Proceedings of the Peradeniya University Research Sessions, Sri Lanka, Vol.13, 18th December 2008

STUDY OF GROUND PENETRATING RADAR (GPR) WAVES UNDER HETEROGENEOUS SOIL CONDITIONS

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Introduction

Ground Penetrating Radar (GPR) has been used to identify and locate underground objects and to estimate soil moisture in deeper layers (Davis and Annan, 2002). It can also be used as a non-destructive tool in water resource managements such as examining the soil moisture variation during irrigation, drainage and advancing wetting pattern (Galagedara *et al.*, 2003; Galagedara *et al.*, 2005a), and capillary effects near the ground surface. Clear understanding of the wave behavior, selection and picking of the correct wave and its travel time, estimation of the sampling depth etc., are tedious task especially in complex subsurface conditions. Therefore, understanding the behavior of GPR wave propagation under complex heterogeneous soil conditions, different soil layer thickness and frequency by using numerical simulation will be useful in field applications of the GPR method. Objectives of this study were to; (i) comprehend the behavior of ground penetrating radar wave propagation under complex heterogeneous soil conditions, (ii) analyze the effect of soil layer thickness under different moisture contents and frequency on ground penetrating radar resolution.

Methodology

Numerical simulation

Numerical simulation with two layer soil model (Galagedara *et al.*, 2005b) was used by entering the selected relative dielectric constant (Kr) values related to four different moisture content in the Reddish Brown Earth (RBE) soil as; wet over dry, dry over wet, saturation over irrigation and irrigation over saturation (Table 1).

Common Mid Point (CMP) survey methodology was used and survey starts at the middle of the domain at the air-media l interface (Fig. 1). Both antennas are moved away from each other starting from this common mid point at a 0.1 m interval (Galagedara *et al.*, 2005b). These four combinations of two-layer soil model was used to simulate 20 GPR waves for 450 MHz and 200 MHz frequencies at each model run. The GPRMAX2D with 3 different electrical conductivities (0, 0.1,1 S/m) was used by gradually reducing the upper layer thickness (increasing the lower layer thickness towards the surface) of each two-layer model (Fig. 1).

Table 1. Moisture content and relative dielectric constant in selected moisture conditions of RBE soil.

Moisture condition	Moisture content (cm/m)	(Kr)
FC (wet)	29.1	16
PWP (dry)	16.8	9
Saturation	41.0	26
50% of the available water (irrigation)	22.6	12

Data analysis

The simulated output data were fed into "Picker" wave picking software (Sensor and Software Inc., 2003) and observed the behavior of ground waves and reflected waves in each model run. Further, arrival times of each direct ground and reflected events were picked and recorded. The estimated inter-layer moisture contents and layer thickness were analyzed graphically and statistically for each model run.

Results and discussion

Estimation of soil moisture content in upper layers

Estimated soil moisture content using the direct ground wave of GPR (Galagedara *et al.*, 2005a) started to change when upper layer thickness was gradually reduced. The minimum upper layer thickness where the moisture content starts to change due to the effect from the lower layer can be called as the minimum layer thickness or the "sampling depth" of the GPR direct ground wave. When the upper layer thickness reaches zero or near zero, the estimated moisture content will be equal to the true moisture content of the lower layer (Galagedara *et al.*, 2005b).

In both 200 MHz and 450 MHz frequencies, the estimated moisture content started to increase when the upper layer thickness was smaller than the minimum layer thickness for dry over wet soil layer (Fig. 2A) and irrigation over saturation soil layer models. As for the wet over dry soil layer (Fig. 2B) and saturation over irrigation soil layer models, the estimated moisture contents started to decrease when the upper wet layer thickness was smaller than the minimum thickness. However, the minimum layer thickness was found to be larger for the 200 MHz frequencies than the 450 MHz frequencies in all model conditions.

Estimation of the upper layer thickness

Estimated depths to the lower layer (wet, dry, saturated or irrigated layer depend on the selected model) were compared with actual depths in the each conceptual model. As shown in Figure 3, regression lines between the estimated depth and the true depth have strong linear relationships (regression correlation $R^2 \geq 0.99$). However, as seen in all model runs, regression lines are shifted above (depth is over estimated) from the 1:1 line. This over estimation implies that the measured travel time to the reflector is higher than the true travel time.

At the high electrical conductivity (1 S/m), all models failed due to high-energy attenuation recoded in literature (Davis and Annan, 2002). Simulated data with the 200 MHz frequency were difficult to pick at higher electrical conductivities due to a large wavelength. Intercepts at each simulation were significant (intercept $\neq 0$) due to a time shift when the peak of reflected wave was picked. All wet over dry and saturation over irrigation soil layer models (upper layer was wetter than the lower layer) were significant due to the influenced of the refracted wave.

Conclusions

The refracted wave can cause problems in field applications of the GPR method when a sharp wetting front contrast exists especially during early hours of irrigation. Also, it was found that the 450 MHz frequency antenna had higher vertical resolution than the 200 MHz frequency antenna. Therefore, the 450 MHz frequency antenna is much better than the 200 MHz frequency antenna when estimating small layer thickness or locating underground features such as utility cables, drainage pipe etc.

References

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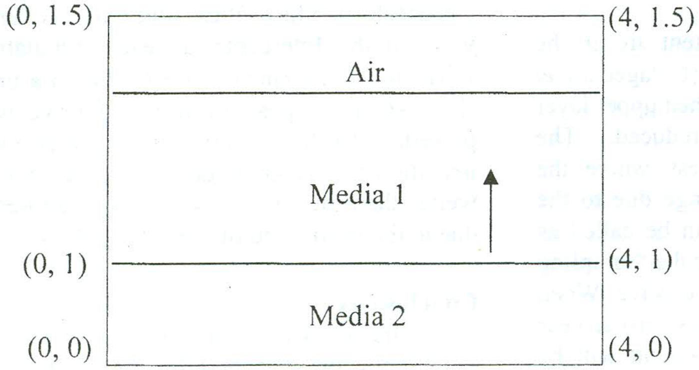

Figure 1. Schematic diagram to show the two-layer model domain (Galagedara *et al.*, 2005b).

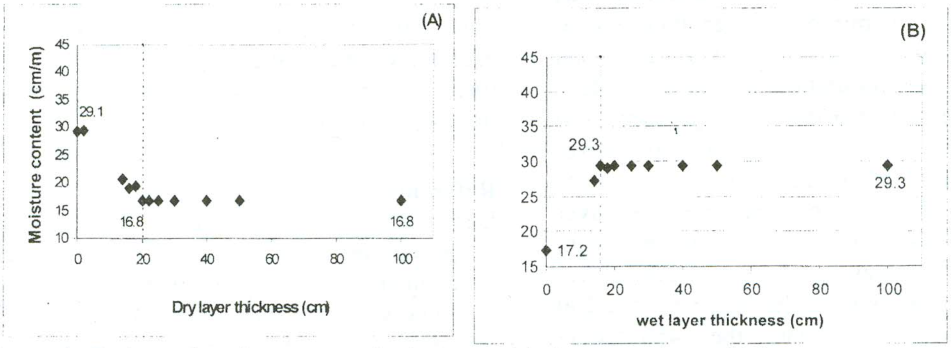

Figure 2. Estimated moisture content changes with the upper layer thickness at zero conductivity in dry over wet soil layer model (A) and wet over dry soil layer model (B) for 450 MHz frequency.

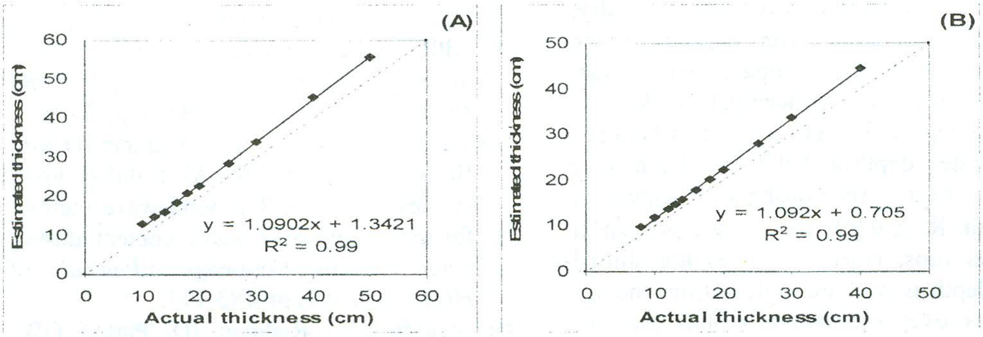

Figure 3. Comparison of the estimated depth (upper layer thickness) to the lower layer against the actual upper layer thickness with the 450 MHz frequency for wet over dry soil layer (A) and saturation over irrigation soil layer (B) models at 0.1 S/m conductivity.