the vibroseis.

A final note of interest relates to the placement and post-test recovery of the instruments. The instruments will be housed in cone tips for ease of placement. The cone tips will be made of nylon because it is easy to mill, durable, and has a unit weight close to soil, and therefore, they are less likely to sink during liquefaction. However, a disadvantage of nylon cone tips is that they are not as strong as metal cone tips and cannot withstand being pushed to the depth of the liquefiable layer in this study (i.e., ~3m (or ~12')). Rollins et al. (2005) solved this problem in their study by pre-drilling a slurry-filled bore hole to a depth of about 1' shallower than the desired placement depth of the instrument. The cone tips then only need to be pushed the additional foot from the bottom of the bore hole to the desired placement depth. Rollins et al. found that the cone tips were strong enough to withstand penetrating 1' of soil, which also is enough distance from the slurry to ensure that the measured response is not significantly influenced by the slurry-filled bore hole. However, in this approach, the slurry mixture is very important. If the slurry is too thin, the holes will collapse due to the pressure from the surrounding liquefied soil, rendering the extraction of the instruments very difficult. Accordingly, the authors tested various slurry mixtures in a liquefaction tank to determine the minimum thickness that would maintain a borehole during liquefaction. Slurry made with 80lb of bentonite per 100gal water maintained the integrity of a 4" diameter borehole in the liquefaction tank as shown in Figure 5.

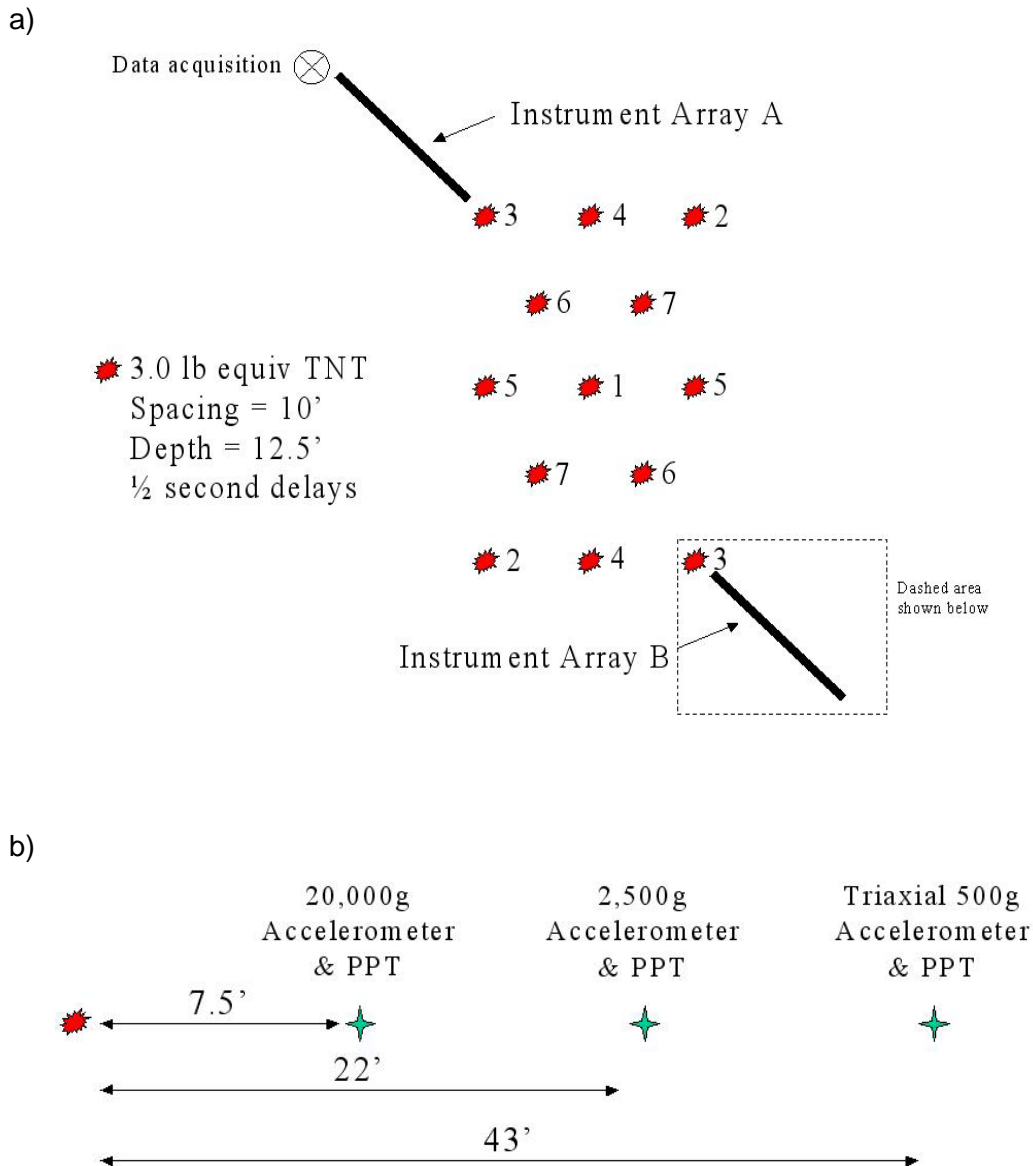


Figure 4. a) Instrumentation layout during explosive compaction. The numbers next to charges represent the order of the delays. b) Detail of individual instrument array (3 instrument nodes per array). Each instrumentation node will connect to a wireless transmitter.

### Performance/Health Monitoring

The authors believe that with a little more research and experience geotechnical health monitoring could be as mature a field as structural health monitoring. Lynch and Loh (2006) describe several examples of wireless sensing networks used for structural performance and health monitoring of civil infrastructure,

including bridges and buildings of various construction materials and sizes, offshore structures; even vehicles can be monitored (e.g., naval vessels and aircraft). Lynch and Loh also point out that the wireless transfer of data to remote data repositories can simplify and decrease the cost of cable-based monitoring systems. For example, Straser and Kiremidgian (1998) report that, in structural health monitoring systems, cable installation alone can represent 25% of the total system cost with over 75% of the installation time dedicated solely to routing cables.



Figure 5. View of excavated sand in liquefaction tank showing the open borehole.

Garich and Blackburn (2007) describe the use of wireless sensors to monitor landslide risk. By attaching soil moisture probes and MEMS accelerometers (used to monitor inclination) to wireless transmitters, Garich and Blackburn were able to successfully monitor field conditions at a test site on Texas A&M University's campus for one week. Because the instrumentation in their study was designed to have low current draw, the power to the system was sustained using solar panels and rechargeable batteries. Their wireless prototype monitoring system provided real-time information about soil conditions that could be used to provide early warning of a landslide.

Another example of wireless sensing applications in geotechnical health/performance monitoring is the second NEESR project in which the authors are involved. This project, currently in laboratory development, focuses on the health monitoring of buried pipelines after earthquake-induced ground movement, with particular attention on water distribution networks. Clean water is essential to emergency response, making assessment of water delivery systems crucial to recovery from earthquakes, tsunamis, hurricanes, or other disasters. Eiding (1996) ranks water systems as the most vulnerable lifeline during earthquakes. For example, loss estimation models show that Seattle, WA would

be without water for up to 20 days following a M8.5 event centered 100km from the city and Oakland, CA would be without potable and raw water distribution for several months after a M7 event on the Hayward fault (Kennedy et al., 1991; G&E Engineering, 1992).

Because pipelines are buried and often very congested in urban areas, rapid post-disaster assessment and response is very difficult. Currently, inspection techniques include visual inspection using cameras, infrared thermography systems (ITS), and ground penetrating radar (GPR). Each of these methods requires interpretation of the results, which is labor intensive. Most sensor-based inspection methods are also prohibitively expensive. For example, smart pigs, rubberized packages fitted with sophisticated instrumentation, and fiber optic monitoring have excellent performance characteristics, but are too expensive for most pipeline applications. One of the more practical sensor-based inspection techniques, acoustic and ultrasonic emission transducers can monitor the propagation properties (e.g., attenuation, velocity, reflections) of elastic waves and correlate them to the physical condition of the system. They have performed well in metallic pipes where there is little attenuation of the signals with distance. However, this method is of limited value in concrete pipes because the poor elastic wave characteristics of cementitious materials that cause quick attenuation with distance, forcing sensors to be too closely spaced for this method to be practical.

The NEESR pipeline project will use wireless sensing technologies to develop a self-sufficient health monitoring system for buried pipelines using two sensor systems. First, electrical probes will be mounted on the outer surface of concrete pipes. The inner steel lining will act as the second probe point. An actuation interface will apply sinusoidal electrical signals to the pipeline while a sensing interface will record the corresponding voltage response at the same probe location, as shown in Figure 6a. The electrical impedance spectroscopy (EIS) data, from input-output phase-gain properties, can be used to quantitatively measure the concrete pipe's strain. This is possible because concrete is a piezoresistor and has resistance that varies linearly as a function of strain. Additionally, acoustic emission will be measured in steel pipes and the internal steel sleeve of concrete pipes. Both active and passive acoustic sensing will be used. During active acoustical sensing, elastic stress waves will be generated using piezoelectric actuators. These waves will be measured by piezoelectric sensors, where time-of-arrival and amplitude will correspond to either a healthy or damaged pipe. This is pictured in Figure 6b. During passive acoustic sensing, pipe segments will undergo various modes of damage (e.g., decoupling, sliding, and flexural failure), and the resulting acoustic waveforms will be captured and analyzed by the wireless sensors. Characteristic amplitude-to-duration ratios, frequencies, energy contents and other aspects of the recorded waveforms will be analyzed to determine methods of differentiating failure modes and of detecting damaged locations.

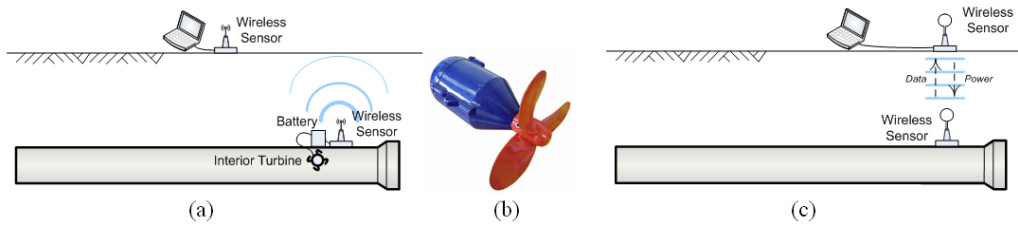


Figure 6. Power delivery to buried wireless sensors: a) internal turbine to harvest energy from water flow; b) Ampair 100W water generator; c) power delivery from above by electromagnetic coupling.

Hardening of sensors to withstand the underground environment, decreased communication range between sensors, and powering sensors in an environment where changing batteries is impossible are some anticipated challenges with this system. To ensure that water does not damage the wireless sensor, a waterproof container will be added to the wireless system discussed previously. Preliminary calculations suggest the higher dielectric constant of soil compared to air will reduce the communication range from 300m to 7.5m (~1000' to ~25'). Future tests will confirm the range, but 7.5m (~25') is sufficient compared to the depth of most buried pipelines. The in-situ powering of the instruments is the most challenging problem and two novel solutions are proposed and shown in Figure 7. The first uses the water flowing through the pipeline to turn a small hydraulic turbine that is electrically connected to a rechargeable battery outside of the pipe. The proposed turbine will provide enough power to keep the wireless sensor battery pack, which contains five rechargeable AA batteries, fully charged at all times. A fully charged battery pack provides the sensor roughly eight hours of power, enough transmission time to locate the problem in the event of a rupture. The second approach is very similar to the principle of radio frequency identification (RFID) where a reader remotely delivers power to an RFID sensor through electromagnetic coupling. An inductive antenna placed above a wireless sensor integrated with an identical inductive antenna would generate a magnetic field by applying alternating current to the buried inductor. This magnetic field will induce a small current in the buried inductive antenna. Tests will determine if the attenuation of the magnetic field with soil depth and type will provide enough power to fully charge the wireless sensor.

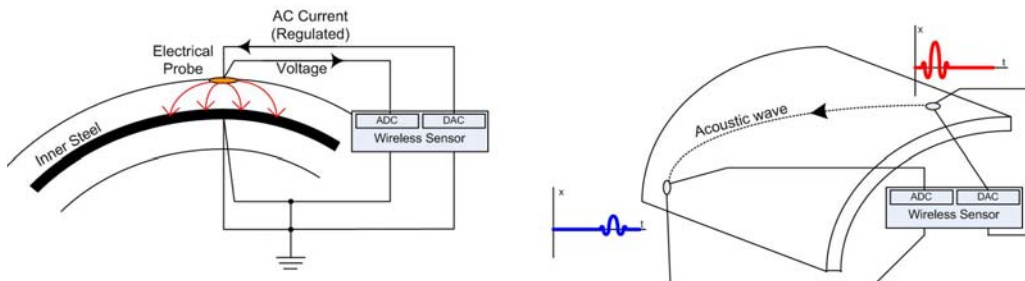


Figure 7. a) Electrical impedance probing of the concrete pipe; b) acoustic inspection to identify pipe damage.

## Summary and Conclusions

This paper describes a wireless sensor prototype and its use in two NEESR projects at the University of Michigan. In the sand aging project, accelerometers and pore pressure transducers attached to the wireless DAQ will record the response of a saturated sand deposit wherein liquefaction will be induced. Monitoring accelerations while liquefying the soil via explosive compaction, vibrocompaction, and vibroseis will allow for comparison of aging effects as a function of the energy that each method imparts. Accurate pore pressure readings will ensure that monitored strength gain is due to aging and not temporary changes in effective stress due to elevated excess pore water pressure.

The buried pipeline project will further demonstrate the use of wireless systems in geotechnical applications. Electrical probing and acoustic emission testing will allow health monitoring of buried pipelines, improving post-disaster assessment and repair operations. The wireless system will be adapted for underground use through waterproofing, decreased distances between transmitters and receivers, and in-situ power generation.

The wireless sensing system used in these projects interfaces with traditional sensors using a 16 bit ADC converter. On board computing with 128kB of RAM and 128kB of ROM allow for data aggregation and processing. A 900MHz radio transmitter provides communication ranges of 300m (~1000') line-of-sight and an estimated 7.5m (~25') through soil. The authors believe that the experience gained from the using these sensors in the projects described above will demonstrate the value of wireless sensing and potential for wider use in geotechnical applications.

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