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Uses of Dielectric Constant Reflection Coefficients for Determination of Groundwater Using Ground-Penetrating Radar

A.D. Vasudeo, Y.B. Katpatal and R.N. Ingle

Department of Civil Engineering,
Visvesvaraya National Institute of Technology, Nagpur-440011, Maharashtra, India

Abstract: A method to determine ground-penetrating radar GPR velocities, which utilize dielectric properties of geological material is presented. The method determines the relative dielectric constant ratio at interface boundaries where the radar wave is traveling from a low-velocity to a high-velocity medium. Using dielectric formulae analysis it has been found the fastest means to determine the velocity of saturated medium below the deepest detectable reflector. The relative dielectric constant ratio is in good agreement with the relative dielectric constant ratio calculated from the known velocities.

Key words: Dielectric Constants · Ground penetrating radar · Groundwater

INTRODUCTION

Ground-penetrating radar GPR has gained popularity in recent years owing to its speed and ease of use. Velocity analysis has been limited to common midpoint CMP (Common Mid Point Method) surveys, which give the velocity structure above a reflector at a single location. Ground penetrating radar (GPR, sometimes called ground probing radar, georadar, subsurface radar, earth sounding radar) is a noninvasive electromagnetic geophysical technique for subsurface exploration, characterization and monitoring (history) [1]. It is widely used in locating lost utilities, environmental site characterization and monitoring, agriculture, archaeological and forensic investigation, unexploded ordnance and land mine detection, groundwater, pavement and infrastructure characterization, mining, ice sounding, permafrost, void, cave and tunnel detection, sinkholes, subsidence, karst and a host of other applications [2]. It may be deployed from the surface by hand or vehicle, in boreholes, between boreholes, from aircraft and from satellites. It has high resolution for imaging the subsurface, with centimeter scale resolution sometimes possible [3]. Two points are often required to be considered in signal de-noising applications: eliminating the undesired noise from signal to improve the Signal-to noise Ratio (SNR) and preserving the shape and characteristics of the original signal [4].

The electrical and magnetic properties of rocks, soils and fluids (natural materials) control the speed of propagation of radar waves and their amplitudes [5]. In most cases, the electrical properties are much more important than the magnetic properties. At radar frequencies, electrical properties are dominantly controlled by rock or soil density and by the chemistry, state (liquid/gas/solid), distribution (pore space connectivity) and content of water [6]. Electrical properties by Roberts and Daniels [7], come in two basic types: one that describes energy dissipation and one that describes energy storage. Electrical dissipation comes as the result of charge motion (or transport) called conduction. Electrical conductivity is the ability of a material to transport charge through the process of conduction, normalized by geometry to describe a material property. Dissipation (or energy loss) results from the conversion of electrical energy to thermal energy (Joule heating) through momentum transfer during collisions as the charges move [2]. Electrical storage is the result of charge storing energy when the application of an external force moves the charge from some equilibrium position and there is a restoring force trying to move the charge back. This process is dielectric polarization, normalized by geometry to be the material property called dielectric permittivity [8]. As polarization occurs, causing charges to move, the charge motion is also dissipative. In either case, charge motion is described by the diffusion

Corresponding Author: A.D. Vasudeo, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur-440011, Maharashtra, India

equation. Charges moving with finite velocity result in frequency dependent properties described by over damped harmonic oscillators and the Debye single relaxation equation at frequencies below tens of gigahertz. Adding the storage force balance in the acceleration term to the diffusion equation results in a wave propagation equation [9]. The combined electrical and magnetic storage (polarization) terms through the properties of dielectric permittivity and magnetic permeability control the velocity of electromagnetic wave propagation.

Dielectric Properties: The electrical mechanisms of importance to ground penetrating radar are the electrical conduction losses, mostly from metals, salt water and other good conductors which dissipate the energy as heat: these are good reflectors, easy to see with radar, but impossible to see through or past (radar can see through fresh water) [10].

Dielectric polarization relaxation by rotational orientation of the water molecule: a (amplitude)>10 GHz process in free water, but in the 10 kHz range in ice, 10 MHz range in clathrate hydrates and at frequencies from 100 Hz to 100 MHz caused by interactions inside pore structures [11]. These losses are proportional to the amount of free or mobile water present.

The active surface chemistry and high surface areas cause Electrochemical polarization at the interface between water and clay minerals like montmorillonite. This isimportant below 100 MHz [2]. This is not significant in finely ground "rock flour" engineering size fraction clay, which has high surface area but low chemical reactivity. The wavelength of propagating energy is sent in random directions by scales of geological heterogeneity comparable to the wavelength. Pea gravel becomes important above 1 Ghz [12]. Scattering is both good and bad. If there is no scattering, then there is nothing for the radar to detect. If there is too much scattering, then the radar can'tdetect anything through the scatter.

These electrical mechanisms create frequency dependence resulting in dispersion (frequency dependent velocity and attenuation that change pulse shape with distance of propagation), contrast resulting in scattering and they cause energy losses which limit depth of investigation. Energy is also lost in magnetic relaxation and by geometric spreading losses (see radar equation) [7]. Geometric spreading losses result as the propagating wave front expands away from the source (transmitter) antenna and the power is spread over the surface of the antenna pattern (much like being spread over the surface area of a balloon).

Table 1: Dielectric values for common materials [2]

Material	Dielectric Value	Velocity (mm/ns)
Air	1	300
Water (fresh)	81	33
Water (Sea)	81	33
Coastal sand (dry)	10	95
Sand (dry)	3-6	120-170
Sand (wet)	25-30	55-60
Silt (wet)	10	95
Clay (wet)	8-15	86-110
Clay soil (dry)	3	173
Marsh	12	86
Agricultural land	15	77
Pastoral land	13	83
Average soil	16	75

Geology is not uniform, homogeneous and isotropic in space [13]. The processes that create near surface geology leave behind patterns with variations in space (heterogeneity), orientation (anisotropy) and scale (grain size and sorting and fracturing for example). These spatial variations may be quantitatively mapped and statistically described with great effectiveness by using the high resolution of ground penetrating radar [14]. Such high-resolution images may be used to infer and map the geological process that created the patterns. Anisotropy may alsoappear as preferred orientations with better or worse wave propagation characteristics (as in relative to the cleat in coal or rebar in concrete) [15]. Heterogeneity, anisotropy and scale also appear in polarization, scattering and clutter limitations of depth ofinvestigation and detectability. Heterogeneity may also be a function of temporal variation because of daily or seasonal rainfall and water table fluctuations.

Estimating Velocity from the Dielectric Constant: By using the standard values of dielectric constants or velocities; or two way travel time available for different materials, the groundwater level can be estimated.

$$V = \frac{C}{\sqrt{\varepsilon_r}} \tag{1}$$

$$TT = \frac{1}{V} = \frac{\sqrt{\varepsilon_r}}{C} \tag{2}$$

$$TT\ (ns) = 6.6\sqrt{\varepsilon_r} \tag{3}$$

Where,

C = Speed of light (3×10^8 m/s)
ϵ_r = Dielectric constant
V = Velocity (m/ns)
TT = Two-way travel time per unit (slowness), ns/m

Locate Object of Known Depth: Acquire a line of GPR data perpendicular to the long axis of a target of known depth, such as a tank or pipe. Determine the round-trip travel time to the target from the GPR data [16]. Alternatively enter different dielectric constant values until the correct depth to the target appears on the depth scale of the GPR data, or estimate the velocity of the radar wave through the subsurface material using:

$$\text{Velocity} = \frac{2 \times \text{Depth}}{\text{Travel Time}} \tag{3}$$

The depth of unknown targets can now be estimated using:

$$\text{Depth} = \frac{\text{Velocity} \times \text{Travel Time}}{2} \tag{4}$$

Geometric Scaling: Because a cylindrical object, such as a pipe, has many surfaces that are normal to the antenna radiation pattern as the antenna approaches and passes over the pipe at right angles, a hyperbolic diffraction results in the data. The hyperbola can be used to find the depth to the pipe when only a distance along the ground and a time ratio, which is easily scaled off the data, are known as per the study represented by Leuschen and Plumb [9]. As the antenna approaches a pipe, the pipe begins to be detected by the antenna when the line of sight between the pipe and the antenna is approximately 45°. The reflection from this pipe arrives at a time that is equal to the "slant range", tz, or distance between the target and the antenna. As the antenna gets closer to the pipe, the time of the pipe arrival decreases.

If it is assumed that the subsurface distance Z is, on the average, equal to distance X and that the subsurface pipe dimensions are insignificant (ex. pipe diameter is less than one-quarter of the depth to the pipe) relative to the other dimensions then:

$$X^2 + Y^2 = Z^2 \tag{5}$$

and,

$$\frac{t_y}{t_x} = \frac{Y}{Z} \tag{6}$$

Where,
X = distance along the surface in feet or meters
Y = depth of pipe in feet or meters
tz = travel time or "slant range" to pipe
ty = vertical incidence travel time to pipe

By combining the above two equations we obtain:

$$Y = \frac{X}{\sqrt{\left(\frac{t_z}{t_y}\right)^2 - 1}} = KX \tag{7}$$

Note that the equation requires only the distance along the surface to be known and that a ratio with no dimensions be scaled off the data. In practice, the simplest use of the equation results when the ratio t_y / t_z is chosen to be a convenient number such as 1.4, in which case the factor K becomes 1 to within 2% and the depth of the pipe is equal to the distance X.

Table 2: Estimated water level analysis taking into account dielectric constant

Date (2008)	Position (m)	Travel time (ns)	Velocity (m/ns)	Dielectric constant	Average dielectric constant	water level (m)
23rd January	-	240	0.10	9.00	9.00	13.17
13th March	12.50	200.36	0.10	9.00	8.22	13.15
	128.50	187.73	0.11	7.44		
23rd March	12.50	223.83	0.12	6.25	6.25	13.15
	128.50	214.80	0.12	6.25		
13th May	12.50	184.12	0.11	7.44	6.84	12.55
	128.50	196.75	0.12	6.25		
23rd June	128.50	207.58	0.10	9.00	9.00	12.09

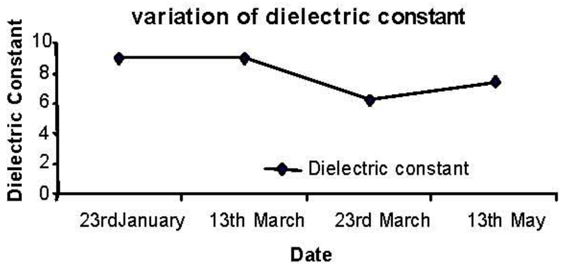

Fig. 1: Variation of dielectric constant at 12.50m

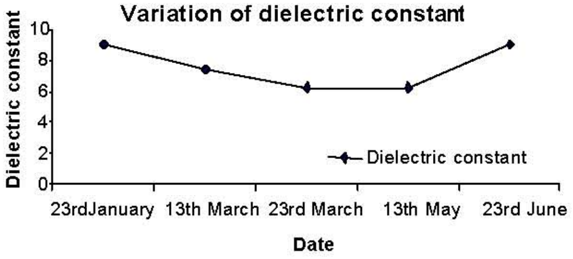

Fig. 2: Variation of dielectric constant 128.50m

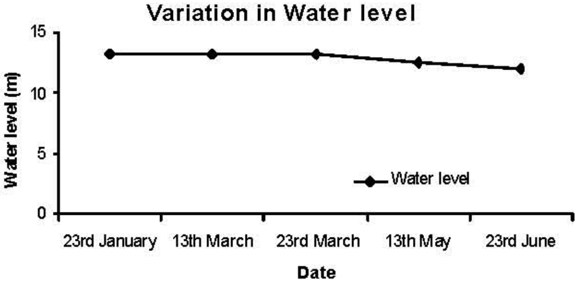

Fig. 3: Water level after averaging dielectric constants

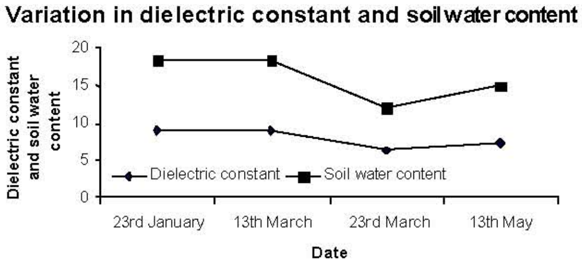

Fig. 4: Dielectric constant and soil water content at 12.50m

Estimation of Water Level by GPR Using Dielectric Constants: On 23rd January 2008, the data was collected in both time and point base. For this data a dielectric value 9.00 was substituted by assuming a basaltic type rock. The common offset between transmitter and receiver was kept 0.60m. For point base data collection, the survey points were marked at 2.00m. For this setting of point base data collection, interpretable profiles could not be obtained. Therefore, for the next surveys, the offset between transmitter and receiver was kept as 1.00m and the survey points were marked at 0.50m. The CMP gathers were collected at 12.50m and 128.50m to compute the wave velocities. The velocities corresponding to maximum amplitude of reflection were used. On 13th March, 23rd March, 13th May and 23rd June velocity values as observed are shown in Table 2.

CONCLUSION

The GPR method records microwave radiation that passes through the ground and is returned to the surface. A transmitter sends a microwave signal into the subsurface and the radar waves propagate at velocities that are dependent upon the dielectric constant of the subsurface medium. Changes in the dielectric constant due to changes in water saturation, cause the radar waves to reflect and the time taken by the energy to return to the surface relates to the depth at which the energy was reflected. Thus, the interpretation of this reflected energy yields information on variation of ground water level. Data are most often collected along a survey profile, so that plots of the recorded signals with respect to survey position and travel-time can be associated with images of geological structure as a function of horizontal position and depth. GPR can be collected fairly rapidly and initial interpretations can be made with minimal data processing, making the use of GPR for geophysical investigation quite cost-effective.

REFERENCES

1. Moffatt, D.L. and R.J. Puskar, 1976. A subsurface electromagnetic pulse radar. Geophysics, 41(3): 506-518.
2. Conyers, L.B. and D. Goodman, 1997. Ground-Penetrating Radar: An Introduction for Archaeologists, AltaMira Press.
3. Atekwanna, E.A., W.A. Sauck and D.D. Werkema, 2000. Investigations of geoelectrical signatures at a hydrocarbon contaminated site. J. of Applied Geophysics, 44(2): 167-180.
4. Zehtabian, A. and H. Hassanpour, 2009, A Non-destructive Approach for Noise Re duction in Time Domain, World Applied Sci. J., 6(1): 53-63. 2009: ISSN 1818-4952.
5. Birken, R. and R. Versteeg, 2000. Use of four-dimensional ground penetrating radar and advanced visualization methods to determine subsurface fluid migration. J. of Applied Geophysics, 43(2-4): 215-226.

6. Beres, M. and F.P. Haeni, 1991. Application of ground-penetrating-radar methods in hydrogeologic studies. Ground Water, 29(3): 375-386.
7. Roberts, R.L. and J.J. Daniels, 1997. Modeling near-field GPR in three dimensions using the FDTD method, Geophysics, 62(4): 1114-1126.
8. Guy, E.D., J.J. Daniels, S.J. Radzevicius and M.A. Vendl, 1999. Demonstrating of using crossed dipole GPR antennae for site characterization. Geophysical Research Letters, 26(22): 3421-3424.
9. Leuschen, C. and R. Plumb, 2000. A matched-filter approach to wave migration. J. of Applied Geophysics, 43(2-4): 271-280.
10. Benson, A.K., 1995. Applications of ground penetrating radar in assessing some geological hazards: examples of groundwater contamination, faults, cavities. J. Appl. Geophysics, 33(1-3): 177-193.
11. Mellett, J.S., 1995. Ground penetrating radar applications in engineering, environmental management and geology. J. of Applied Geophysics, 33(1-3): 157-166.
12. Cook and C. John, 1960. Proposed monocycle-pulse, VHF radar for airborne ice and snow measurements. AIEE Trans. Commun. And Electron., 79(2): 588-594.
13. Olhoeft, G.R., 2000. Maximizing the information return from ground penetrating radar. J. Appl. Geophysics, 43(2-4): 175-187.
14. Greaves, R.J., D.P. Lesmes, J.M. Lee and M.N. Toksöz, 1996. Velocity variations and water content estimated from multi-offset, ground-penetrating radar. Geophysics, 61(3): 683-695.
15. Peters, L., J.J. Daniels and J.D. Young, 1994. Ground penetrating radar as a subsurface environmental sensing tool. Proceedings of the IEEE, 82(12): 1802-1822.
16. Daniel, D.E., Editor, 1993. Geotechnical Practice for Waste Disposal. Chapman and Hall.