Cutting-Edge Lead and Copper Detection: A COMSOL and Deep Learning Synergy

Zul Kazeem

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Thesis Advisor: Prof. XYZ

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Case Western Reserve University
Case School of Graduate Studies

We hereby approve the thesis[1] of

Zul Kazeem

for the degree of

Doctor of Philosophy

Prof. XYZ

Committee Chair, Advisor — Date
Civil Engineering

Pocapolise Eugene

Committee Member — Date
Civil Engineering

Demeter Insomia

Committee Member — Date
Civil Engineering

Eucalyptus Koala

Committee Member — Date
Civil Engineering

[1]We certify that written approval has been obtained for any proprietary material contained therein.

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Civil and Environmental Engineering

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ABSTRACT

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This article presents an innovative approach for detecting lead and copper in buried pipes by integrating COMSOL Multiphysics simulations with machine learning techniques. The enhanced model includes a soil block to replicate real-world conditions and utilizes accelerometers for data acquisition. The collected data is processed and analyzed using a convolutional neural network (CNN) to accurately identify the presence of these metals. This method aims to offer a more efficient and non-invasive solution to metal detection in water systems.

1 Introduction

1.1 Background

The detection of lead and copper in water systems is not only crucial for public health but has gained renewed urgency with the Environmental Protection Agency's,[1] mandate to replace all lead pipes within the next 10 years. Lead contamination, in particular, poses severe health risks, including developmental delays, neurological impairments, and cardiovascular issues, especially in children and pregnant women. Similarly, elevated levels of copper can cause gastrointestinal distress and other health complications. Traditionally, detecting these metals in buried pipes has relied on invasive methods such as physical excavation and chemical testing, which are labor-intensive, time-consuming, and disruptive to water supply systems. Moreover, these methods often require significant resources and may not provide real-time monitoring capabilities.

In response to these challenges, water authorities and researchers are actively exploring innovative, non-invasive detection methods that can accurately identify lead and copper pipes without the need for extensive excavation. This pursuit has led to advancements in simulation software and machine learning techniques, offering promising avenues for enhancing detection capabilities.

This study addresses these pressing needs by proposing a novel approach that integrates COMSOL Multiphysics simulations with machine learning algorithms. By combining the detailed environmental simulations provided by COMSOL with the analytical power of machine learning, this method aims to provide a robust and efficient solution for detecting lead and copper in buried pipes.

The integration of COMSOL simulations allows for the creation of realistic models that simulate the complex interactions between pipes, soil conditions, and other environmental factors. This includes adding a soil block to replicate the conditions in which pipes are buried, ensuring that the simulations closely mimic real-world scenarios. Furthermore, the use of accelerometers for data acquisition adds a layer of precision by capturing vibration and response data, which are critical indicators for detecting the presence of metals based on their distinct physical properties.

In parallel, machine learning techniques, particularly convolutional neural networks (CNNs), are employed to analyze the collected data and distinguish between lead and copper pipes. By training the CNN with a large dataset generated from COMSOL simulations, this study aims to enhance the accuracy and reliability of metal detection, thereby offering water authorities a practical tool for identifying and prioritizing pipe replacements.

1.2 Motivation

Lead and copper contamination in drinking water is a significant public health concern,[2]. Traditional detection methods involve physical inspections and chemical tests, which can be both time-consuming and disruptive. Recent advancements in simulation software and machine learning offer potential solutions to these challenges by providing non-invasive, accurate, and efficient detection methods.

Overall, this integrated approach not only addresses the immediate need for efficient metal detection in water systems but also sets the stage for future advancements in real-time monitoring and predictive maintenance strategies. As water utilities strive to comply with regulatory mandates and safeguard public health, innovative solutions that blend simulation technologies with advanced analytics are poised to play a pivotal role in transforming how lead and copper contamination are managed in infrastructure systems.

2 Literature Review

Numerous studies have explored various methods for detecting lead and copper in water systems. Traditional methods include physical inspections and chemical testing, which have limitations in terms of cost and efficiency. Recent research has not focused on the use of simulation software, such as COMSOL Multiphysics, and machine learning algorithms to enhance detection capabilities. This is thus an integrating these technologies for practical applications remains an area of active research. The following article is structured as thus: the methodology that describes the process that was used for the experiment, the result that shows the output from the model, the discussion, and finally the conclusion.

3 Methods

3.1 Computational Methods

3.1.1 Model

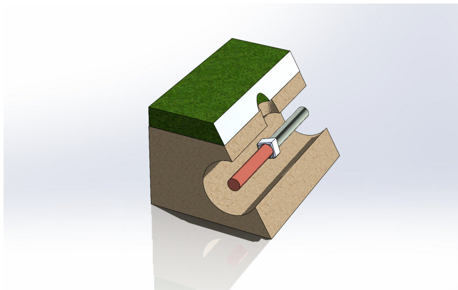
The simulation model consists of a soil block with uniform properties to replicate real-world conditions as much as possible but also to the extent that the model can allow. Steel was chosen as the material for the rod to be used with a hydraulic jack of 1000KN to ensure effective load transmission to the pipe.

The model is built using COMSOL Multiphysics using the solid mechanic model to simulate the effect of load on the pipe. The enhanced model was imported into Matlab, where random values were assigned to the pipe and load properties to simulate various scenarios. This step was essential for generating a comprehensive dataset.

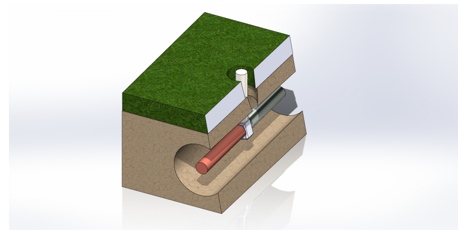
3.1.2 Dataset Generation

Approximately 5000 datasets were generated to train the machine learning model. The large dataset is critical for improving the accuracy and reliability of the CNN used for detection.

$$\rho\left(\frac{\partial^2 u}{\partial t^2}\right) = \nabla \cdot \mathbf{S} + \mathbf{F}_v \tag{3.1}$$

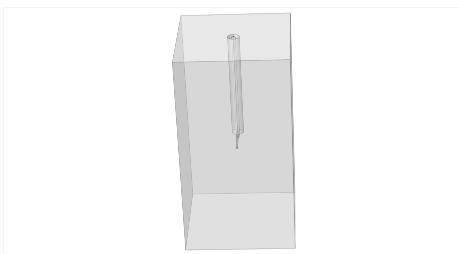


(a) Section of the buried Copper and Lead Pipe

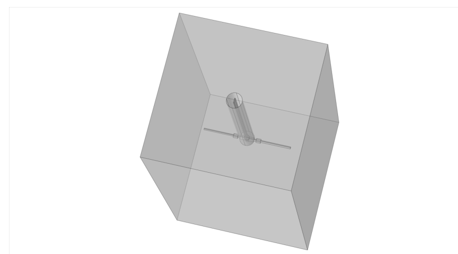


(b) Section of the buried Copper and Lead Pipe with steel rod

Figure 3.1. Section of the buried Copper and Lead Pipe with steel rod



(a) Side View



(b) Top View

Figure 3.2. Side and Top View of the Solid

Data Categorization. The generated data was separated into two categories: lead and copper. This categorization enabled the CNN to learn the distinct characteristics of each metal.

Model Training. The categorized data was used to train the CNN, aiming to develop a robust detection system capable of identifying the presence of lead and copper pipes that are buried withiout digging, saving cost.

4 Results

4.1 Computational Results

The integration of COMSOL simulations with machine learning resulted in a comprehensive dataset representing various real-world scenarios. The CNN was trained with this data, showing promising accuracy in distinguishing between lead and copper based on the recorded acceleration readings.

Description	Point graph
X	Height
0	5.817362260551916E-20
1	5.817362260551916E-20
2	6.046114033737459E-20
3	5.076492751732623E-20
4	2.0101101950650483E-20
5	6.082783728329581E-20
6	6.082783728329581E-20
7	6.082783728329579E-20
8	1.3190892577783899E-20
9	4.7556868646350063E-20
10	4.755686864635008E-20
11	4.7556868646350033E-20

Table 4.1. Result of Lead and Copper after Sinusoidal load has been applied.

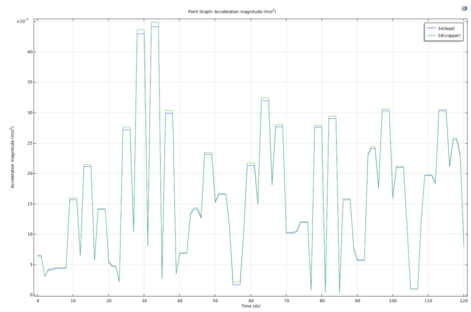


Figure 4.1. The graph that distinguishes between lead and copper.

5 Discussion

The combined use of COMSOL and machine learning demonstrated significant potential in improving the efficiency and accuracy of metal detection in water systems. The enhanced model, which includes a soil block and steel rod, effectively simulates real-world conditions. The generated dataset and subsequent training of the CNN highlight the feasibility of this approach. However, the process was slowed by the computational resources required, indicating a need for optimization in future work.

6 Conclusions

This study presents a novel method for detecting lead and copper in buried pipes by integrating COMSOL simulations with machine learning techniques. The enhanced model and extensive dataset generation contribute to a more accurate and efficient detection system. Future work will focus on optimizing the computational aspects and further validating the model with real-world data.

7 Future Research

Future work on the detection of lead and copper using convolutional neural networks (CNNs) can expand in several directions. Firstly, integrating additional heavy metals such as mercury, arsenic, and cadmium into the detection model would broaden its applicability and usefulness. This expansion would involve gathering extensive datasets for these metals, followed by training and validating the model to ensure high accuracy and reliability. Additionally, improving the data collection techniques by incorporating advanced sensors and equipment could enhance the precision of the model. This improvement would involve collaborations with experts in sensor technology and data acquisition to develop a more robust and accurate detection system.

Another promising avenue is the development of a real-time monitoring system for detecting lead and copper in soil or water samples. Integrating IoT (Internet of Things) devices could enable remote monitoring and data collection, providing real-time updates and alerts for contamination levels. Moreover, exploring other machine learning algorithms such as Random Forest, SVM (Support Vector Machines), or Deep Learning techniques like RNN (Recurrent Neural Networks) and LSTM (Long Short-Term Memory) networks could potentially improve the performance of the current CNN model. Extensive field testing and validation in various environments would be crucial to ensure the model's robustness and accuracy in real-world conditions. Collaborations with environmental agencies or institutions for large-scale validation studies could provide valuable insights and further enhance the model's reliability.

References

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