



# Automatic Identification of Underground Pipeline Based on Ground Penetrating Radar

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**Abstract.** The underground pipelines of cities are complex and diverse, and they are responsible for important functions such as energy transportation and information transmission. In urban life and construction, it is necessary to grasp the location and depth of underground pipelines. Ground Penetrating Radar (GPR) is a real-time and efficient non-destructive detection technology. It has the advantages of fast detection speed, high resolution, easy operation and wide detection range. Therefore, it is the preferred method for urban underground pipeline detection. Based on the electromagnetic wave reflection mechanism of GPR detection underground pipeline, this paper proposes a new method of non-excavation and non-destructive on-site detection to identify underground pipe diameter, determine the position and radius of underground circular pipeline, and realize the automatic identification to underground pipeline.

**Keywords:** Underground pipelines · GPR · Automatic identification

## 1 Introduction

There are many types of underground pipelines in the city, including wire and cable for electrical signal transmission, pipes of various materials for water and oil gas transmission, and pipes for complex underground drainage systems. Underground pipelines play a major role in information transmission and energy transmission, providing convenience and guarantee for urban life [1, 2]. However, due to the imperfect and unsatisfactory information of underground space in the early stage of urban construction, underground pipelines often face problems such as aging, diversion and error mining during the continuous construction of the city. These problems will not only affect normal city life, but also cause accidents such as fires, water cuts, and power outages. In order to avoid such a situation, comprehensive investigation, recording and system management of underground pipelines are required [3].

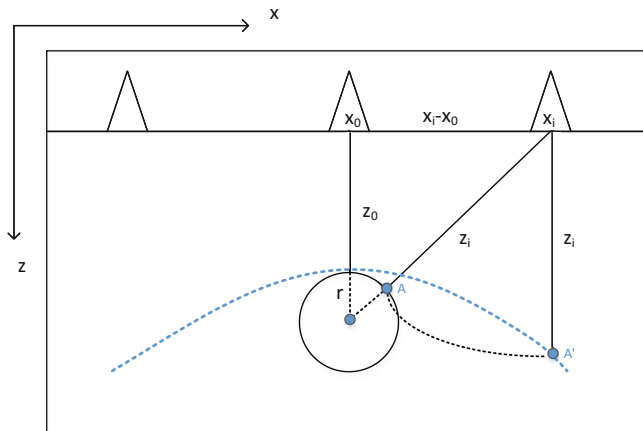
Ground Penetrating Radar (GPR) is a highly efficient shallow stratigraphic geophysical detection technology with the advantages of fast detection speed, high resolution, flexible operation, non-destructive detection, and low cost [4, 5]. The preferred tool for pipeline detection. In the process of actually detecting underground pipelines, the radar image generated by ground penetrating radar mostly relies on manual discrimination, which has high dependence on the operator's experience. It can only judge

the position and depth of the pipeline, and lacks the identification of the pipe diameter information.

Based on GPR to detect the electromagnetic wave reflection mechanism of underground pipelines and the special circular shape of underground pipelines, after the operations of noise reduction and edge extraction on the acquired images, this paper uses the idea of “three-point rounding” to calculate the position of pipelines and the diameter of pipelines.

## 2 Underground Pipeline Echo Signal Characteristics

In the process of the ground penetrating radar advancing along the ground in the direction perpendicular to the pipeline, the transmitting antenna emits high-frequency pulsed electromagnetic waves to the underground, and when the local lower pipeline is within the detection depth range of the antenna wave, the echo signal of the target can be received. Figure 1 shows the schematic diagram of transmitting and receiving the co-located antenna ground penetrating radar to the underground pipeline. In the figure, the horizontal axis is the horizontal position of the antenna at the time of detection, and the vertical axis corresponds to the depth of the ground.



**Fig. 1.** Circular pipeline echo characteristics

If the echo received by the radar during the advancement of the ground penetrating radar along the surface of the earth is regarded as the signal returned from the point directly below the antenna, the virtual point targets are arranged according to the position to be illuminated, and the dotted line in Fig. 1 is obtained. That is to say, when the ground penetrating radar appears at the  $x_i$  position, the reflected wave at the point A of the pipe will appear at the point A' on the captured image. As can be seen from Fig. 1, the antenna can form a triangle at two points  $x_i$  and  $x_0$  and three points in the center of the pipeline, and the three sides follow the Pythagorean theorem, i.e.

$$(x_i - x_0)^2 + (z_0 + r)^2 = (z_i + r)^2 \quad (1)$$

Where  $r$  is the radius of the pipeline,  $z_0$  is the buried depth at the top of the pipeline,  $z_i$  is the distance between the antenna and the outer wall of the pipeline when the antenna is in the  $x_i$  position, and is also the distance from the echo signal received by point  $x_i$ . In the actual acquired image, the vertical axis of the image reflects not the distance  $z$ , but the two-way travel time  $t$  (reception delay) of the echo, and the delay and distance satisfy the relationship  $z_i = vt_i/2$ . Substituting the above equation

$$(x_i - x_0)^2 + \left(\frac{vt_0}{2} + r\right)^2 = \left(\frac{vt_i}{2} + r\right)^2 \quad (2)$$

Further conversion equation

$$\frac{(t_i + 2r/v)^2}{(t_0 + 2r/v)^2} - \frac{(x_i - x_0)^2}{(vt_0/2 + R)^2} = 1 \quad (3)$$

Each raw data pair  $(x_i, t_i)$  of the underground pipeline satisfies this equation. From this equation, it can be seen that the echo edge of the pipeline is a hyperbolic equation with  $(x_0, t_0)$  as a vertex. In order to solve the pipe radius  $r$  and the pipe depth position  $z_0$ , theoretically, the standard equation of the hyperbola can be obtained first, and corresponding to the Eq. (3),  $r, v, t_0, x_0$  can be obtained, but through experiment It is found that it is not easy to directly distinguish the four parameters of the hyperbolic equation from the image, so this paper studies other methods to calculate the position and radius of the pipeline.

### 3 Automatic Identification of Underground Pipelines

#### 3.1 Using gprMax to Establish an Underground Pipeline Echo Model

gprMax is modeled on the theory of electromagnetic wave propagation. The time domain finite difference method (FDTD) is used to solve the numerical solution of Maxwell's equations in various points in space. The core idea of FDTD is to discretize a 3D space into a large number of meshes. The size of each mesh is  $\Delta x \times \Delta y \times \Delta z$ , calculate the electric field strength and magnetic field strength in each mesh. Figure 2 shows an 8-space discrete space model.

The Maxwell relationship between the electric and magnetic fields in different directions within the grid is as follows

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - J_{S_x} - \sigma E_x \right) \quad (4)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - J_{S_y} - \sigma E_y \right) \quad (5)$$

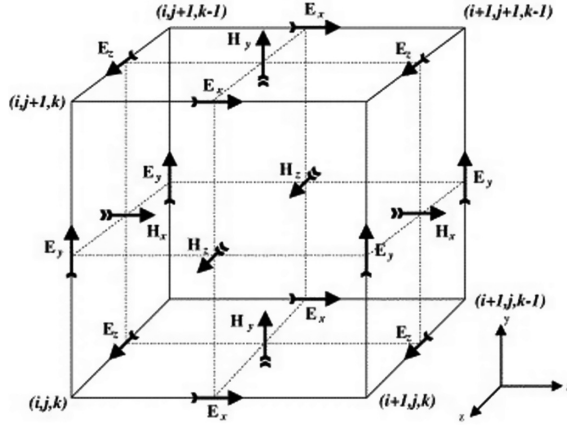


Fig. 2. FDTD discrete space

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - J_{S_z} - \sigma E_z \right) \quad (6)$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - M_{S_x} - \sigma^* H_x \right) \quad (7)$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - M_{S_y} - \sigma^* H_y \right) \quad (8)$$

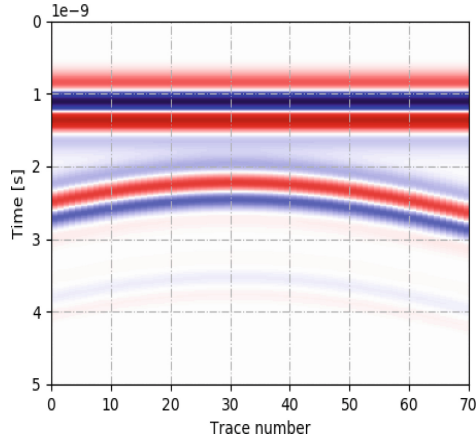
$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - M_{S_z} - \sigma^* H_z \right) \quad (9)$$

These equations are discrete in both time and space and can be solved in an iterative manner in the time domain. At each iteration, the electromagnetic field goes one step further in the grid, which simulates the field strength at each point in space.

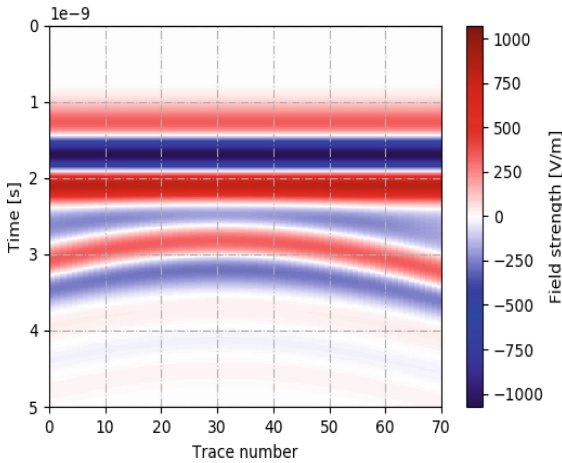
The basic conditions to be set by gprMax modeling include: the size of the detection area, spatial resolution, time window, underground environment, excitation and boundary conditions.

Figures 3 and 4 are a B-scan diagram of the underground pipeline when the center frequencies of the two excitation sources are 1.5 GHz and 900 MHz, respectively. The horizontal axis of the B-scan shows the number of tracks scanned, and the horizontal axis represents the echo time. The horizontal stripes appearing when the echo time is small in the figure are ground echoes. After the echo time increases, the curve that appears is the echo of the underground pipeline.

As can be seen from the figure, the higher the center frequency, the higher the spatial resolution, which is consistent with the theory, indicating that gprMax is more accurate in calculating the reflected echo.



**Fig. 3.** B-scan map at center frequency of 1.5 GHz



**Fig. 4.** B-scan map with center frequency of 900 MHz

### 3.2 Pipeline Identification Method

Both the tube depth and the tube diameter are estimated based on the acquired image, and the echo of the tube in the image has a hyperbolic characteristic. It is relatively easy to find the hyperbolic vertices to estimate the depth of the pipeline, even if it is judged by hand, there will not be too much error. At present, the application of ground penetrating radar in pipeline identification is mainly used to estimate the location of underground pipelines. It is not possible to directly determine the diameter of the pipe from the image, because the echo hyperbola is not a linear correspondence with the pipe cross-section circle.

In this paper, the method of “three-point rounding” is used in the research of pipe-pipe deep automatic identification. The traditional three-point circle method is to determine the center position and radius of the circle by three points on the circle. Here we determine the center and radius by reflecting three points on the hyperbola of the echo edge. It has been analyzed before. From Eq. (2), we can see the relationship between the position and delay of the measuring point and the coordinates and radius  $r$  of the vertex. In order to calculate the vertex coordinates and the radius  $r$ , three measuring points are selected and recorded. The position and time delay of these three measuring points can list three equations consistent with Eq. (1). With these three equations, the three variables of vertex coordinates and radius can be determined. Point to circle method, the equation is

$$\begin{aligned}(x_1 - m)^2 + (n + r)^2 &= \left(\frac{vt_1}{2} + r\right)^2 \\(x_2 - m)^2 + (n + r)^2 &= \left(\frac{vt_2}{2} + r\right)^2 \\(x_3 - m)^2 + (n + r)^2 &= \left(\frac{vt_3}{2} + r\right)^2\end{aligned}\quad (10)$$

Where  $(x_1, t_1)$ ,  $(x_2, t_2)$ , and  $(x_3, t_3)$  are the coordinates of the three points on the edge, respectively, and  $m$  and  $n$  are the horizontal and vertical coordinates of the vertices of the pipeline, respectively. In a picture to be processed, the number of tracks  $x'$  is often expressed in abscissa and the number of samples  $y'$  is plotted on the vertical axis. Their relationship with the horizontal distance  $x$  and the delay  $t$  is

$$x = ax' \quad (11)$$

$$t = \Delta t \bullet y' = \frac{T}{N}y' \quad (12)$$

Where  $a$  represents the track pitch,  $T$  represents the time window, and  $N$  represents the number of sample points. These values can be set in one sample, so they are known quantities. Substituting Eqs. (11) and (12) into Eq. (10),  $x'$  and  $y'$  are represented by  $x$ ,  $y$ , which can be obtained.

$$\begin{aligned}(a(x_1 - m))^2 + (bn + r)^2 &= (by_1 + r)^2 \\(a(x_2 - m))^2 + (bn + r)^2 &= (by_2 + r)^2 \\(a(x_3 - m))^2 + (bn + r)^2 &= (by_3 + r)^2\end{aligned}\quad (13)$$

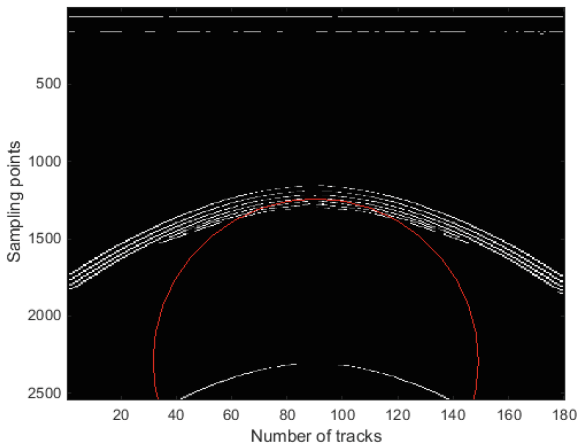
Here  $b = \frac{T}{N} \bullet \frac{v}{2}$  is a constant. The Canny operator obtains three different positions on the extracted edge. It is worth noting that before substituting the three coordinate points into the above equations, the ordinate should be subtracted from the position of the road surface. Because the road surface position in the image is not on the  $x$ -axis, and the equation is based on setting the road surface position to the  $x$ -axis.

## 4 Simulation Result

In the verification of the effect of the “three-point rounding” method to identify the position and radius of the pipeline, the influence of the selected three edge points on the recognition effect is studied. The error is analyzed by comparing with the real value.

In the model established by gprMax, the antenna center frequency is 900 MHz, the transmission and reception pitch is 0.01 m; the relative dielectric constant of the underground medium is 10, and the conductivity is 0.01; the interval between each channel is 0.01 m, the number of collection points per channel is 2545, and the time window is 30 ns; The pipe radius is 0.4 m and the pipe depth is 0.6 m. From the above-determined conditions,  $a = 5.5915e-04$  and  $b = 0.01$  in the Eq. (13) can be calculated.

Select points (30, 1375), (70, 1121), (130, 1214) on the extracted edges to test, determine the depth and radius of the pipeline, and draw the circular section of the pipeline into the edge extraction map, such as Fig. 5 shows.



**Fig. 5.** Pipeline section

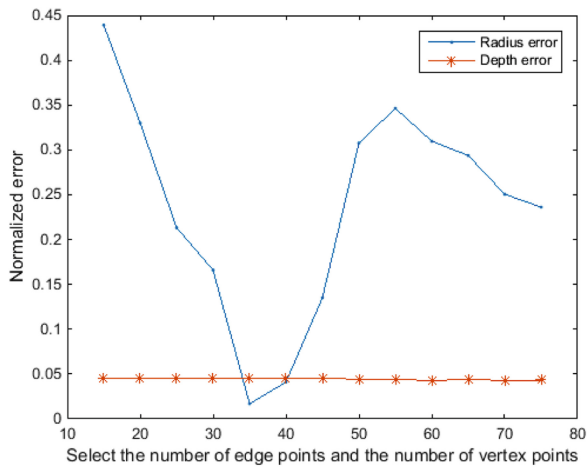
The cross-sectional view shows that the pipeline vertices are tangent to the hyperbolic vertices, which is consistent with the theory. This model was tested several times, and the three edge points selected for each test were positioned differently. Table 1 shows the tube depth and diameter and their errors measured at different points.

The rule for selecting coordinates in the table is to select a point close to the vertex of the hyperbola, and the other two points are symmetric about the vertex and closer to the hyperbolic vertex.

In order to facilitate the observation of the relationship between radius error, depth error and selected points, the error line graph is used to analyze the error trend, as shown in Fig. 6.

**Table 1.** Pipe diameter and pipe depth error when selecting different edge points

Edge point 1	Edge point 2	Edge point 3	Radius/m	Depth/m	Radius error	Depth error
(15, 1640)	(82, 1238)	(165, 1640)	0.4945	0.6273	0.2362	0.0455
(20, 1589)	(82, 1238)	(160, 1588)	0.5003	0.6270	0.2506	0.0451
(25, 1540)	(82, 1238)	(155, 1540)	0.5175	0.6274	0.2937	0.0456
(30, 1495)	(82, 1238)	(150, 1495)	0.5238	0.6268	0.3096	0.0447
(35, 1453)	(82, 1238)	(145, 1454)	0.5385	0.6271	0.3464	0.0452
(40, 1418)	(82, 1238)	(140, 1419)	0.5230	0.6271	0.3075	0.0452
(45, 1394)	(82, 1238)	(135, 1394)	0.4541	0.6272	0.1352	0.0453
(50, 1364)	(82, 1238)	(130, 1364)	0.4164	0.6265	0.0410	0.0442
(55, 1337)	(82, 1238)	(125, 1337)	0.3932	0.6267	0.0169	0.0445
(60, 1311)	(82, 1238)	(120, 1330)	0.3336	0.6254	0.1659	0.0424
(65, 1282)	(82, 1238)	(115, 1282)	0.4853	0.6267	0.2132	0.0445
(70, 1269)	(82, 1238)	(110, 1269)	0.2681	0.6255	0.3299	0.0425
(75, 1254)	(82, 1238)	(105, 1254)	0.2244	0.6260	0.4391	0.0433

**Fig. 6.** The influence of the selection of edge points on the error

## 5 Conclusion

The error of the pipe diameter identified by the “three-point rounding” method is controlled within 0.45, and the error at the lowest time can reach about 0.01, so it is feasible to use this method for pipeline identification. The depth estimation is more accurate and the selection of the three edge points has little effect on the depth estimation. The selection of the three edge points has a great influence on the estimation of

the pipe diameter. If the edge point is too far or too close to the pipeline, it will cause a relatively large error, and a minimum error will occur at a certain position in the middle.

In a position too close to the center, the curvature of the hyperbola is large, and the small change of the coordinate value of the selected point will have a great influence on the shape of the whole curve, so it is easy to cause errors. In the position far away from the pipeline, the reflection point of the antenna wave on the pipeline surface is not necessarily on the connection line between the center of the pipeline and the measurement position, that is, the condition that does not completely conform to the Pythagorean theorem, so the use of “three points” Large errors occur when the circle method is used.

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## References

1. Wang, Y., Chen, W.: Research on detection of parallel underground pipeline with small intervals, (3), 22–25 (2011)
2. Li, X.B., Hong, L.B.: Development and application of urban underground pipeline detection and management technology, (4), 5–11 (2010)
3. Liu, Y.Y., Yang, L.: Application of ground penetrating radar in underground pipeline detection, (3), 73–76 (2015)
4. Jol, H.: Ground Penetrating Radar: Theory and Applications. Elsevier Science, Amsterdam (2009)
5. Neal, A.: Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth-Sci. Rev.* **66**(3), 261–330 (2004)