Modelling of ERT for Household Underground Pipe Detection using COMSOL Multiphysics

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ABSTRACT

Electrical resistance tomography (ERT) is a widely used in geophysical application. The purpose of this paper is to investigate the possibility of ERT systems to detect leakage or cracking of household underground pipe. A COMSOL Multiphysics software is implemented as the main tool for modelling ERT systems. 8 electrodes were modelled in 2 dimensions. At the same time, tomograms were also obtained and analyzed using MATLAB software. A linear back projection algorithm is implemented to reconstruct the image of the attractive area. Several different size and positions of underground leaking were analysed. The average value of MSSIM for all results is 0.01. This is because the smearing effect occurred when the linear back projection was implemented. In summary, a non-invasive strategy based on ERT is projected to be deployed for detecting leaks or cracks in underground pipes, but more research is required.

Keywords: ERT, geophysical, COMSOL, crack detection

1. Introduction

Electrical resistance tomography (ERT) is a method for determining the subsurface distribution of electrical resistivity based on resistance measurements received from a sensor organised in any geometric configuration [1]. A tomography procedure can enhance the productivity and efficiency of a process for detecting subterranean pipe leaks [2], [3]. The core concept behind process tomography is to employ several sensors to scan a pipe or vessel. This reveals information about the components' nature and distribution within the sensing area. The result of the measurement signal from the sensor is amplified, filtered, and processed on the computer using a specific image reconstruction technique to create a cross-sectional image [4].

Besides, ERT can also be used to reconstruct the images of biological targets, various types of rock or cavities under the soil, and block structures in a similar way [5], [6], [7]. The process has contributed to the fields of hydrogeology, geophysics, management of oil reservoirs, engineering studies, and others [7], [8]. Instrumentation advancements and data inversion algorithms have paved the way for 2D imaging of time-dependent processes, as well as extensions to include induced-polarization effects.

Electrical resistivity surveying is a versatile prospecting method applicable to groundwater location, archaeological evaluation, and contaminant monitoring. It is a common method for shallow subsurface investigations, especially for groundwater studies [2]. Moreover, a leak detection method based on soil sampling is expensive. Hence, subsurface resistivity measurements based on tomography approach to detect leakage from buried pipes are considered in this paper. The tomogram of a pipe leaking represents the initial state for repair purposes, and it should be detected prior to starting the construction work. In another meaning, the person in charge does not need to drill the soil randomly before the pipe leakage can be detected and changed by the plumber.

2. Basic ERT for geophysics application

Electrical surveys are used to resolve the subsurface resistivity distribution by doing a measurement on the ground surface [7], [9]. The true resistivity of the subsoil can be determined by using these data. Ground resistivity is affected by several geological factors, including mineral and fluid composition, porosity, and the degree of water saturation in the rock. For decades, mining, hydrogeological and geotechnical studied have relied on electrical resistivity surveys [5], [10]. Lately, it's being utilised for environmental surveys. Besides, Ohm's Law is a fundamental law used for resistivity studies because it conducts the flow of current in the ground. The basic form of Ohm's Law for current flow in a steady medium is represented by equation (1).

$$J = \sigma E \qquad (1)$$

Where
J = Current density
σ= Conductivity of the medium
E= Electric field density

In geophysical analysis, the medium resistivity ρ, which is equivalent to the reciprocal of the conductivity($\rho=1/\sigma$), is generally used. Equation (2) shows the relationship between electrical potential and field intensity.

$$E = -\nabla\varphi \qquad (2)$$

Where
E = Electric potential
φ = Field intensity

By combining equations (1) and (2), it will get the equation in (3). This equation later was used as the basis in modelling of ERT system using COMSOL Multiphysics.

$$J = -\sigma\nabla\varphi \qquad (3)$$

Furthermore, there are a variety of methods in geophysics that can be used to investigate the soil's resistivity, but it all depends on the relative positions of the current (transmitter) and potential (receiver) electrodes. The sensitivity of the resistivity value, the background noise level, and the type of structure to be mapped all influence the "best" array for a field survey [2], [11]. In general, the configurations of electrode arrays that are regularly used for 2-D imaging surveys are the surface placement approach of electrodes, such as are Wenner [12], Schlumberger [2], dipole-dipole [2], and pole-dipole [2]. Based on Ref. [2] and [12], Table 1 shows the advantages and disadvantages of each common method applied to the ERT system.

Table 1. Advantages and disadvantages for each technique applied in ERT for geophysical application

Technique	Advantages	Disadvantages
Wenner [12]	• Easily calculated in the field. • In comparison to other array geometry, instrument sensitivity is less important. • To produce observable potential differences, relatively tiny current magnitudes are required.	• All the electrodes must be shifted to a new position while sounding. • Longer current cable to get image deep into the earth. • High sensitivity near the surface in homogeneities

Schlumberger [2]	• The potential electrodes' cable length is shorter. • It has higher resolution, greater probing depth, and a shorter field deployment time than the Wenner array.	• Long current electrode cables are required. • The recording instrument needs to be very sensitive. • Coordination among the field crew may be complicated.
Dipole-dipole [2]	• It is easier to deploy in the field because the wire length is short.	• A large generator may be required to deliver a larger current magnitude for the measurement.
Pole-dipole [2]	• It reduces the deformation of equipment surfaces.	• Asymmetrical

Other than that, as in Ref. [13], a cross-borehole method is also used for ERT in geophysical applications. The main difference between the cross-borehole method compared to the other methods is that the array electrode will protrude into the soil as shown in Figure 1. A cross-borehole approach is a common method for researching complex or deep terrain, such as cavity detection, site characterization, and monitoring of groundwater recharge [5],[13]. The resolution of surface resistivity imaging decreases with depth [13]. It also provides a more homogenous model resolution vertically. Surface electrodes are not always possible to use. For example, the ground beneath a bridge foundation or a building may need to be studied. If all electrodes are in the same plane, mixed surface and borehole electrodes should be used for better resolution. In the borehole or on the surface between the boreholes, the electrodes should not be too widely apart. Borehole ERT survey successfully handles the resolution issue of weak survey signals at deep sites as compared to the traditional surface ERT resistivity method. The survey resolution of borehole ERT is multiple times higher than surface ERT survey for the same depth in survey locations, which can improve the features of geological structure at higher resolution in the measured profile, allowing for more intuitive interpretation. This technique was applied in this paper as a basis to identify the household underground pipe crack.

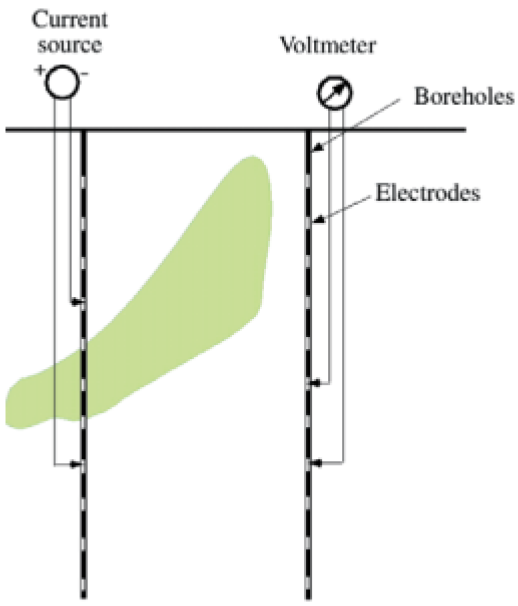


Figure 1. Example of the electrode array of 4 electrodes measurement for cross-borehole ERT [13]

3. Methodology

This work concentrates on the model and simulation of 2-Dimensional of ERT system for household underground pipe crack detection using COMSOL Multiphysics and to obtain the tomogram by using MATLAB software. Firstly, the system is designed and developed using ac/dc physics in COMSOL Multiphysics. The model of the ERT system mimicked the real implementation. Later, the sensor reading performances will be tested and analysed including the tomograms. The COMSOL Multiphysics was chosen because it can handle coupled processes or systems including many concurrently occurring physical fields, as well as the study and knowledge of these processes and systems. The general steps in designing and developing the ERT model are:

1) Choosing the space dimension, physics, and study. Here. The 2-dimensional, electric current (ec) under ac/dc physics and stationary study were chosen.
2) Create the geometry of the ERT system.
3) Define boundary probe for each line of each electrode that faces into the soil as channel 1 until 8.
4) Define material for each domain. The electrical conductivity properties for each material were inserted here.
5) Set electrical signal either current signal or ground for each respective channel.
6) Generating the mesh
7) Generating study
8) Analyse results

In addition, the rectangle geometry was used to draw the pipe and electrodes. For this case, the parameters such as diameter of the pipe, number of electrodes, and size of the electrode are based on the literature review. For this paper, the parameters that were set are shown in Table 2 and Figure 2 illustrates the geometry of the system with 8 electrodes implemented. Each boundary of the channel of the ERT model must be defined as the transmitter or receiver. Also, the excitation electrode was set at 5mA using a terminal in COMSOL. It was decided to use only the DC signal in this project. By doing this, made the modelling simpler and enabled us to get a positive value for the sensor reading as well as avoiding a very small reading value at the receiver. As a start, channel 1 will be set as a transmitter, channel 2 through channel 4 will be set to the ground, and the voltage measurement will be obtained from channel 5 through channel 8. After that, the process will be repeated for channel 2 as the transmitter, channels 1, 3 and 4 will be set as ground, and again for channel 5 till 8 as the receivers. Then, after all the channels on the left side are done as the transmitter, the process will switch whereby the electrodes on the right side will be set as the transmitter and all the electrodes on the left side will be used as the receiver channels. The sequence of the process is completed after all the channels for both sides become transmitters. Figure 3 shows an example of when channel 3 was set as the transmitter.

Table 2. The detail of parameters used in COMSOL

Item	Parameter	Value
Pipe	Diameter of pipe	2 inches
	Material	High density polyethene
	Electrical conductivity [14]	(HDPE) $10^{-13}[S/m]$
	Relative permittivity	2.4
Electrodes	Diameter of electrode	5mm
	Length of electrode	2 inches
	Material	Copper
	Relative permittivity	1
	Electrical conductivity [15]	$5.998^{7}[S/m]$
Soil	Relative permittivity	10
	Electrical conductivity [16]	$10^{-3}[S/m]$
Water	Relative permittivity	81
	Electrical conductivity	$9.1e - 3[S/m]$
Insulator pad	Relative permittivity	4
	Electrical conductivity	$0.005[S/m]$
	Material	FR4

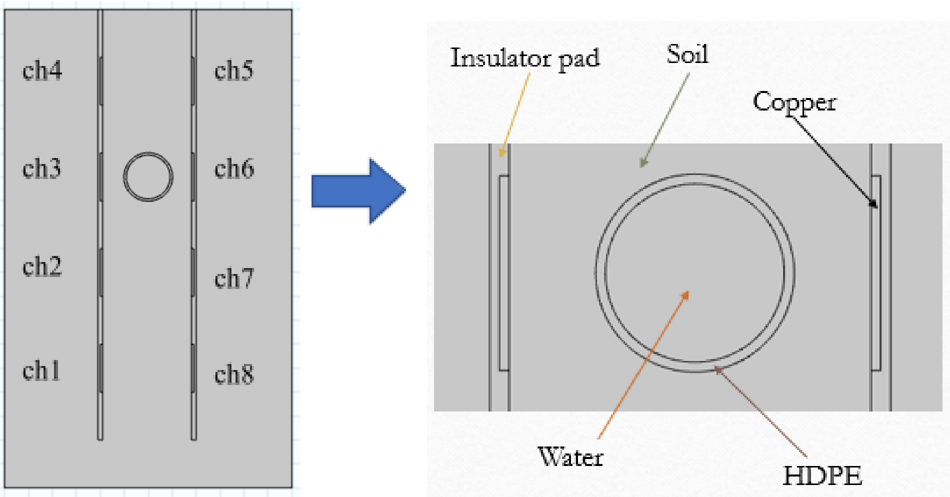


Figure 2. Geometry of the ERT system with label

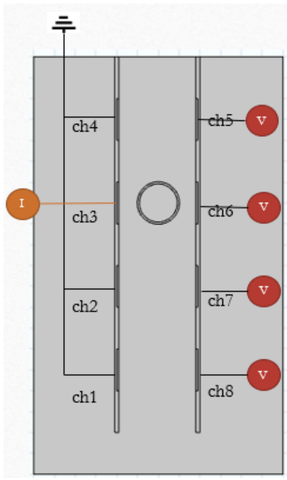


Figure 3. Example configuration of the electrodes when channel 3 was set as the transmitter

The mesh ERT model was generated as shown in Figure 4. The mesh type is physic-controlled, and the extra fine mesh was chosen in this paper. Different type of mesh gives a different type of result because the greater the mesh, the accurate the result. But it requires more time consumption to complete the result.

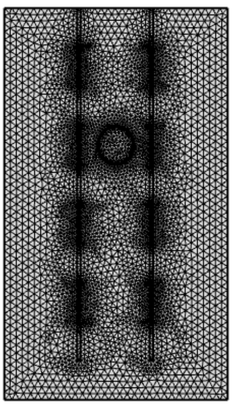
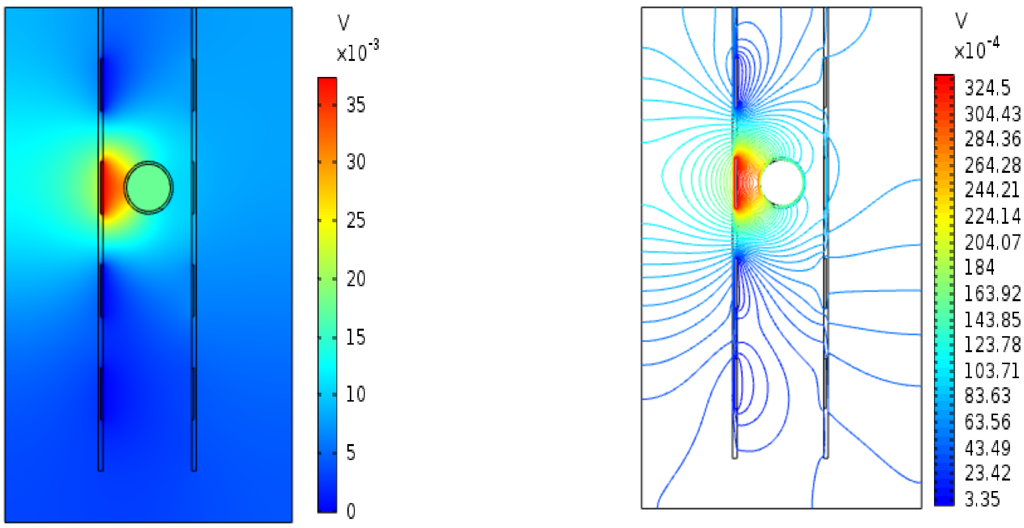


Figure 4. Extra fine mesh set for the system

Finally, the result of the electrical potential distribution was generated after meshing the system. Figure 5 shows the example of the electrical field line distribution for surface and streamline when channel 3 was set as excitation electrode and the existence of pipe. Simultaneously, only 4 receiver electrodes, which were channels 5,6,7, and 8, were set as the detection channels. These steps were repeated until a total of M= 64 (8x8) measurements were obtained.



(a) surface (b) streamline

Figure 5. Example of electrical potential distribution surface and streamline when channel 3 set as terminal

The measurement data was then exported to MATLAB as the sensor data and applied as part of the linear back projection (LBP) algorithm as in Ref [13], [14] to obtain the tomogram. The main reason for using the LBP algorithm is because it obtains the tomogram faster compared to the iterative algorithm. However, the disadvantage of the LBP is it will produce a smearing effect on the image obtained. Furthermore, based on the LBP algorithm, the sensitivity map is needed as a part of getting the tomogram. The sensitivity map is a sensor map for the ERT model. MATLAB is used to obtain the normalized sensitivity maps before they are multiplied with the sensor loss reading. In this paper, the pixel used for the sensitivity map is 144x144 pixels and it was chosen to improve the quality of the sensitivity projection of each of the electrodes [17], [18]. Later, several tests were done to analyze the performance of the sensor and tomogram obtained.

4. Results and Discussion

For the analysis stage, several sizes of the leak and distinguish locations of the leak were created. The same size of HDPE pipe was used as the tested medium and placed between channel 3 and channel 6. For this case, channel 3 was set as the excitation source. To begin, Table 3 depicts the electrical distribution when single, medium, and large leaking sizes were evaluated. Then, in Table 4, the results of the surface and contour of electrical field distribution for two different places of leaking that happened on the right and left sides of the pipe are shown. Because of the differences in relative permittivity and electrical conductivity between soil and water, the surface and contour lines were deformed while approaching the barriers, as shown in Tables 3 and 4. Also, it can be seen that the increment size of leakage increases the distortion of the voltage distribution. Besides, the different positions of leakage also can be seen from the result obtained in Table 4. When the pipe leaks close to the excitation source, it is significantly more influenced than when the pipe leaks far away from the transmitter.

Table 3. Comparison of the surface and contour with the different size of leaking

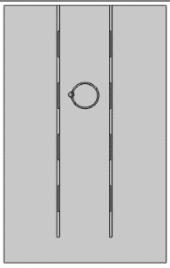
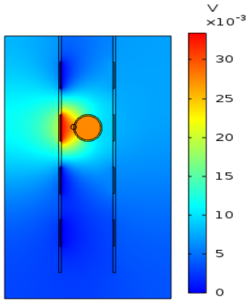
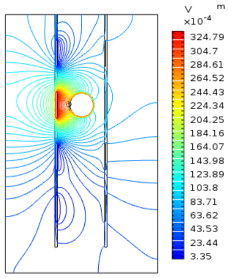
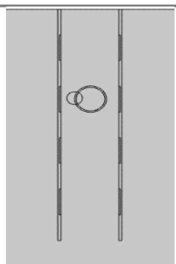
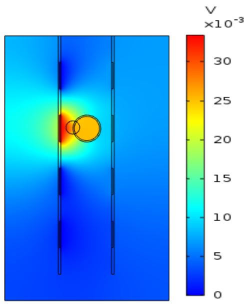
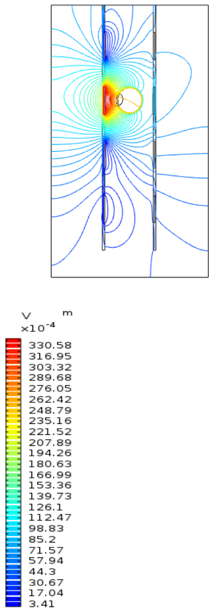
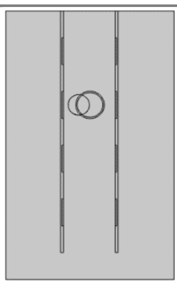
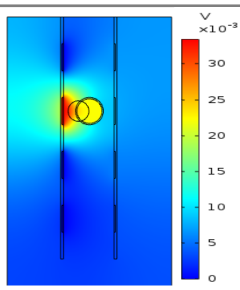
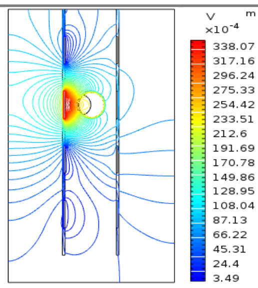
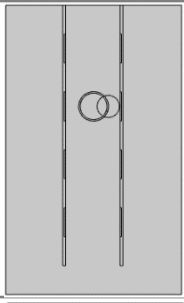
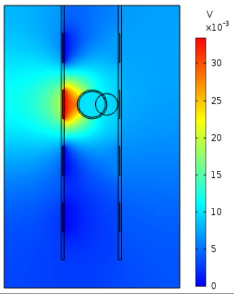
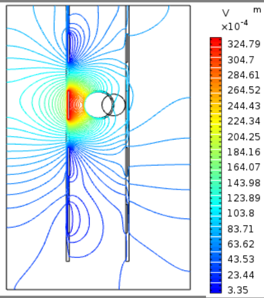
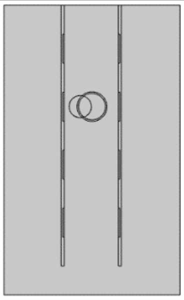
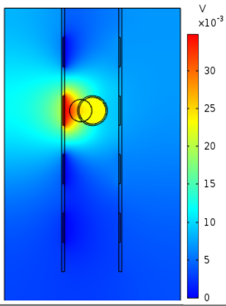
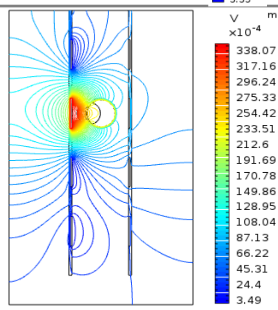
Size of leak	Geometry	Surface	Contour
Small			
Medium			
Large			

Table 4. Comparison of the surface and contour with the different size of leaking

Position	Geometry	Surface	Contour
Right			
Left			

Furthermore, the simulation continued with obtaining the tomograms for those conditions. Later, the multiscale structural similarity (MSSIM) approach as in Ref. [17] was applied to image analysis. The MSSIM value range index is 0 to 1. When MSSIM = 1, the two images are considered identical. A higher MSSIM index value indicates that the reconstructed image is close to the reference image. For the different sizes of the leak, the results obtained in Table 5 show the location of the leakage pipe on the right side. It was done to differentiate from the results obtained in Table 3. Table 6 shows the tomogram of when the different leaks occurred. Based on Table 5, it can be seen that a different pattern of tomograms can be obtained. The different size of the leak generates the different tomogram. When a bigger leakage occurs, a better and easier tomogram can be generated by the LBP. At the same time, it can also be observed by the MSSIM index. The MSSIM index shows the higher value when the leak occurred was bigger. In addition, from Table 6, the tomogram shows the position where the leak occurred. The value of the MSSIM should be the same due to the size of the leak. However, the results obtained show another way around and the average value of MSSIM for all the tomograms is just around 0.01. It is happened due to the smearing effect that had been occurred in the LBP algorithm as mentioned before and hence produced a poor image.

Table 5. Tomogram for different leaking size

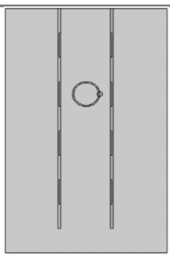
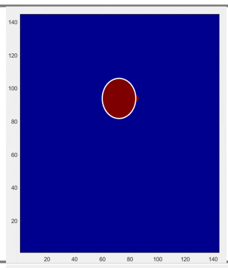
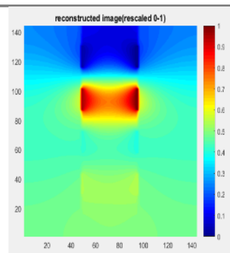
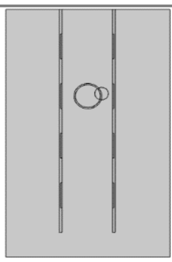
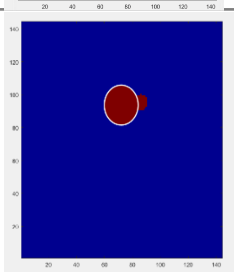
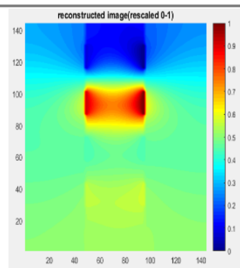
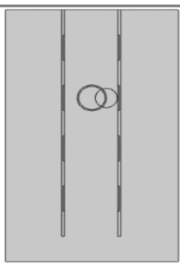
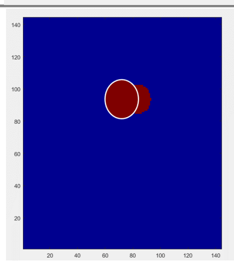
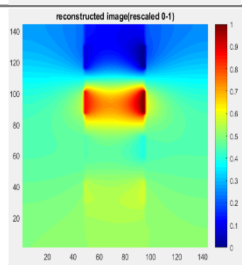
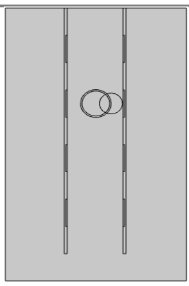
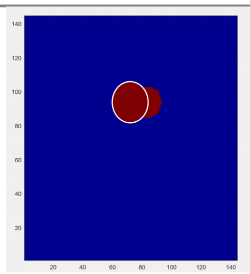
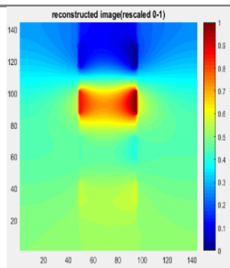
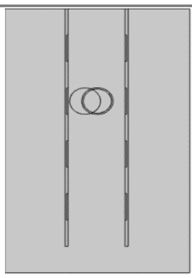
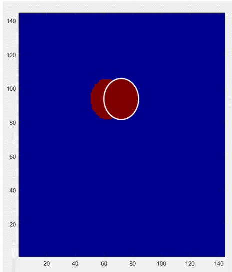
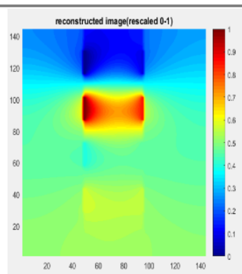
Size of leak	Leaking size	Reference image	Tomogram	MSSIM
Small				0.0101
Medium				0.0108
Large				0.0131

Table 6. Tomogram for different positions of leak

Position of leak	Leaking size	Reference image	Tomogram	MSSIM
Right				0.0131

Left				0.0148

5. Conclusion

In conclusion, the ERT system was able to identify the different locations of cracks and the increment size of cracks in the underground household pipe. The modelling based on COMSOL Multiphysics was successfully implemented for this purpose, as well as MATLAB for the image reconstruction part. Unfortunately, the MSSIM index just shows an average of 0.01 value. Hence, further investigation is needed to get better results. More different tests, such as multiple cracks, upper and lower location of cracks, and different materials of pipe, will be considered for future work.

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