APPLICATION OF GPR IN URBAN UTILITY DETECTION RANGING AND CHARACTERIZATION

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Abstract

Keeping track of underground utilities through maps or real physical signs is essential for their maintenance and quick repairs, whenever required, without causing much obstruction to day to day life. It is not uncommon that maps are misplaced or real physical signs are destroyed. In such situations, digging and excavation becomes unavoidable during repair works. Ground penetrating radar (GPR) is one of the non invasive methods which now are being applied for detection, ranging and characterization of subsurface buried objects. GPR employs radar pulses, sends them into ground, then get back scattered energy from dielectric discontinuities in the subsurface. Frequency of antennae determine their capacity to detect and resolve the buried objects (depth of penetration is worth a mention). Hence, 400MHz and 200MHz frequency antennae are generally used for utility mapping at shallow depths up to 4 to 5 meters.

GPR response to buried objects is very much dependent upon buried object locations, their constituents, their surroundings and antennae properties. It is very crucial to have a database of GPR responses corresponding to various influencing factors over their ranges of variability either by experimental or simulation studies. In the present work, an attempt has been made to generate data so as to know the dependence of GPR responses on changes in the influencing factors. Simulations have been carried out by using exclusive GPR simulation software called GPRMax. Several typical ground scenarios have been simulated and effects of various object, medium and antennae parameters on response of GPR have been studied and relationships have been established between them using response surface method (RSM). Finally, real GPR data has been compared with simulated data and interpreted.

Keywords: Urban utilities, Buried objects, GPR, Simulation, Response Surface Method.

1. Introduction

Construction activity in urban areas, particularly, infrastructure development related work, has now reached a frenetic pace in most metropolises. Mumbai is no exception. Inevitably, any excavation in developed and densely populated areas requires information regarding buried utilities. Such information is frequently not available even in new construction sites. Accidental damage to utilities like pipes and cables is common, and at times, of dangerous consequences. The need for *a priori* knowledge of the buried objects cannot be overemphasized.

Detection, ranging and characterization of the utilities are the three integral components of gathering information about them. Ground penetrating radar (GPR) offers an unique opportunity to gather this information. The ability of a Ground penetrating radar to respond to electromagnetic discontinuities in the ground makes it possible to detect metallic/ non metallic buried objects, subsurface layers, underground void formations etc. Therefore, GPRs have been very useful in utility mapping, in particular. They also find application in geotechnical, geological, archaeological, structural and environmental investigations and in mine detection, mass burial site mapping and so on.

A GPR sends a pulse of known central frequency into the ground and picks up the waves backscattered from the buried objects and the contrasting subsurface layers. The resulting response is presented in the form of a radargram, which depicts the variation of amplitude of reflected signals with (traverse) distance and depth or time of travel of pulse. The amplitudes of the returned signals and patterns in them depend on many factors like (a) antenna parameters such as central frequency and polarization, (b) host medium parameters like dielectric permittivity and (c) object parameters like shape and size and relative dielectric permittivity and conductivity. Interpretation of the radargram requires an understanding of the influence of these parameters. Conducting laboratory or full scale field studies under controlled conditions is an obvious, but expensive, solution. An attractive alternative is the numerical simulation of the propagation of the electromagnetic waves into the medium containing buried objects using Finite Difference Time Domain (FDTD) technique since computing resources are now easily available. This could, however, be a time-consuming computational process. Considerable simplification can be achieved by using Response surface method (RSM), which fits a polynomial to a relationship between input variables and responses of any experiment or process with limited number of outputs. An investigation of the use of simulation and RSM is the subject matter of the present study.

1.1 Significant response governing factors

In order to carry out simulations, it is necessary to identify the significant parameters that have an influence on the output response. RSM helps to identify the significant inputs. When the actual dependence of a system response on its constituent variables is not known but the governing equations are, then RSM helps to establish an equivalent relationship. RSM is a statistical technique (Zangeneh et al., 2002; Myers and Montgomery, 2006), which helps to replace the true response of a system or a process using an equivalent polynomial surface.

Let a general true response f be represented by Eq. (1),

$$y = f(\varsigma_1, \varsigma_2, \varsigma_3 \ldots\ldots \varsigma_k) + \gamma \quad (1)$$

$$y = f(\zeta_1, \zeta_2, \zeta_3 \ldots\ldots \zeta_k) + \gamma$$

where, ζ_1 to ζ_k are the actual variables on which a system depends and γ is a term representing sources of variability not accounted for in f and treated as a statistical error.

RSM builds an equivalent polynomial surface using least square regression analysis to minimize this error.

The equivalent second-order polynomial, involving two variables/factors, is given as shown in Eq. (2):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \quad (2)$$

where x_i are called coded variables, which are transformed values of the actual variables ξ_i , to the domain of [-1,1] and β_{ij} are called regression coefficients. This can be easily extended to the case of several variables. In building this surface, the factors are treated as random variables and three levels (mean and ± standard deviation) are considered.

The three - level, three - factor experiment uses 27 function values as illustrated in Fig. 1 (http://solutions.knovelblogs.com). The coefficients can be obtained by solving for β using Eq. (3):

$$y = x\beta + \gamma \quad (3)$$

$$y = x\beta + \gamma$$

where β is the column vector of regression coefficients, and γ is the column vector containing the random errors. Then, substituting the β values in Eq. (2), we get the response surface and the relative influence of the variables on the ultimate response.

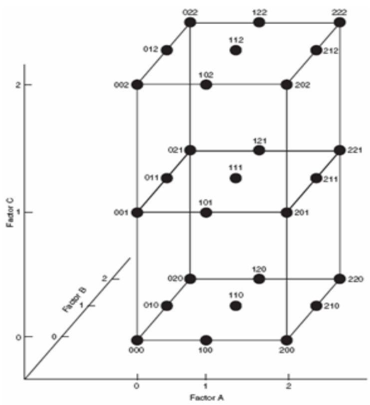


Figure 1: Levels of factors and analysis domain for a 3 - factor experiment (http://solutions.knovelblogs.com).

1.2 Simulation of GPR Responses by FDTD

The foregoing shows that useful relationships can be established between input variables and output response through a series of simulations using a specified random set of parameter values. These simulations mimic the propagation of electromagnetic waves in the medium. The travel of GPR pulses is an example of propagation of electromagnetic waves through a medium and is governed by Maxwell's equations (4) to (7) and constitutive equations (8) and (9):

$$\text{Faraday's law}: \nabla \times E = -(\delta B/\delta t) - M \tag{4}$$

$$\text{Ampere's law}: \nabla \times H = J + (\delta D/\delta t) \tag{5}$$

$$\text{Gaussian theorem}: \nabla . D = \rho_e \tag{6}$$

$$\nabla . B = \rho_m \tag{7}$$

$$\text{Electric Displacement and Electric Field}: D = \varepsilon E \tag{8}$$

$$\text{Magnetic Induction and Magnetic Field}: B = \mu H \tag{9}$$

where,

E = electric field in volt/m, ***D*** = electric displacement field in coulombs/square meter, ***H*** = magnetic field in ampere/m, $\nabla\times$ = divergence operator in per meter, ***B*** is magnetic flux density in webers per square meter, ***(δ/ δt)*** = partial derivative w.r.t. time, ***J*** = total current density in amperes per square meter, ***M*** = magnetic current density in volts per square meter, $\boldsymbol{\rho_e}$ = free charge density in coulombs per cubic meter, $\boldsymbol{\rho_m}$ = magnetic charge density in webers per cubic meter, $\boldsymbol{\varepsilon}$ = permittivity and $\boldsymbol{\mu}$ = permeability.

Numerical simulation of electromagnetic wave propagation using FDTD involves solution of the above equations by discretization of the medium into a spatial grid (Diamanti, 2008). Once the medium is discretized, electric and magnetic field components are placed at these discrete positions in space and Maxwell's equations are solved in time at discrete time instants. To solve these equations, first, the Maxwell's curl equations are converted to finite scalar derivatives in space and time. Simulation of the phenomenon of propagation is achieved using a forward difference time marching algorithm that computes the field values at a future time instant from the values of a past time instant.

There are simulation tools available for simulation of electromagnetics in Elsherbeni and Demir (2009). But, a special purpose FDTD tool for GPR data, GprMax, is available in (www.gprmax.org.). In Giannopoulos (2005), working of GprMax is demonstrated with a few examples. A-scan simulation above lossy and dispersive soils is described in Uduwawala et al (2005). The frequency responses of GPR using A-scan and B-scan simulations are discussed in Oguz and Gurel (2002). Effects of surface roughness and medium in- homogeneity are examined in Uduwawala et al (2005) and Oguz and Gurel (2002). A demonstration of pavement modeling and pavement layers thickness calculations through A-scan simulations is presented by Zhang et al (2010). In the present work, GprMaxV2.0, which employs FDTD method, is used for B-scan simulations to understand the fundamental behavior of GPR. Parameters like medium relative dielectric permittivity, antenna frequency, pipe diameter and material have been varied to understand GPR response. Further, in the present work, RSM has been used to model the GPR responses (amplitude) for the problems studied.

1.3 Utility Detection and Role of Simulation

The importance of simulation studies lies in the fact that detection of buried pipes using GPR under real field situations is still an active area of research. There are several commercial companies which use proprietary software and offer a variety of GPR services (http://www.geophysical.com; http:www.nyld.com/index.asp). But, success depends on a number of factors such as host medium-pipe material combinations, depth, size and number of pipes and frequency of antennae, amongst others. Turkel et al. (2009) have given an excellent comparison of the GPR technique with electromagnetic method based on an actual case study. They have also highlighted the possibility of erroneous detection using GPR. But, another important dimension of the problem is the determination of depth, diameter and dielectric permittivity of the material of the buried pipes. Notable contributions to this aspect are those of Shihab and Al-Nuaimy (2005), Windsor et al. (2005) and Umar and Al-Nuaimy(2009). This is an area where a database of typical responses of pipes under a variety of conditions coulc help. Simulation can play a vital role in development of the database. This has been the motivation for the present study.

1.4 Scope and Objectives

Detection, ranging and characterization require a fundamental understanding of the effect of various parameters on which GPR response depends. The scope of the present study is to carry out FDTD simulations and establish relations through RSM which will help interpret real radargrams.

The objectives of the present study are:

(i) to relate, through FDTD and RSM, amplitude of GPR response to factors which influence it

(ii) to study the influence of significant parameters with a view to interpret real radargrams.

For this purpose, several simulation studies were carried out. Real GPR data was also collected through field work at selected locations. These were locations where buried pipes were known to be present and were accessible in order to ascertain their geometrical parameters.

2. Simulation of Fundamental Behaviour of GPR

Simulations are carried out with a view to understand the implication of influence of various parameters on detection, ranging and characterization. **Detection** refers to identifying the presence of a buried utility. It is well known that a buried cylindrical object produces a hyperbola in a radargram. Therefore, a problem of a buried pipe has been considered and the visibility, location and size of hyperbolae have been used to evaluate the effects of main influencing parameters i.e. host medium relative dielectric permittivity, antenna frequency, size and material of pipe. **Ranging** refers to the determination of the depth of the buried object. Effect of medium relative dielectric permittivity on depth has been studied through simulation. **Characterization** refers to identification of the material of the object. So, the material type, as defined by the object relative dielectric permittivity has been varied in simulation studies.

Further, RSM is used to build an equivalent polynomial response equation of a desired degree. In the following section, such RSM based simulations have been described for 3 and 4 Factorial problems / experiments.

3. GPR Response (Amplitude) as a Function of its Influencing Factors

An attempt has been made here to systematically study problems of varying complexity to bring out significant effects.

3.1 The four parameter problem

A typical problem of a buried pipe in soil is analysed first. The geometry of the media (air and soil) and the object are shown in Fig. 2. The response to GPR in such an object-medium combination would depend essentially on pipe diameter (x_1), object relative dielectric permittivity (x_2), soil relative dielectric permittivity (x_3) and antenna frequency (x_4). The medium is assumed to be homogeneous, dry and of conductivity = 0.001S/m.

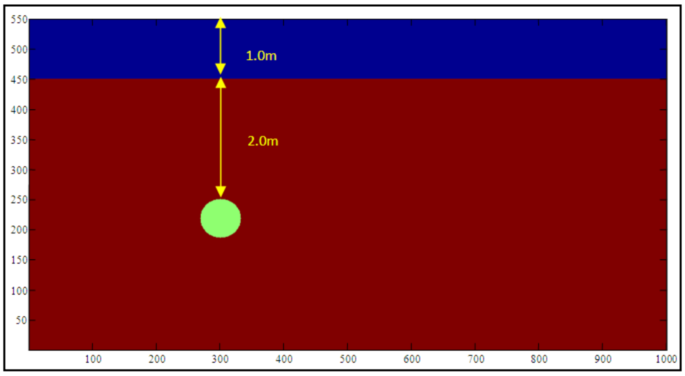


Figure 2: Problem statement for Four parameter and Three parameter problems

The values selected for input factors based on the experiences during real GPR data collections are: $x_1 = 0.64$m, 0.8m, 0.96m; $x_2 = 6, 10, 14$; $x_3 = 2,4,6$; $x_4 = 200$MHz, 400MHz,600MHz

Being a three – level, four factorial experiment, 81 combinations of the random variables are used and radargrams are generated through FDTD. The amplitude at the crown of the hyperbola is the response parameter. Amplitude (A) at the crown of the hyperbola, expressed as a 2nd order polynomial function of influencing factors is found to be as shown in Eq.(10):

$$A = +1.32031 - 4.85821x_1 - 0.057857x_2 + 0.20482x_3 + 6.55065E\text{-}04x_4 + 0.20234x_1x_2 - 0.16025x_1x_3 + 2.45887E\text{-}003x_1x_4 + 0.021273x_2x_3 + 7.42951E\text{-}06x_2x_4 - 1.26282E\text{-}04x_3x_4 + 2.60122x_1^2 - 5.61073E\text{-}03x_2^2 - 0.034176x_3^2 - 2.02638E\text{-}006x_4^2 \tag{10}$$

The standard errors associated with the coefficients are, respectively, 0.052, 0.021, 0.021, 0.021,0.021, 0.026, 0.026, 0.026, 0.026, 0.026, 0.026, 0.037, 0.037, 0.037 and 0.037. ANOVA shows that x_1, x_2, x_3, x_4, x_1x_2 and x_1x_3 are the significant factors and that, effect of frequency on the amplitude is very less compared to effect of pipe diameter, object relative dielectric permittivity and soil relative dielectric permittivity.

3.2 The three parameter problem

Hence, to bring out the effects of the significant parameters on the response, frequency is now kept constant at 200 MHz and a 3 - factorial problem i.e. three influencing factors/ input variables with three levels is analysed. The problem geometry is same as in Fig. 2. The three factors chosen are pipe diameter, soil relative dielectric permittivity and object relative dielectric permittivity and response is the amplitude at the crown of the hyperbola. Using RSM, amplitude has been expressed as polynomial function of pipe diameter (x_1), object relative dielectric permittivity (x_2) and soil relative dielectric permittivity (x_3) at ideal conditions (conductivity = 0.001S/m, medium is homogeneous, dry and of suitable frequency for required penetration). The input factors are, as before, $x_1 = 0.64$m, 0.8m, 0.96m; $x_2 = 6, 10, 14$; $x_3 = 2,4,6$.

Simulations have been carried out for 27 combinations and corresponding amplitudes at the crown of the hyperbola have been computed and used as responses. The resulting relationship between Amplitude and the three factors is expressed as a 2nd order polynomial function of influencing factors in Eq. (11):

$$A = +1.25925 - 2.38889x_1 - 0.067993x_2 - 0.11917x_3 + 0.20326\,x_1x_2 + 6.92448E\text{-}003x_1x_3 + 0.013273x_2x_3 + 0.87331x_1^2 - 3.75938E\text{-}003x_2^2 - 5.31708E\text{-}003x_3^2 \tag{11}$$

The standard errors associated with the coefficients are, respectively, 0.020, 0.009, 0.009, 0.009, 0.011, 0.011, 0.011, 0.016, 0.016 and 0.016. ANOVA (ANalysis Of VAriance) shows that x_1, x_2, x_3, x_1x_2, x_2x_3 and x_2^2 are the significant factors. This further confirms the importance of the object and medium permittivties. The amplitude variation with these parameters is shown in Fig. 3.

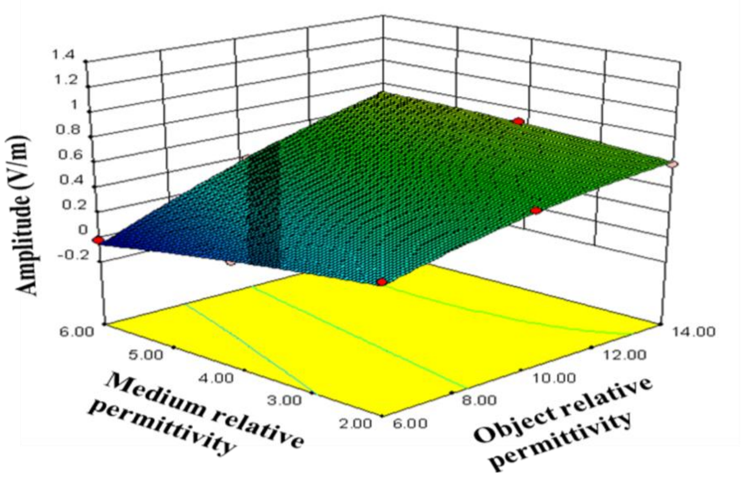


Figure 3: Variation of amplitude with medium and object relative permittivities at pipe dia = 0.8m

On the basis of these simulations, effect of medium dielectric permittivity and pipe material dielectric permittivity were chosen for further investigation (Sections 3.3 to 3.6).

3.3 Effect of host medium relative dielectric permittivity

In order to understand the importance of range / depth of object on GPR response, further simulations have been done using the following problem geometry (Fig. 4). Since, host medium relative dielectric permittivity has a significant effect on GPR data, it has been varied over a wide range. For this, three different pipe-cover combinations with different dielectric permittivities were identified . They were: concrete pipe –concrete or paver block cover (ε_r = 4), metal pipe- concrete or paver block cover (ε_r = 15) and concrete pipe – wet soil (ε_r = 30). Fig. 5(a) to Fig. 5(c) show simulated results at host medium relative dielectric permittivities = 4, 15and 30 at a frequency of 200 MHz. Similar results for 400 MHz are presented in Fig. 6(a) to Fig. 6(c).

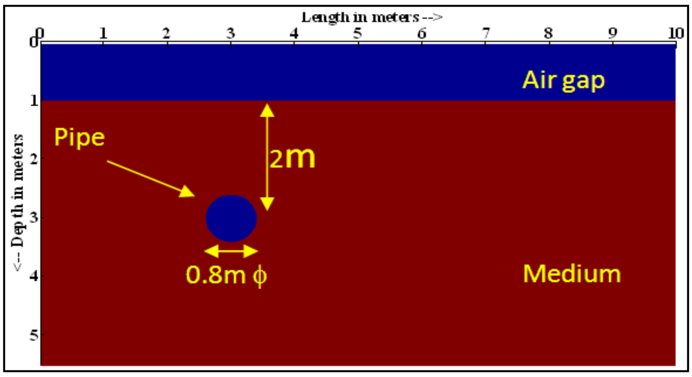
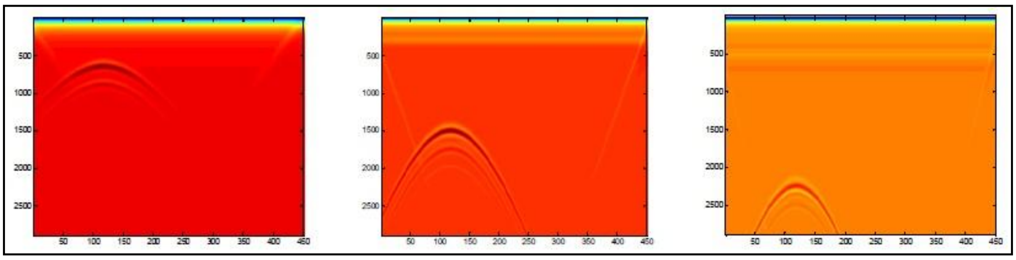
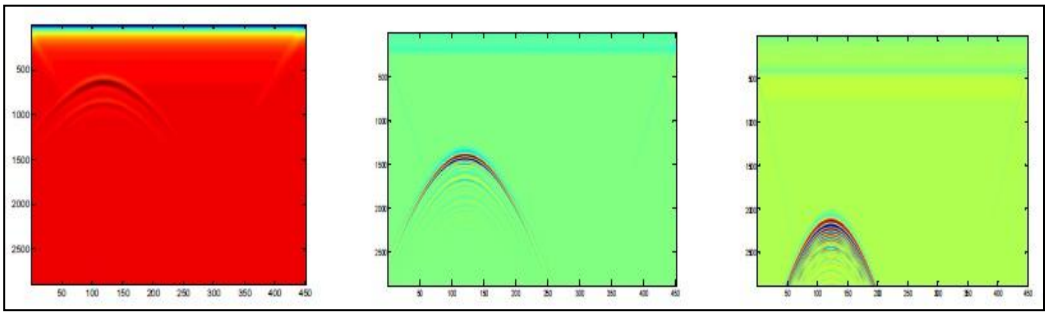


Figure 4: Problem statement for effect of medium dielectric permittivity



(a) $\varepsilon_r = 4$ *(b)*$\varepsilon_r = 15$ *(c)* $\varepsilon_r = 30$

Figure 5: Effect of medium dielectric permittivity at 200 MHz

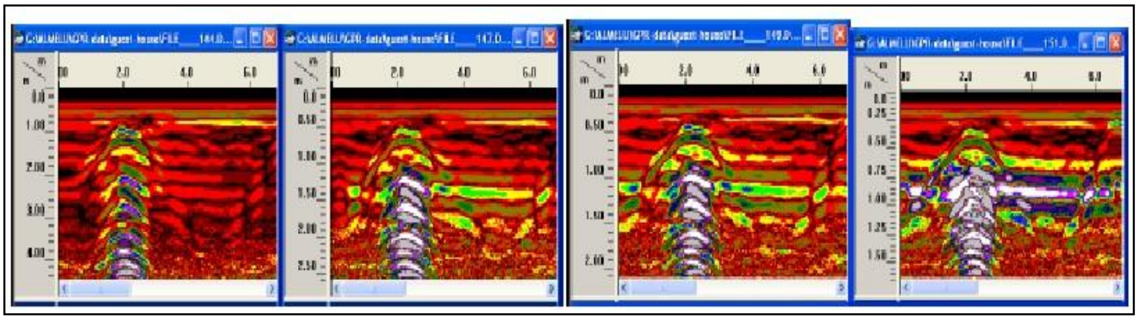


(a) $\varepsilon_r = 4$ *(b)*$\varepsilon_r = 15$ *(c)* $\varepsilon_r = 30$

Figure 6: Effect of medium dielectric permittivity at 400 MHz

3.4 Comparison with real GPR Data

These are compared with real GPR data collected at 200 MHz and different input relative dielectric permittivities at a site where pipe was buried below paver blocks (Fig. 7(a) to 7(d)).



(a) (b) (c) (d)

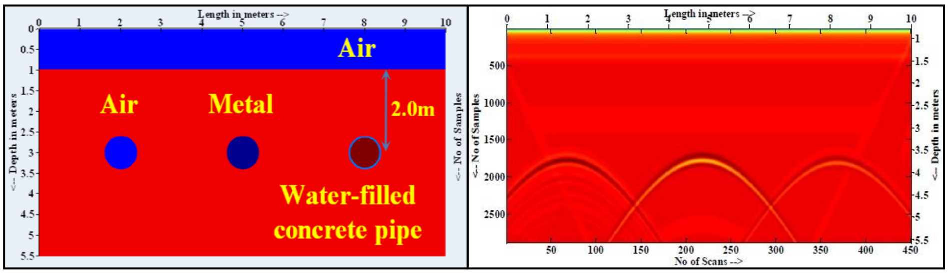
Figure 7: Effect of input relative dielectric permittivities (a) 4, (b) 12, (c) 18 and (d) 30

Any comparison with real GPR data has its inherent difficulties since certain antenna details required for simulation are manufacturer's proprietary confidential information. Nevertheless, a fairly good qualitative comparison is possible. It must be noted that in real GPR data relative dielectric permittivity of the medium is a user-defined input and could be different from the actual field value.

The amplitude values increase with increase in medium relative dielectric permittivity in both real and simulated data. The hyperbola appears at progressively greater depths with increase in medium relative dielectric permittivity in both real and simulated data. Accuracy of ranging, therefore, depends on the influence of medium relative dielectric permittivity. Simulation helps to capture the effect of medium relative dielectric permittivity on shape of hyperbola

3.5 Effect of pipe materials

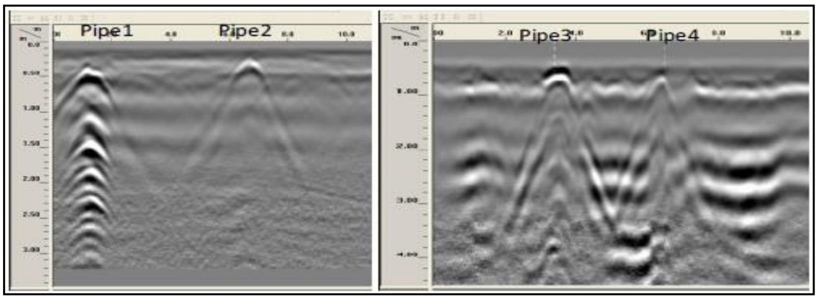
Identifying the type of material of the buried object is another important requirement. The usual material types are metal, concrete and PVC. It is a difficult task since the object dielectric permittivity values for different materials could vary within narrow limits and the ranges may overlap. The problem statement for effect of different pipe materials is given in Fig. 8(a). Here, from left to right, a void, a metal pipe, a concrete water-filled pipe have been depicted. The simulated results are presented in Fig. 8(b).



(a) *(b)*

Figure 8: Effect of material type (a) problem statement (b) simulation results

Fig. 9(a) shows GPR data collected at 200MHz , over concrete (pipe 1) and metal (pipe 2) pipes buried under paver blocks and Fig.9(b), over two concrete pipes buried in concrete.



(a) *(b)*

Figure 9: GPR data collected over: a) Concrete and Metal pipes b) Two concrete pipes

Simulation shows: (i) the hyperbola due to a void has multiple reflections and there is a (-) ve cycle in the beginning (ii) the hyperbola due to metal cylinder has no multiple reflections and has a positive cycle in the beginning. Amplitude values are highest and (iii) the hyperbola due to water filled pipe has no multiple reflections. It also has a (+) ve cycle in the beginning due to higher relative dielectric permittivity of water. Amplitude values are not high as compared to hyperbola of metal pipe.

3.6 Comparison with GPR data on actual pipes

The hyperbola due to a void has multiple reflections. In Fig. 9(a), Pipe1 is a concrete pipe filled with air. As indicated by simulation, it has multiple reflections. In comparison, Pipe 2, which is of metal, does not show multiple reflections in real as well as simulated data. Water filled pipes have no multiple reflections as indicated in simulation.

4 Conclusions

On the basis of above studies, following conclusions may be drawn.

1) GPR response as a function of influencing factors , as obtained from 3 and 4 factor experiments show:

    i) Consideration of frequency as an additional parameter shows that increasing frequency increases the amplitude marginally.

    ii) The amplitude depends on diameter and relative dielectric permittivity of the object rather than on soil relative dielectric permittivity

2) In general, simulation helps to gain a better understanding of the real GPR response. In both the simulated and real GPR data:

    i) The depth of the hyperbola is increasing with increase in relative dielectric permittivity;

    ii) the size however decreases in simulated data while it remains unchanged in real data due to the fixed relative dielectric permittivity of the medium

3) RSM is an effective tool to represent the unknown relationship of GPR response with the various influencing parameters. It could be used for predicting change patterns in amplitudes due to changes in significant influencing parameters.

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